Moisture Control for Dense-Packed Roof Assemblies in Cold Climates: Final Measure Guideline

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Chris Schumacher and Robert Lepage

Abstract:

There is little consensus on the incidence of and physics behind moisture problems in dense-packed roof assemblies. Only a handful of field research projects have considered the moisture performance of dense-packed roof assemblies and the majority of these were proprietary studies that were not made public. This document focuses on dense-packed insulation retrofits to roof assemblies in cold climates and identifies, describes and compares four strategies that designers, builders and manufacturers have implemented to avoid moisture problems in dense-packed roof assemblies.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

7.1.3 Moisture Control for Dense-Packed Roof Assemblies in Cold Climates: Final Measure Guideline

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Building Science Corporation

November 2012

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Definitions

ABS	Air Barrier System
BA	Building America Program
BSC	Building Science Corporation
ccSPF	Closed-Cell Sprayed Polyurethane Insulation
CFI	Cellulose Fiber Insulation
Dense-packed Insulation	Loose-fill fiber insulation that has been installed to high densities (usually more than 3.5 pcf for cellulose) using an insertion tube and techniques described in the BPI "Residential Building Envelope Whole House Air Leakage Control Installer Certification"
DOE	Department of Energy
EPS	Expanded Polystyrene
GWB	Gypsum Wall Board
MC	Moisture Content
ocSPF	Open-Cell Sprayed Polyurethane Insulation
OSB	Oriented Strand Board
RH	Relative Humidity
XPS	Extruded Polystyrene

1 Introduction

The following Guideline addresses moisture control strategies for assemblies that are insulated with dense-packed insulation. The vast majority of dense-packed insulation is installed in retrofit applications. Pioneers of the weatherization movement developed the dense-pack insulation method: loose fill insulations (primarily cellulose) were forced into the empty framing spaces in existing wall, roof & floor assemblies using insertion tubes and high pressure blowers. The method prevented insulation voids and ensured that cavities were completely filled with higher densities of cellulose insulation. Fitzgerald, Nelson & Shen provided one of the earliest explanations of the dense-pack insulation technique in an article for the January 1990 Home Energy Magazine (HEM 1990).

Many contractors and cellulose sales people falsely believe that dense-pack assemblies are 'airtight'. This has been shown not to be the case (Derome 2005, Schumacher 2010) – with disastrous consequences in mixed and cold climates, including climate zones 5, 6, 7 and 8, where roof rafters have been 'dense packed' with no provision for rafter ventilation (to remove moisture) or for control of condensing surface temperatures (to minimize moisture accumulation) (Lstiburek 2010). Approximately two (2) assemblies in ten (10) fail – typically within 10 years (Fitzgerald 2010).

This document, *Guideline for Moisture Control in Dense-Packed Assemblies*, focuses on dense-packed insulation retrofits to roof assemblies in cold climates. It is expected that other assemblies (e.g. retrofit floor applications, double-stud high performance walls in new construction, etc.) will be addressed in future guidelines.

There is little consensus on the incidence of and physics behind moisture problems in dense-packed roof assemblies. Only a handful of field research projects have considered the moisture performance of dense-packed roof assemblies and the majority of these were proprietary studies that were not made public. The only laboratory testing of these assemblies, conducted at Concordia University, focused on retrofits to the roof assemblies of historical buildings in Montreal (Derome & Fazio, 2000). Key field and laboratory findings are summarized in this Guideline. Demonstrative hygrothermal simulations are used to explain why some dense-packed roof assemblies work while others fail.

This Guideline identifies, describes and compares four strategies that designers, builders and manufacturers have implemented to avoid moisture problems in dense-packed roof assemblies.

The *Guideline for Moisture Control in Dense-Packed Assemblies* is intended for designers and contractors working in the weatherization and renovation industries.

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2 Risk Identification

For over 20 years now the retrofit industry has employed dense-pack insulation techniques to install insulation in poorly and uninsulated assemblies that are difficult to access (usually because they are enclosed by interior and exterior finishes that cannot be removed). Dense-packed insulation is increasingly selected for upgrades to existing wall assemblies, floor assemblies and inaccessible roofs (e.g. low-slope roofs, cathedral ceilings, etc.) Dense-packed insulation may also be used in the construction of the cathedralized attic assemblies necessary to bring ductwork into the conditioned space or to convert traditional ventilated attics to conditioned living spaces.

It is generally accepted that the dense-pack insulation technique improves the thermal comfort and performance of the building by reducing both conductive heat loss and air leakage through enclosure assemblies; however, the approach is not without its risks and industry experience has led some to suggest that *dense-packed roof assemblies* need greater attention (Lstiburek 2010).

2.1 Moisture Sources

Dense-packed roof assemblies are subject to the same moisture sources as all roof assemblies: bulk water (introduced by leakage), built-in moisture, and water vapor (introduced by vapor diffusion or air leakage).

Bulk Water

The largest potential moisture source in roof assemblies is bulk water leakage. Bulk water is introduced at the exterior of roof assemblies in the form of rainwater and meltwater (from ice & snow). The means and methods to prevent the bulk water penetration and moisture damage are well developed and understood. Roof underlayment and eaves protection prevent incidental water (i.e. water that penetrates the roofing) from moving below the sheathing and into the body of the assembly or through to the occupied space (Lstiburek, 2006). Flashings prevent bulk water penetration at interfaces with walls, at openings (e.g. windows and hatches) and at service penetrations (e.g. plumbing & electrical stacks, air intake/exhaust vents, etc.) (Lstiburek, 2006).

Built-in Moisture

Moisture is said to be ‘built-in’ when damp or wet materials are enclosed in an assembly during construction. Built-in moisture can be introduced through the use of wet materials or through unprotected materials that are wet by rain or meltwater during construction.

Built-in moisture is not typically a significant moisture source for dense-packed roof assemblies. Dense-pack insulation contractors avoid using wet insulation materials as these tend to plug up the installation equipment (i.e. the hoses and injection tubes). Furthermore, dense-packed insulation is typically installed in existing assemblies or in new assemblies after the roofing is installed so the materials are not left unprotected from rain or meltwater during construction.

Water Vapor

Another moisture source, water vapor, is often considered but not as well understood. Through the winter months in cold and mixed climates the indoor air can provide a significant source of water vapor. Water vapor moves into and through the assembly by two mechanisms: vapor diffusion and airflow. Methods to control vapor diffusion and air movement are well documented (Latta, 1973, Hutcheon, 1985, Quirouette, 1985, Straube, 2005) but rarely well executed. Airflow is capable of transporting hundreds of times more moisture than vapor diffusion (Wilson, 1961); hence it is important to control airflow to prevent moisture problems and ensure the durability of the building enclosure.

Many contractors and cellulose sales people falsely believe that dense-pack assemblies are 'airtight' and immune to air leakage-related moisture problems. This has been shown not to be the case (Derome 2005, Schumacher 2010) – with disastrous consequences in cold and mixed climates where roof rafters have been 'dense-packed' with no measures to minimize moisture accumulation or to promote drying. Approximately two (2) assemblies in ten (10) fail – typically within 10 years (Fitzgerald 2010).

Unfortunately there is little consensus on the incidence of and physics behind moisture problems in dense-packed roof assemblies and, as a result, there is little guidance on measures to avoid these problems. This document seeks to fill that gap.

2.2 Hygrothermal Simulation of Dense-Packed Roof Assemblies

Modern hygrothermal simulation software provides building scientists with a means of exploring moisture problems in dense-packed roof assemblies. The authors strongly caution against using *only* hygrothermal simulations as the basis for the design of any building assembly. Hygrothermal simulations are but one tool available to building scientists and should be used in combination with other important tools: experience (forensic, field, laboratory), theory (moisture, heat, etc.) and common sense.

WUFI Pro 5.1 is one of the most advanced commercially available hygrothermal simulation programs in use today. It is used by many in the construction industry in North America, Europe, Asia and other parts of the world. The accuracy of WUFI accuracy has been verified (by the Fraunhofer Institut Bauphysik in Holzkirchen, Germany – www.wufi.de) against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over the past 15 years.

WUFI Pro 5.1 was used to prepare demonstrative hygrothermal simulations to facilitate an explanation and comparison of the hygrothermal performance observed through forensic work, laboratory testing and field research. The varied field experience and lack of consensus on moisture problems is explained. Finally, the document presents and compares four real world strategies to avoid moisture problems in dense-packed roof assemblies.

Climate

Theory suggests that colder roof surface temperatures should result in more moisture problems in dense-packed roof assemblies. This is influenced by a number of factors: there can be a higher rate of vapor diffusion (due to higher vapor pressure differences); there is a greater potential for air leakage condensation (due to colder condensing surface temperatures); and higher roof sheathing equilibrium moisture contents (due to colder temperatures and higher RH at the sheathing). Field experience confirms that dense-packed roof assemblies in northern climates experience more problems than those in southern climates.

For the purposes of our demonstrative hygrothermal simulations we have chosen to use the WUFI climate data for the city of Chicago. Metropolitan Chicago is the third largest city in the United States; it has a significant population (almost 9.5 million as of the 2010 U.S. census) and housing stock (approximately 3.4 million housing units as of the 2010 census); the city is located in a cold climate (DOE Zone 5) and the results of the simulations are expected to be relevant for many other large, Zone 5 urban centers including Detroit, Boston, Denver, Pittsburgh, Albany, Indianapolis (EERE, 2010).

Figure 1 shows the outdoor temperature and relative humidity (RH) from the WUFI climate file for the city of Chicago. The range of hourly measured RH (blue) and temperature (orange) are represented by the thin lines while the running average is represented by the thick lines.

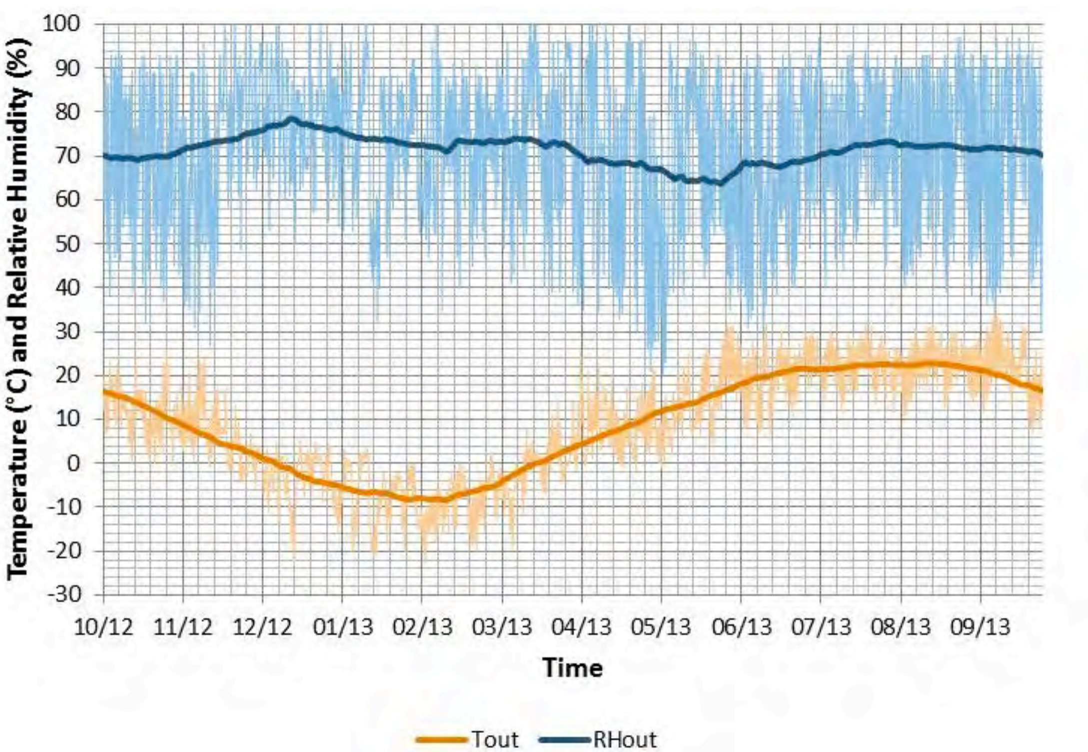


Figure 1 – Temperature and RH for the Climate of Chicago

Indoor Conditions

Building enclosure performance is often strongly connected to indoor conditions. Hygrothermal simulations were prepared to demonstrate the impact of various wintertime indoor relative humidity levels. Figure 2 shows the indoor temperature and RH assumed for the demonstrative hygrothermal simulations. The indoor temperature was assumed to vary between 20 °C (68 °F) in the winter and 24 °C (75.2 °F) in the summer. Three levels of indoor moisture are considered: 'low' (20% RH in winter), 'normal' (30% RH in winter) and 'high' (40% RH in winter). For reasons that will become obvious, the simulations did not consider 'very high' wintertime humidity (e.g. 50% RH) although some homeowners do maintain their houses at these often-problematic levels. In all cases the summertime RH was assumed to peak at 60%.

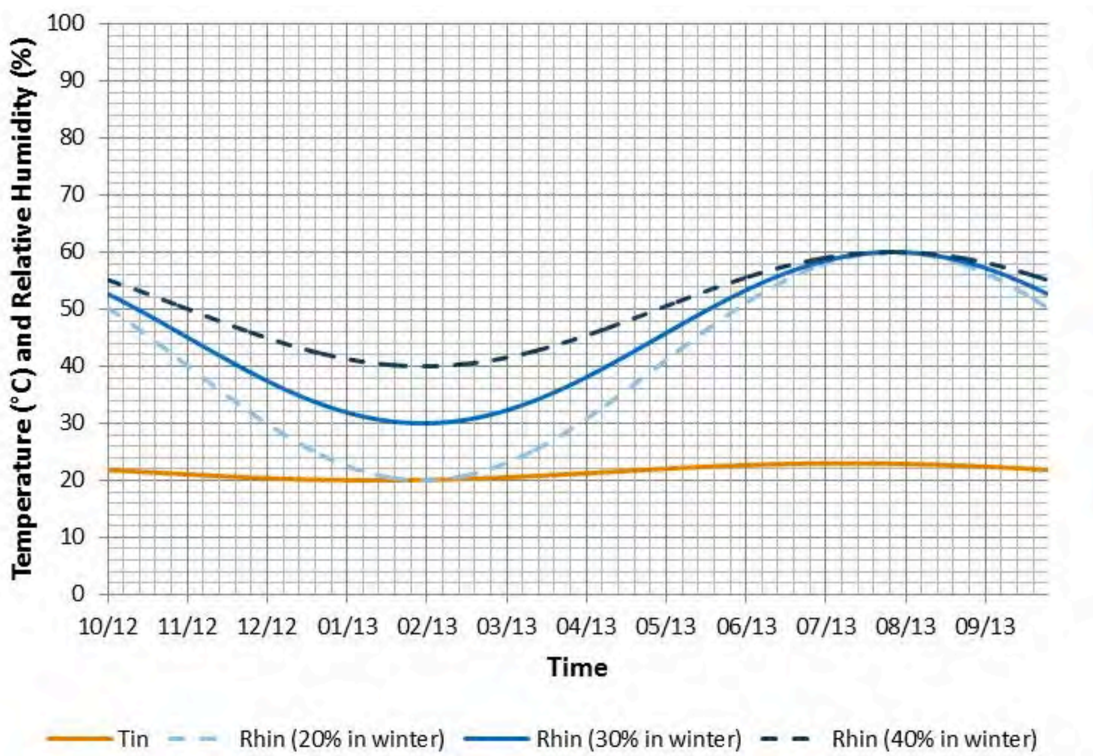


Figure 2 – Indoor Temperature and RH Assumed for Hygrothermal Simulations

Many wrongly believe that lower wintertime indoor humidity levels result in comfort problems including dry skin, eyes, etc. however, authoritative references now recognize that, at temperatures below 25 °C (77 °F), there is little connection between humidity and human comfort (ASHRAE HOF 2009).

It is not uncommon for older and / or leaky houses in cold climates to have very low wintertime indoor humidity levels (e.g. 10-20% RH); however, humidity levels can increase (e.g. to 40-50% RH) when airsealing measures result in extreme reductions in air leakage (e.g. to 2 ACH50 and lower). High indoor humidity levels (especially in materials) are related to dust mites, mold (often as a result of surface condensation) and other human health concerns (ASHRAE HOF 2009).

Building scientists recommend installing ventilation systems to control wintertime humidity levels. At minimum homeowners often wish to control indoor RH to prevent condensation on windows. Table 1 presents recommended maximum RH levels to prevent condensation at various outdoor temperatures (adapted from ASHRAE Systems & Equipment 2008). The middle column has been added to indicate the number of hours below the given outdoor temperature during a typical Chicago year (TMY3 for Chicago O'Hare).

Table 1 – Maximum Indoor Relative Humidity to Avoid Window Condensation

Outdoor Temperature			Limiting RH (%)	
(°C)	(°F)	Hours in Chicago	Single Glazing	Double Glazing
5	41	3140	41	60
0	32	1788	31	52
-5	23	895	23	45
-10	14	382	17	39
-15	5	147	12	33
-20	-4	25	9	28
-25	-13	0	6	24
-30	-22	0	4	20
-35	-31	0	3	17

This analysis of Table 1 suggests that indoor humidity levels of 40% RH will result in over 3000 hrs of condensation on a single glazed window and almost 400 hrs of condensation on a double glazed window. Forensic experience suggests that interstitial (i.e. hidden) condensation can occur in assemblies even when there is no evidence of condensation on window surfaces.

Typical Pre-retrofit Roof Assembly

Figure 3 shows an example of a typical pre-retrofit roof assembly. Uninsulated and poorly insulated cathedral ceiling and low-slope roof assemblies are popular candidates for retrofit using dense-pack insulation techniques. Dense-pack insulation techniques have also been used to convert conventional ventilated attics (i.e. roof assemblies with insulation on the attic floor) into cathedralized attics (i.e. roof assemblies with insulation between the rafters or trusses). The roof assembly of Figure 3 is framed with dimensional lumber rafters; however, the dense-pack insulation retrofit approach is also valid for assemblies that are framed using other methods such as parallel chord trusses or wood-I joists.

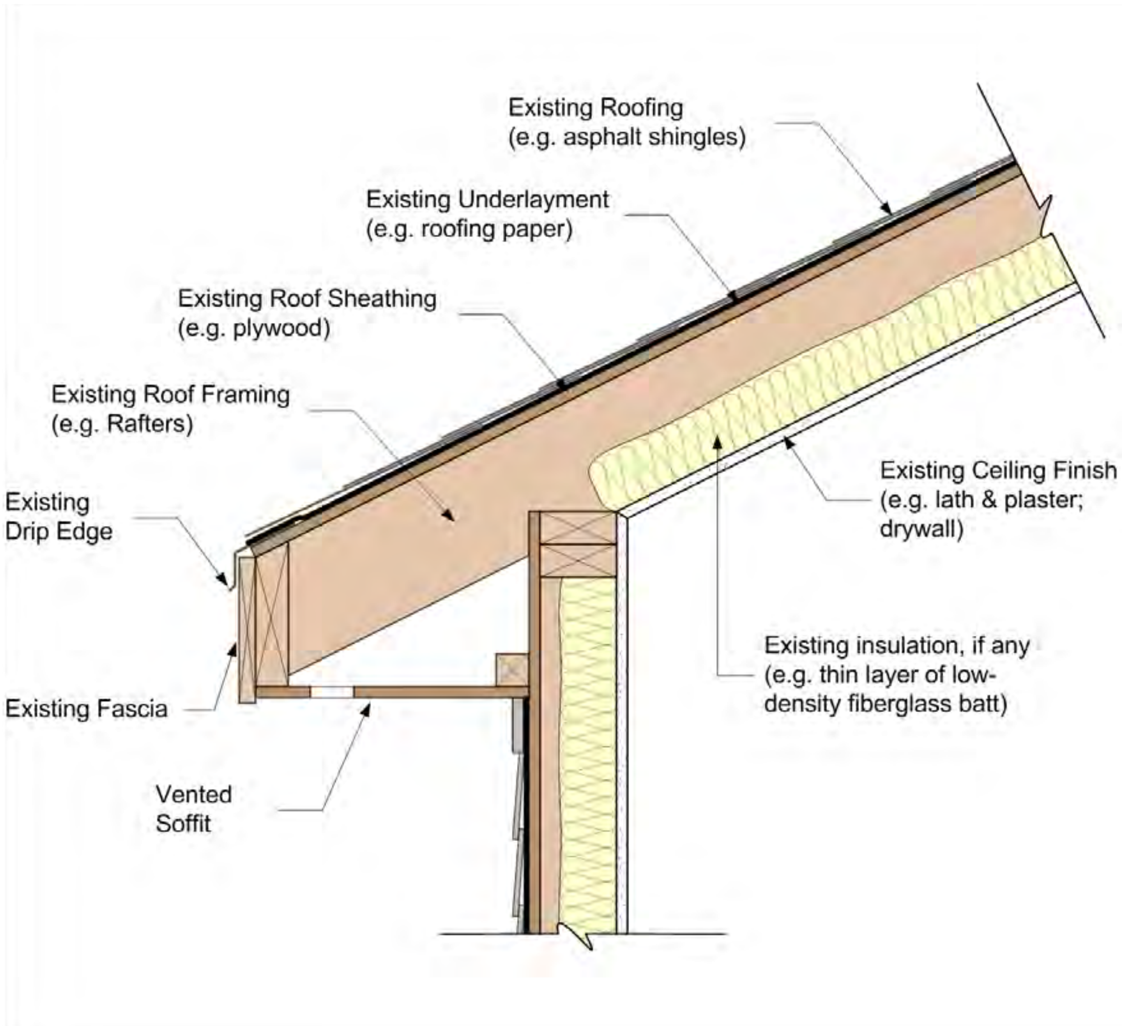


Figure 3 – Example of Pre-Retrofit Assembly for Hygrothermal Simulations

Common (& Potentially Problematic) Insulation Retrofit

Figure 4 shows the most common insulation retrofit solution for a roof assembly that did not have any existing insulation (e.g. typical of many houses constructed before the 1960s). Fiberglass batt insulation is used to plug the opening at the bottom of the framing cavity. Insulation is installed from the outside (through the soffit) or install holes are drilled through the existing ceiling finish. An insertion tube technique is used to dense-pack the cavity space with loose-fill insulation (e.g. cellulose or glass fiber). The soffit is replaced and any install holes are plugged and the ceiling finish is repaired. Wall and floor cavities are typically retrofitted with dense-packed insulation at the same time.

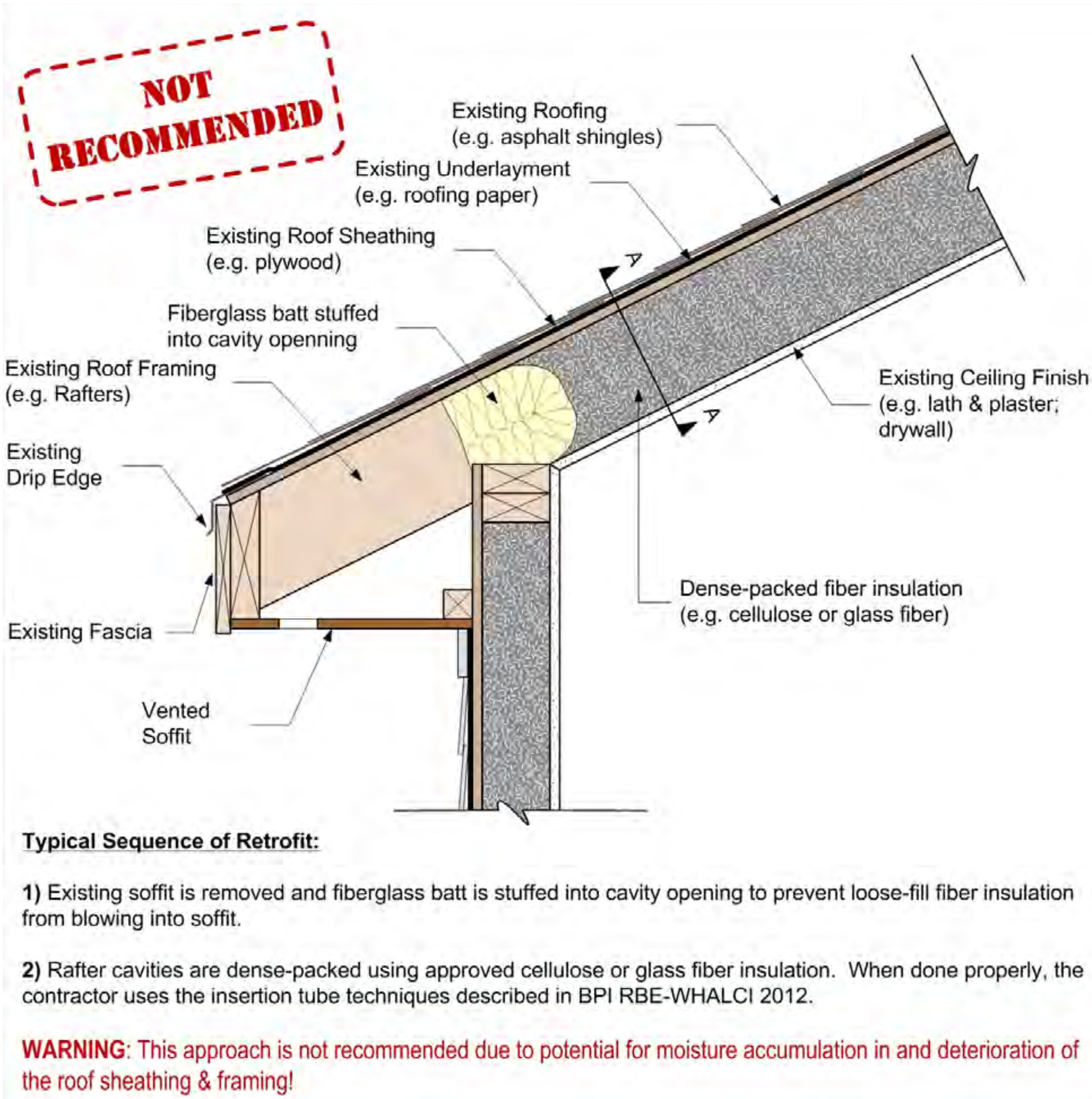


Figure 4 – Example of Common (not recommended) Insulation Retrofit

Thin layers of existing low-density fiberglass batt insulation are easily compressed to a fraction of their original thickness (usually less than 25 mm or 1 in.) by the expanding dense-pack insulation. The installer must take care to push the insertion tube into the space on the exterior side of any existing low-density insulation so the expanding dense-pack insulation compresses and crushes the existing low-density insulation material against the indoor side (e.g. lath, GWB).

Figure 5 shows the model of the common (not recommended) retrofit assembly that was created for the demonstrative hygrothermal simulations. The model reflects a slice through the insulated part of the assembly (Section AA) of Figure 4.

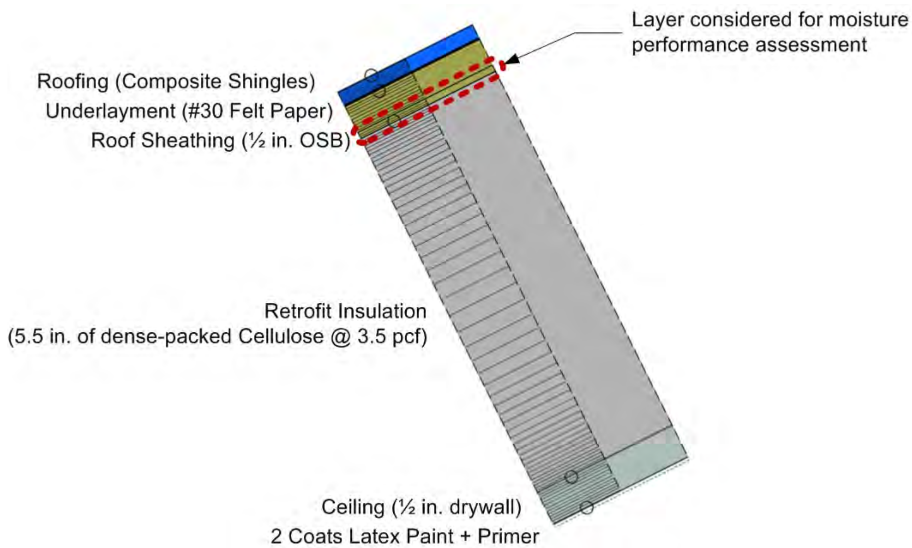


Figure 5 – Model of Common (not recommended) Retrofit Assembly for Hygrothermal Simulations

Assessing Moisture Performance

Laboratory testing and field experience indicate that roof sheathing deterioration can result from moisture problems in dense-packed roof assemblies (Derome & Fazio 2000, Fitzgerald 2010, Lstiburek 2010). Wood-based roof sheathings deteriorate as a result of rot brought on by prolonged exposure to elevated moisture content. The rot tends to start in a thin layer near the inside face of the roof sheathing, as indicated by the dashed red box on the model of Figure 5. In this document the moisture performance and relative risk of different scenarios are assessed by considering the predicted temperature and moisture content in a 1/8 in. thick layer at the inside face of the roof sheathing.

Figure 6 shows the predicted temperature (orange line) and moisture content ($MC\%_{wt}$, blue line) at the inside of the roof sheathing in the common retrofit assembly (from Figure 5) for a North-facing roof with wintertime indoor at 40% RH. Three years of predicted conditions are shown in the plot. The MC appears higher in the first year because a starting sheathing MC of 12% was assumed for the simulations; the assembly dried over the first year and the sheathing started the second year under 10% MC; the predicted conditions for the third year match those of the second year so the simulation is said to be in pseudo equilibrium.

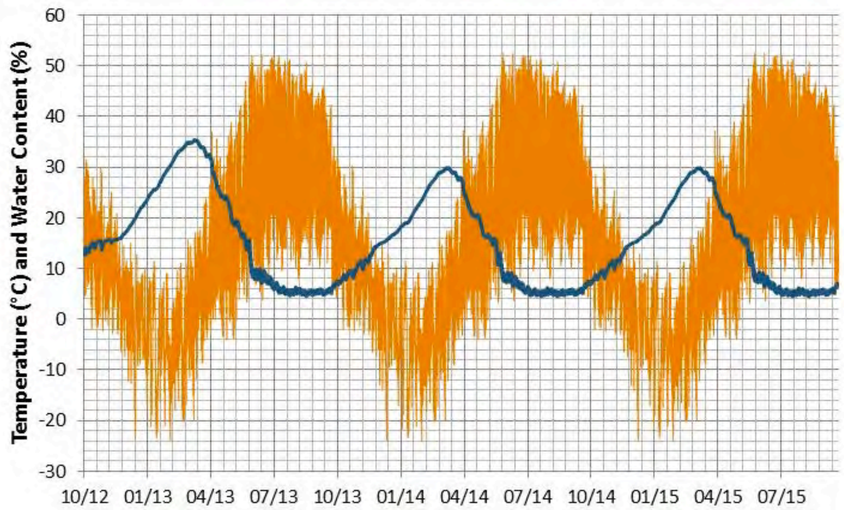


Figure 6 – Predicted Temperature & MC at Inside of Sheathing on North-facing Common Retrofit Assembly with Wintertime Indoor 40%RH

Mold growth is generally accepted to occur when wood moisture contents are in excess of 20% and the temperatures are in the range of 4-40°C (39-104°F). Rots typically require moisture contents in excess of 28%. (Viitanen 1988, Hens 2000, Sedlbauer 2004, Wang et. al. 2010)

The important considerations for assessing the risk of mold and rot are temperature, moisture content and time. Figure 7 summarizes all three of these to facilitate an assessment of the risk for biodegradation of the roof sheathing. The light grey line shows the number of hours the inside face of the sheathing is predicted to be at or above 12% MC for any given temperature (in 1°C or 1.8°F temperature bins). For example, at a temperature of 0°C (32°F), the MC is predicted to be at 12% or higher for 170 hrs in a year.

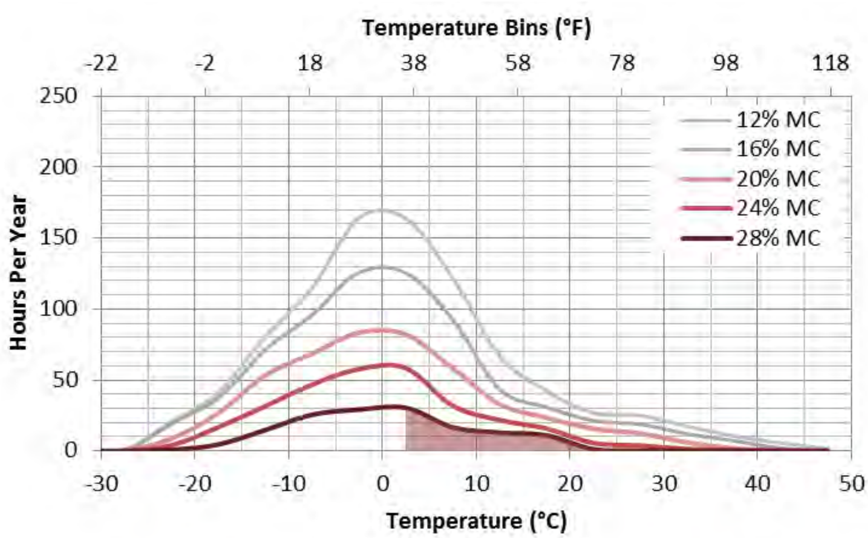


Figure 7 – Biodegredation Risk Plot for North-facing Roof with Wintertime Indoor @ 40%RH

The dark grey line plots the predicted hours of 16% MC and greater. The light red line plots the predicted hours of 20% MC and greater (generally accepted as the threshold MC for mold growth). The medium red line plots the predicted hours of 24% MC and greater. Finally, the dark red line plots the predicted hours of 28% MC and greater (generally accepted as the threshold for rot).

Most historical dense-pack insulation retrofits were completed with cellulose fiber insulation (CFI) and much of the insulation material employed borate fire retardants. In many cases the borates likely prevented mold from growing on wood surfaces that were in contact with the dense-pack insulation (e.g. the underside of the roof sheathing or the top edge of framing members); however the borates cannot prevent rot from developing in the core of the roof sheathing. The shaded area in the plot of Figure 7 indicates the hours for which predicted moisture content and temperature are both conducive to rot.

The predicted moisture contents depicted in Figure 6 agree with the trends identified in large-scale hot box testing at Concordia University and with observations reported by researchers conducting forensic investigations in the field.

Forensic investigators have reported the highest sheathing moisture contents in North-facing roof assemblies; moderate to high moisture contents in East- & West-facing and low-slope roof assemblies; and moderate moisture contents in South-facing roof assemblies. The predicted MCs (for base retrofit roof assemblies facing the cardinal directions), shown in Figure 8, agree with field observations.

The agreement between the demonstrative hygrothermal simulations, theory, laboratory and field observations is important because it suggests that the model has been appropriately setup to capture the trends expected and observed in real life.

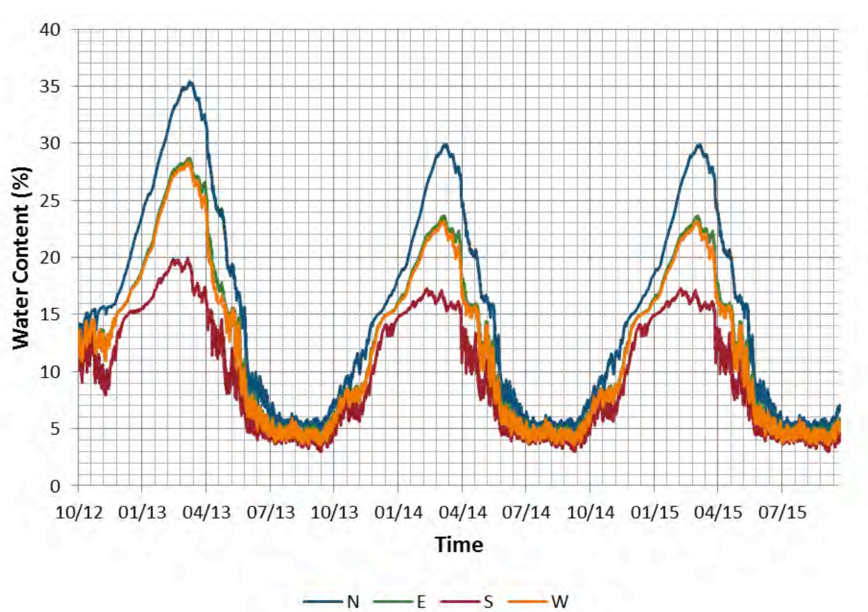


Figure 8 – Predicted MC at Inside of Sheathing on Common Retrofit Roof Assemblies Facing Cardinal Directions and with Wintertime Indoor @ 40%RH

2.3 Why Many Dense-Packed Roof Assemblies Have Worked

Forensic investigations, laboratory studies and hygrothermal simulations all suggest the potential for moisture problems (specifically deterioration of wood sheathing and wood framing) in dense-pack insulated roof assemblies yet many dense-packed roof assemblies appear to demonstrate acceptable performance. How can this be? Much of the explanation likely lies in the wintertime indoor humidity levels that are achieved / maintained in houses that have been retrofit using dense-pack insulation techniques.

Figure 9 shows the predicted MCs for North-facing roof assemblies that are exposed to various wintertime indoor humidity levels. If 'high' (e.g. 40% RH) or higher wintertime indoor humidity levels are experienced, the MC at the inside face of the sheathing is expected to peak at 30% (blue line on the graph) or higher in the early spring when temperatures are sufficient to support rot; conversely, if 'normal' (e.g. 30% RH) wintertime indoor humidity levels are experienced, the MC is expected to peak just over 20% (yellow line on graph); finally, if the low (e.g. 20% RH) wintertime indoor humidity levels are experienced, the MC is expected to peak at around 15% (dark red line on graph). Clearly indoor humidity levels play a significant role in ensuring acceptable moisture performance of dense-pack insulated assemblies.

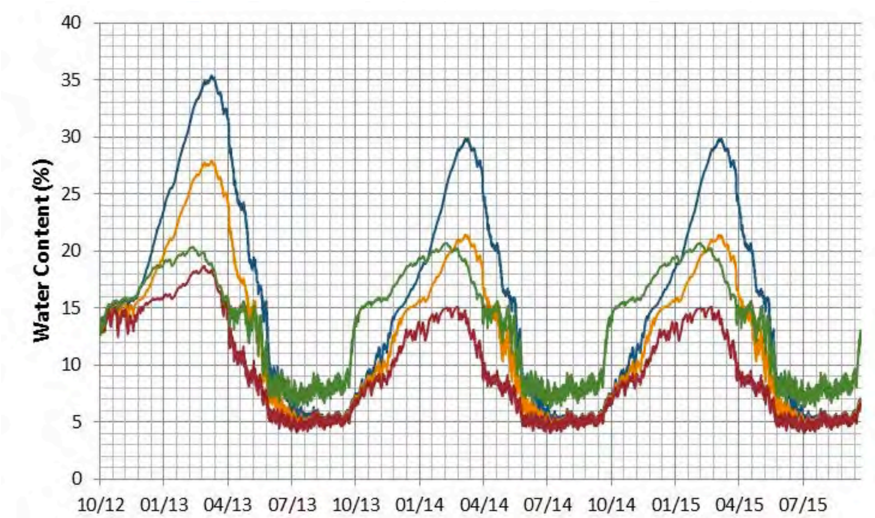


Figure 9 - Predicted MC at Inside of Sheathing on North-facing Roof Assemblies with Various Wintertime Indoor Humidity Levels

There is a strong connection between wintertime indoor humidity levels and building air leakage. Weatherization programs have widely adopted dense-pack insulation because the dense-pack techniques have a reputation for increasing building airtightness, reducing the energy use associated with air infiltration, and improving thermal comfort. In a January 1990 Home Energy Magazine article, Fitzgerald, Nelson & Shen reported pre- and post-retrofit blower door test results for four houses that were retrofit using only dense-pack cellulose insulation: air leakage rates (i.e. cfm50) were reduced by at least 39.6% and as much as 54% (HEM 1990); however, most candidate buildings for retrofit start out very leaky.

It is likely that, when dense-pack insulation techniques are used, the airtightness of many older houses is improved from 10+ ACH50 to 4 - 6 ACH50; enough to result in noticeable operating cost savings & comfort improvements but not enough to result in high wintertime indoor humidity levels. If wintertime indoor humidity is maintained (either accidentally as a result of air leakage or intentionally through the use of mechanical ventilation systems) at lower levels, the incidence of moisture problems will be low.

2.4 Why Some Dense-Packed Roof Assemblies Have Failed

Dense-pack insulation techniques are increasingly used as part of deep energy retrofit projects and in the construction of new, low-energy buildings. Very high levels of airtightness are routinely achieved in these two classes of buildings and higher wintertime indoor humidity levels often exist as a result of low air change rates. Higher wintertime indoor humidity levels are also often measured in multi unit residential buildings (MURBs) where significant amounts of moisture are produced in small volume spaces.

Some have suggested that even 'high' wintertime indoor humidity levels (e.g. 50% RH) could be tolerated if vapor barriers or vapor retarding paints were used to limit vapor diffusion into dense-pack insulated building enclosure assemblies. Misguided hygrothermal simulations of dense-packed roof assemblies with warm side vapor retarders have even been used to support this idea (represented by the green line in Figure 9); however, a number of problems with these assemblies have been identified through field experience:

- Built-in moisture can be trapped between the vapor impermeable roofing on the exterior side of the assembly and the vapor retarding layers on the inside of the assembly;
- Even very small amounts of air leakage can carry enough moisture into the roof assembly to result in elevated moisture contents and deterioration of wood-based structural elements.

Field Experience

Field experience indicates a connection between moisture problems in dense-packed roofs and elevated indoor humidity levels. A number of building scientists and weatherization experts have investigated moisture problems in dense-packed roof assemblies. Fitzgerald has collected photographs and details regarding moisture problems in numerous Zone 3-7 low-slope roofs that were dense-packed with fibrous (air permeable) insulations. Figure 10 shows the damage and air leakage path identified through one such investigation.

Figure 10 – Air Leakage Resulted in Rot of Framing and Roof Deck in 2 Years (Fitzgerald 2010)

Laboratory Experience

Laboratory testing has confirmed the connection between small amounts of air leakage and dangerously high roof sheathing and framing moisture contents in roof assemblies that are dense-packed using the common (not recommended) retrofit approach (Derome & Fazio, 2000). Derome and Fazio measured significantly higher moisture content in dense-packed cellulose insulation that was exposed to airflow travelling along short leakage paths (i.e. less than 400 mm or 16 in.) as illustrated in Figure 11 and lower moisture content in the material that was exposed to airflow travelling along long leakage paths (i.e. over 1.2 m or 4 ft.) as illustrated in Figure 12.

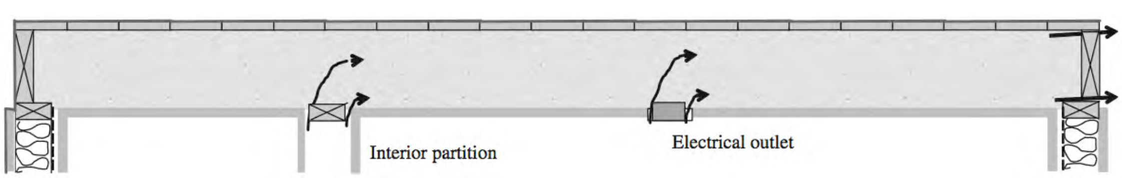
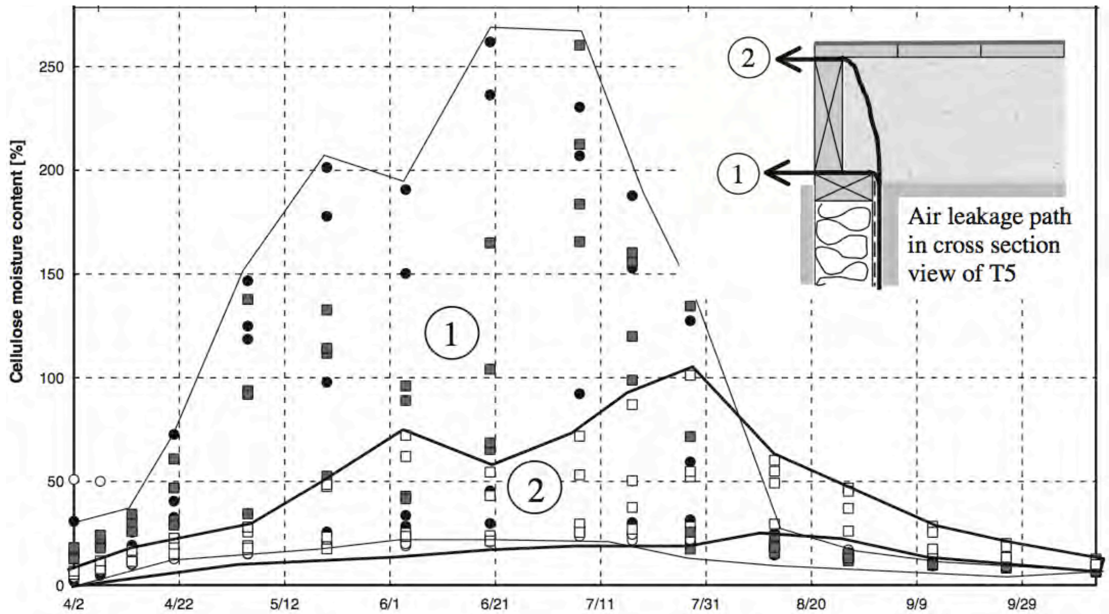
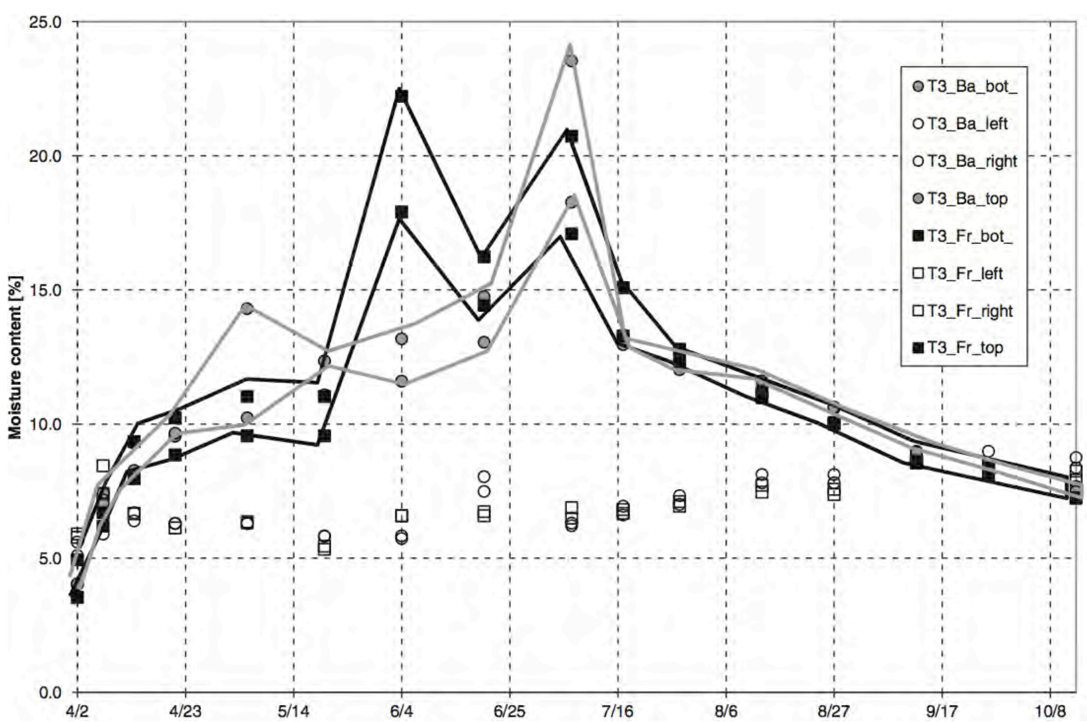


Figure 11 – Long Flow Path Schematic (Derome 2005)



Moisture content in the cellulose insulation of T5 and L5T3 assemblies with short air leakage flow path. The bold-lined zone groups the cellulose specimens under the deck, corresponding to an airflow path 250-400 mm (10-16 in.) long. The fine-lined zone groups cellulose specimens at the bottom of the assembly, corresponding to an air leakage flow path about 100 mm (4 in.) long through the insulation. The inset gives the position of the air paths through a cross-sectional view of the assembly.

Figure 12 – Short Flow Path Schematic & Measured Cellulose MC (Derome 2005)



Moisture content distribution in the cellulose insulation of 200 mm (8 in.) high T3 assembly with long air leakage flow path. The black-lined zone groups the cellulose moisture content samples near the exit end of the assembly. The grey lined zone groups samples close to the interior partition (i.e. the air inlet)

Figure 13 – Long Flow Path Cellulose MC Measurements (Derome 2005)

Estimating Air Leakage Rates for Dense-Packed Assemblies

A recent Building America research report documented test methods developed to measure the airflow resistance of dense-packed insulation materials (Schumacher 2011). The report also summarized benchmark testing of the airflow resistance of more than 30 full-scale wall specimens of dense-packed cellulose insulation. Dense-pack airflow resistance targets were recommended on the basis of these benchmark tests: at an installed density of 3.5 pcf, target airflow rates of 1.68 lps50/m^2 (0.33 cfm50/ft^2) and 5.08 lps50/m^2 (1.0 cfm50/ft^2) were recommended for long path tests (1.15 m or 45.5 in.) and short flow path tests (0.4 m or 16 in.) respectively. In these benchmark tests airflow rates were normalized for the cross-sectional flow area. For the purposes of comparison and discussion it is useful to normalize the flow rates for the test wall surface area and adjusted to in-service pressure differences. The resulting values are summarized in Table 2.

Table 2 – Estimated Air Leakage Rates for Dense-Packed Assemblies

	Long Flow Path	Short Flow Path
Recommended Material Target (Airflow @ 50 Pa/ Cross-sctn. Flow Area)	1.68 lps50/m^2 (0.33 cfm50/ft^2)	5.08 lps50/m^2 (1.0 cfm50/ft^2)
Normalized for Test Wall Surface Area (Airflow @ 50 Pa / Wall Surface Area)	0.050 lps50/m^2 (0.0098 cfm50/ft^2)	0.15 lps50/m^2 (0.030 cfm50/ft^2)
Adjusted to Pressure Diff. of 10 Pa (Airflow @ 10 Pa / Wall Surface Area)	0.013 lps10/m^2 (0.0025 cfm10/ft^2)	**0.031 lps10/m^2 (0.0061 cfm10/ft^2)**
Adjusted to Pressure Diff. of 4 Pa (Airflow @ 4 Pa / Wall Surface Area)	**0.006 lps4/m^2 (0.0012 cfm4/ft^2)**	0.013 lps4/m^2 (0.0025 cfm4/ft^2)

For the pressure differences and flow path lengths considered, the air leakage rate is expected to be in the range of 0.006 lps/m^2 or 0.0012 cfm/ft^2 (for a long flow path and a small, 4 Pa driving pressure) to 0.031 lps/m^2 or 0.0061 cfm/ft^2 (for a short flow path and larger, 10 Pa driving pressure). These air leakage rates, identified by the blue and red shading in Table 2, are justified for dense-pack insulation enclosure retrofits where most of the airflow resistance is provided by the installed dense-pack insulation material.

How Much Air Leakage is Typical?

Little research has been done to quantify the air leakage through various building enclosure elements (e.g. walls, floors, roofs, etc.) in real houses. Harrje, Born, Dickerhoff and others conducted studied air leakage of building components in the early 1980s. This work serves as the basis for the ASHRAE's guidance on air leakage distribution: the ASAHRAE Handbook of Fundamentals suggests that 3 – 30% of the total leakage area is associated with ceiling details (ASHRAE HOF 2009).

Table 3 provides an estimate of the range of ceiling air leakage that might occur through the ceiling of an 1800 sq. ft. one-storey home at a pressure difference of 10 Pa. Table 4 provides similar estimates for a pressure difference of 4 Pa.

Table 3 – Estimated Ceiling Air Leakage at 10 Pa Pressure Difference

Blower Door Test Result	Estimated Total Air Leakage @ 10 Pa		Ceiling Air Leakage					
			Low (3% of total)		Mean (18% of total)		High (30% of total)	
ACH 50	lps	cfm	lps/m^2	cfm/ft^2	lps/m^2	cfm/ft^2	lps/m^2	cfm/ft^2
6	269	569	0.048	0.009	0.29	0.057	0.48	0.095
5	224	474	0.040	0.008	0.24	0.047	0.40	0.079
4	179	379	0.032	0.006	0.19	0.038	0.32	0.063
3	134	285	0.024	0.005	0.14	0.028	0.24	0.047

Table 4 – Estimated Ceiling Air Leakage at 4 Pa Pressure Difference

Blower Door Test Result	Estimated Total Air Leakage @ 4 Pa		Ceiling Air Leakage					
			Low (3% of total)		Mean (18% of total)		High (30% of total)	
ACH 50	lps	cfm	lps/m^2	cfm/ft^2	lps/m^2	cfm/ft^2	lps/m^2	cfm/ft^2
6	148	314	0.027	0.005	0.16	0.031	0.27	0.052
5	123	261	0.022	0.004	0.13	0.026	0.22	0.044
4	99	209	0.018	0.003	0.11	0.021	0.18	0.035
3	74	157	0.013	0.003	0.08	0.016	0.13	0.026

If a ceiling assembly is retrofit with dense-pack insulation and the estimated assembly leakage rates of Table 2 are realized, the assembly would have air leakage comparable to the tightest of the ceiling assemblies (the blue shaded cases) in Table 3 and Table 4.

Dense-pack insulation techniques can and do result in very tight assemblies; however, in cases where all of the air tightness is provided by the dense-pack, there will still be some small amount of air leakage (Schumacher 2011). When warm, moist indoor air leaks from the occupied space, up into the roof assembly, it travels through small voids or 'micro ducts' between the fiber insulation and the bottom of the roof sheathing or framing. Small amounts of air leakage have been demonstrated to cause moisture problems in dense-pack insulated assemblies in the laboratory (Derome & Fazio, 2000) and through forensic field investigations (Fitzgerald 2010, Lstiburek 2010).

Figure 15 presents a biodegradation risk plot for a north-facing common (not recommended) retrofit roof assembly with a wintertime indoor humidity of 40% RH and a very small air leak (0.006 lps/m^2 or 0.0012 cfm/ft^2). When this plot is compared to the no leak case of Figure 7 (reproduced in Figure 14 for convenience), we see a significant increase in the number of hours conducive to rot. The hygrothermal simulations demonstrate the sensitivity to air leakage that has been identified through field investigations and laboratory research.

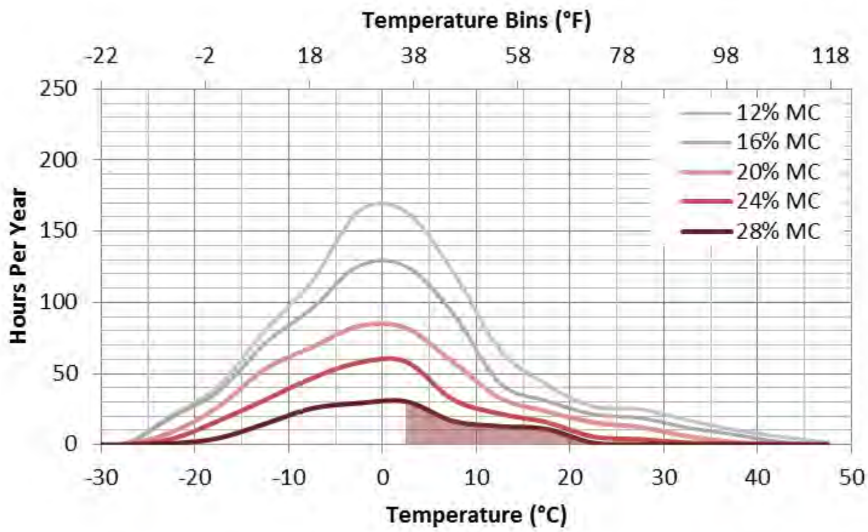


Figure 14 – Biodegredation Risk Plot for North-facing Roof with Wintertime Indoor @ 40%RH (no air leaks)

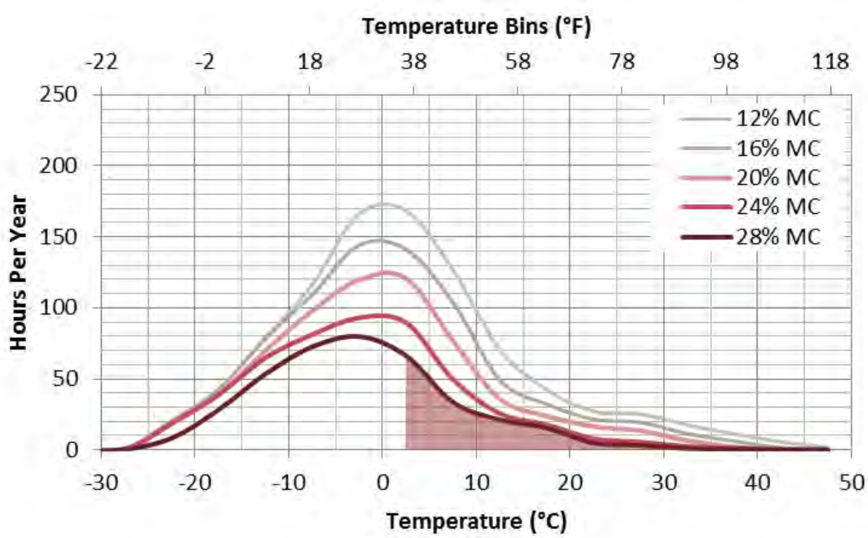


Figure 15 – Biodegredation Risk Plot for North-facing Roof with Wintertime Indoor @ 40%RH and 0.0012 cfm/ ft^2 air leak

Section 3 of this guideline describes and compares four strategies to reduce the potential for moisture problems in dense-packed roof assemblies; Section 4 includes conceptual details and recommendations for implementing the four strategies.

3 System Interactions

The potential for moisture problems can most effectively be reduced by first addressing the moisture source. The most significant moisture sources for dense-packed roof assemblies are bulk water, built-in moisture and indoor relative humidity. Bulk water should be managed through the proper use of roofing materials, underlayments & flashings and through good roof maintenance. Built-in moisture can be avoided through awareness of site conditions and monitoring of material moisture contents up to and immediately preceding close in. Indoor humidity levels should be controlled through the use of proper ventilation systems and, for cold climates, wintertime indoor humidity levels should be maintained above 25%RH for comfort but below 40% RH when outdoor temperatures are below 4.4°C (40°F) and below 30% RH when outdoor temperatures are below -1.1°C (30°F).

It is rarely possible to eliminate all moisture sources so the building enclosure should be designed to balance the rates of moisture deposition, accumulation and drying. The building industry has employed several strategies to manage this moisture balance. This document reviews four of those strategies:

1. Exterior Insulation
2. Hybrid Insulation
3. Bottom-Ventilated Decks
4. Top-Ventilated Decks

The first two strategies are well developed, have a long history of performance in many houses over wide geographic regions and have been adopted by the code; the 3rd and 4th strategies have a shorter history but have received significant attention from builders.

3.1 Exterior Insulation

Exterior insulation provides the most effective means of controlling moisture accumulation at the roof sheathing. In roof retrofits and new construction rigid board insulation (e.g. PIR, XPS, or EPS) is installed over the roof deck as illustrated in the concept drawing of Figure 16. The framing cavity is dense-packed with fiber insulation. The assembly is designed and constructed as an unvented roof and the thickness of the exterior rigid board insulation is established to ensure that the roof sheathing remains above 7.2°C (45°F) when the indoor temperature is 20°C (68°F) and the outdoor temperature is equal to average temperature for the three coldest months.

From NCDC Climate Normals (1971-2000) for the City of Chicago we see that the average outdoor temperature for the three coldest months (Dec, Jan & Feb) is -3.6°C (25.5°F). The required exterior insulation is then (45°F -25.5°F) / (68°F -25.5°F) = 0.458 or roughly 46% of the total installed R-value.

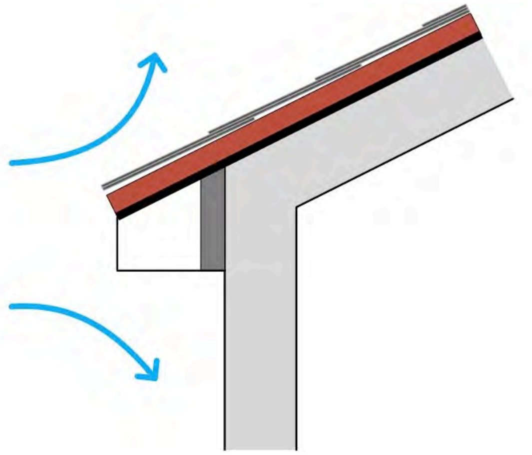


Figure 16 – Exterior Insulation Concept

If an existing roof with 2x6 rafters is fully dense-packed with cellulose insulation the installed R-value in the rafter space will be 5.5 in. x R3.8/in. = R20.9. If 46% of the total installed R-value must be in the exterior insulation then 54% must be in the dense-packed insulation. The total installed R-value has to be R20.9 / (0.54) = R38.7 and the at least R17.8 rigid insulation will have to installed on the exterior of the sheathing[1].

The International Residential Code recognizes the exterior insulation strategy (see R806.4, 'Unvented Attic Assemblies', Item 5.2). Note that higher levels of exterior rigid insulation may be required if the assembly is to meet code requirements for minimum total R-value. This will result in a conservative design as a greater percentage of the insulation installed on the exterior of the sheathing.

Demonstrative hygrothermal simulations illustrate the effectiveness of the exterior insulation strategy. Figure 18 shows the biodegradation risk plot for an exterior insulation retrofit to the north-facing pre-retrofit roof assembly. The modeled retrofit assembly has 138 mm (5.5 in.) of dense packed cellulose in the cavity (R21) and 75 mm (3 in.) of Polyiso foam board (R18) on the exterior of the roof deck. The board foam insulation accounts for 46% of the total insulation R-value. A significant improvement in predicted moisture performance is clear when this biodegradation risk plot is compared to the one for the base assembly in Figure 17 (reproduced from Figure 7).

The exterior insulation maintains the roof sheathing at warmer temperatures during the winter months. Warmer temperatures at the sheathing equate to lower relative humidity at the sheathing and lower sheathing moisture content. The wintertime sheathing moisture content peaks somewhere between 12 and 16 % moisture content, well below any levels considered risky.

[1] This calculation procedure can be used to determine the minimum required amount (i.e. R-value) of exterior insulation for any exterior insulated roof assembly in any climate zone. Different outdoor climates will result in different ratios! Different cavity and exterior insulation R-value/in. will result in different required thicknesses for the insulation!

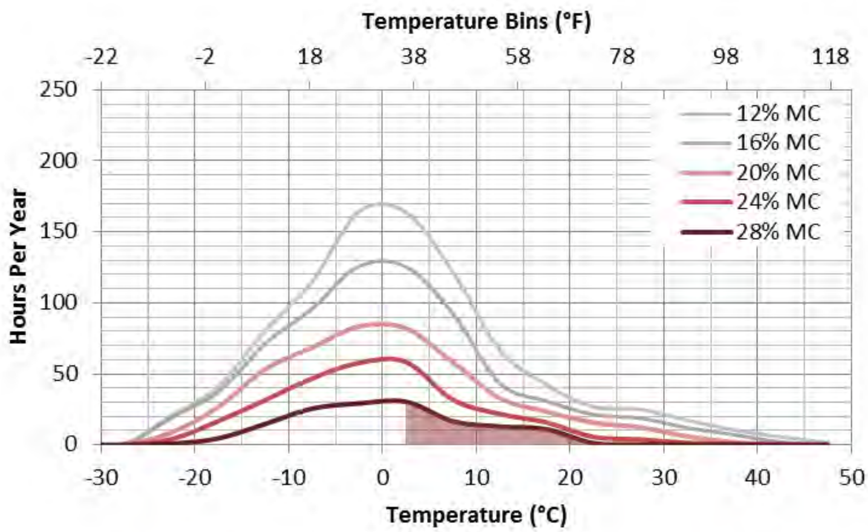


Figure 17 – Biodegredation Risk Plot for North-facing Common Retrofit Roof with Wintertime Indoor @ 40% RH (no air leaks)

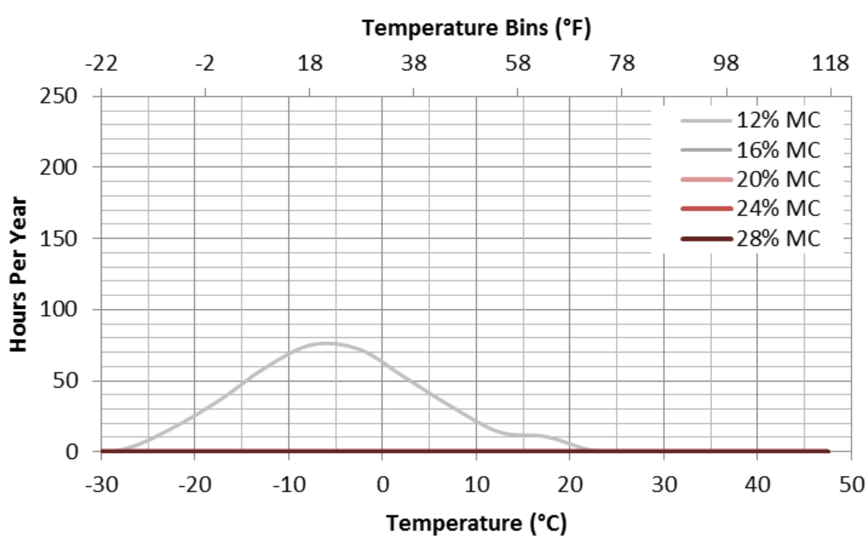


Figure 18 – Biodegredation Risk Plot for Exterior Insulated Retrofit Roof with Wintertime Indoor @ 40%RH (no air leaks)

When sufficient exterior insulation is provided, the assembly can be quite tolerant of small air leaks because the condensation plane (i.e. the roof sheathing) is maintained above the dewpoint temperature of the indoor air. Figure 19 shows the biodegradation risk plot for the exterior insulated retrofit roof when it is subjected to a very small leak (0.006 lps/m^2 or 0.0012 cfm/ft^2). The increase in predicted MC hours is just noticeable when this image carefully compared with the ‘no leak’ image of Figure 18.

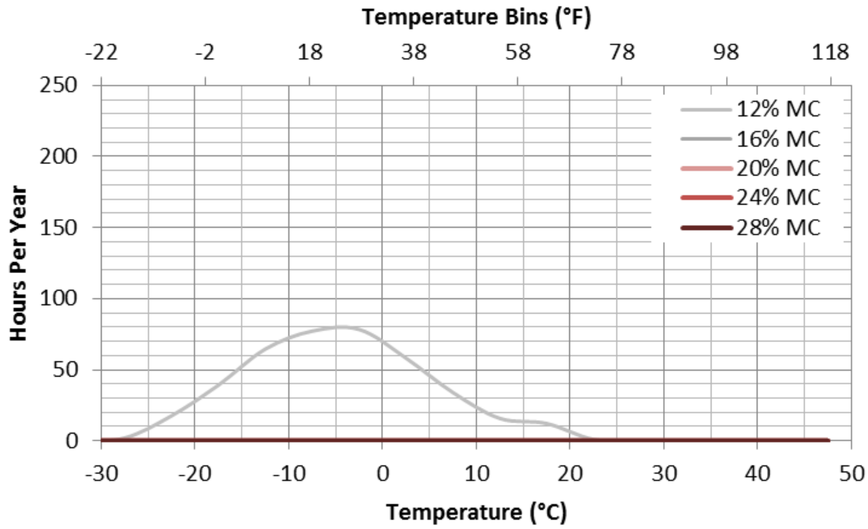


Figure 19 – Biodegredation Plot for Exterior Insulated Retrofit Roof with Wintertime Indoor @ 40%RH and 0.0012 cfm/ ft^2 air leak

Similar results would be expected for a retrofit that adds 89 mm (3.5 in.) or R17.5 of XPS insulation (at R5/in.) or a retrofit that adds 115 mm (4.5 in.) of HDEPS (at R4/in.).

The exterior insulated roof retrofit is not only more moisture tolerant than the common (not recommended) retrofit, it also has a higher installed R-value (R39 vs R21).

3.2 Hybrid Insulation

The hybrid insulation strategy, illustrated in the concept drawing of Figure 20, also seeks to control moisture accumulation in the roof sheathing. In this strategy, closed-cell sprayed polyurethane foam (ccSPF) insulation is applied to the underside of the roof sheathing and then the remaining cavity space is dense-packed with fiber insulation. Closed-cell sprayed polyurethane foam insulation is used because it controls outward vapor diffusion and limits the sheathing moisture content during winter months. The low vapor permeance of the ccSPF also limits inward drying so it is important to control moisture sources in and above the roof sheathing (i.e. the system is less tolerant of roof leaks and built-in moisture).

The hybrid insulated roof assembly is designed and constructed as an unvented roof and can be used for roof retrofits and new construction. The International Residential Code recognizes the hybrid insulation strategy (see R806.4, 'Unvented Attic Assemblies', Item 5.3).

The thickness of the ccSPF insulation is established to ensure that the condensation plane (i.e. the interior skin of the ccSPF) remains above 7.2°C (45°F) when the indoor temperature is 20°C (68°F) and the outdoor temperature is equal to average temperature for the three coldest months.

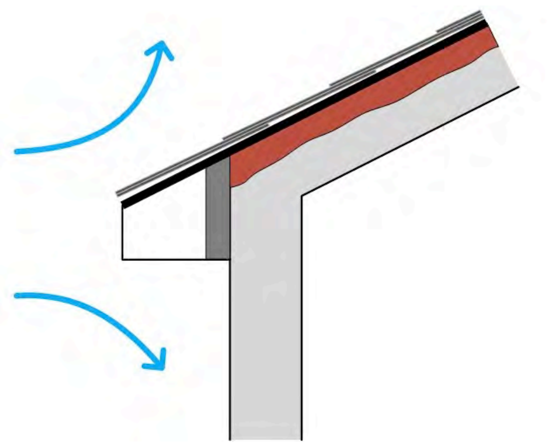


Figure 20 – Hybrid Insulation Concept

For example, consider using the hybrid insulation strategy to retrofit an existing 2x6 rafter roof assembly in Chicago to 2009 code-required R38 for Zone 5 (IRC 2009 Table N1102.1). Recall that the average outdoor temperature for the three coldest months (Dec, Jan & Feb) is -3.6°C (25.5°F). The required R-value for the ccSPF insulation is then (45°F -25.5°F) / (68°F -25.5°F) = 0.458 or roughly 46% of the total installed R-value. If the total R-value for the assembly is to be R38 then the ccSPF must provide R17.5 while dense-packed insulation must provide the remaining R20.5.

To meet the required insulation levels the ccSPF (at R5/in.) will have to be installed at a thickness of 89 mm (3.5 in) and the dense-packed insulation (at R3.8/in) will require a thickness of approximately 138 mm (5.5 in.). This means that 229 mm (9 in.) of insulation must be installed in the roof assembly. Clearly this can only be accomplished by adding additional framing depth to the underside of the existing rafters. Some contractors do this by 'tagging' 2x4s onto the bottom of the rafters.

Whenever possible we recommend that a roof retrofit incorporate code-required levels of insulation; however, retrofits are often completed with less than code-required insulation levels because of spatial limitations. Some contractors have used this argument as a justification for the common (not recommended) dense-packed roof retrofit (i.e. illustrated in Figure 4).

Spatial limitations should not be used as justification for assemblies that are more susceptible to moisture problems. Consider a hybrid insulation retrofit that is limited to the depth of an existing 2x6 rafter space. The previously determined 46:54 R-value ratio (for a hybrid insulated roof in Chicago) can be achieved by installing 57 mm (2.25 in. or about 1 pass) of ccSPF and 83 mm (3.25 in.) of dense-packed cellulose insulation for a total insulation thickness of 5.5 in. and total installed R-value of R23.6.

Demonstrative hygrothermal simulations illustrate the effectiveness of the hybrid insulation strategy. Figure 21 shows the biodegradation risk plot for the compact (5.5 in., R23.6) hybrid insulation retrofit. Again the predicted moisture performance of this assembly shows a significant improvement over the common retrofit assembly (the moisture content at the roof sheathing is never predicted to exceed 12% MC!) and there is little concern of mold growth let alone rot; however, sheathing moisture contents are slightly higher than in the exterior insulated assembly because the roof sheathing experiences colder wintertime temperatures.

The ccSPF layer has a low vapor permeance so the skin of the foam acts as the 'condensation plane'. When a sufficient thickness of ccSPF insulation is applied, the condensation plane (i.e. the inside skin of the spray foam) is maintained above the dewpoint temperature of the indoor air and, as a result, the hybrid-insulated assembly is very tolerant of small air leaks.

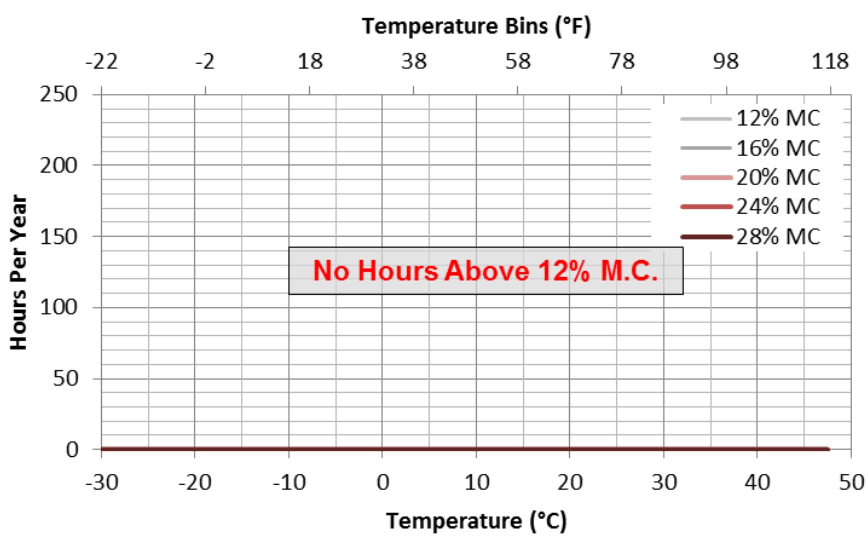


Figure 21 – Biodegredation Risk Plot for Compact (5.5 in., R23.6) Hybrid Insulation Retrofit Roof with Wintertime indoor @ 40%RH (no air leaks)

3.3 Bottom-Ventilated Deck

Ventilated gaps can also be employed to limit moisture accumulation in and promote drying of the roof sheathing. This more conventional approach to roof assemblies, illustrated in the concept drawing of Figure 22, is recognized in the code. IRC R806.3 requires a minimum 25 mm (1 in.) space between the underside of the roof deck and the top of the insulation.

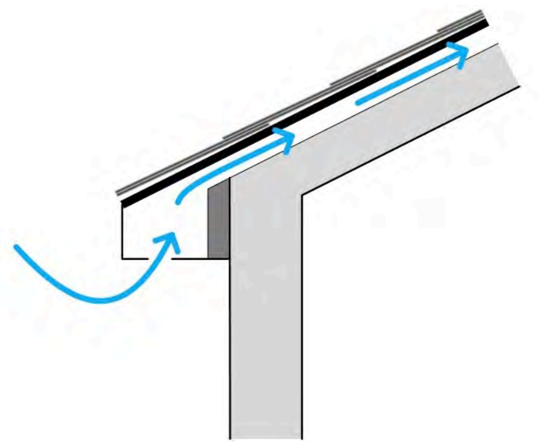


Figure 22 – Bottom-Ventilated Deck Concept

Conventional ventilated roof construction practices must be adapted for use with dense-pack insulation techniques; a baffle is required to contain the dense-pack insulation and ensure continuity of the airspace. The baffle must be strong enough to resist the air pressures associated with the dense-pack insulation technique and maintain a continuous airspace throughout the service life of the assembly. Gaps under 1 in. thickness do not meet the minimum code requirement; however, the use of a continuous baffle may ensure a gap of less than 1 in. exists whereas a displaced piece of batt can easily eliminate the 1 in. air space in conventionally constructed roof.

Vapor permeable baffles are recommended as these promote drying of the dense-pack insulation materials. Further research is needed to identify the minimum allowable permeance for the baffle. A minimum of 570 $ng/Pa{\cdot}s{\cdot}m^2$ (10 US perms) is currently suggested.

This bottom-ventilated deck strategy can result in excellent moisture performance; however, the ventilation gap consumes cavity space that could be filled with insulation. For this reason the bottom-ventilated deck approach is suited to situations where the cavity can be increased by ‘tagging’ framing extensions onto the bottom of existing framing elements.

Contractors have used a variety of different methods to create a baffled space in bottom-ventilated dense-packed roof assemblies:

- Foam Attic Insulation Baffles – standard foam attic insulation baffles are installed in a continuous fashion from the vent opening at the ridge to the vent opening at the eave. Unfortunately manufacturers do not published vapor permeance values for these products.
- Furring & EPS – 1x furring is installed down the sides (and center for 24 in rafter spacing) of the cavity to create a 19 mm (3/4 in.) space; a baffle of 25 mm (1 in.) EPS board is fastened the inside of the furring. At higher relative humidity (i.e. 90% RH) 1 in. of Type 1 EPS has a permeance of 216 ng/Pa·s·m^2 (3.8 US perms).
- Furring & Insulation Mesh or Vapor Permeable WRB – 1x furring is installed down the sides and center of the cavity to create a 19 mm (3/4 in.) space; an insulation mesh or vapor permeable WRB is fastened to the inside of the furring to create the insulation baffle. Many WRBs are available with a vapor permeance of 10 or more US perms. For this approach to be successful, the mesh or WRB must be installed taught to minimize bulging (reduces depth of the airspace) when the dense-pack insulation is installed.

  Note: Some contractors have suggested using a baffle of cardboard. The cardboard has a high vapor permeance however, it is susceptible to mold and decay. The authors advise against using cardboard baffles in these applications.
- Drainage Mat & Permeable Facer – a 10-19 mm (3/8 - 3/4 in.) thick drainage mat is used to create a continuous airspace against the underside of the sheathing. A vapor permeable mesh or WRB is installed as a facer (in this case a baffle) to prevent dense-pack insulation from filling the spACE. Some products combine the drainage mat and facer (e.g. Home Slicker® 10 Plus Typar®, Stuc-O-Flex Waterway® 9120, etc.) Many WRBs have a vapor permeance of greater than 10 US perms; however, the ventilation effectiveness of these spaces is questioned.

The foam attic insulation baffle approach is well established in some geographic regions. The furring and insulation mesh / vapor permeable WRB approach most closely follows conventional practices and code requirements. A high vapor permeance airspace might be most easily created using a drainage mat with integrated permeable facers .

The effectiveness of any ventilated gap depends greatly on the airflow or ventilation rate. The ventilation rate is a function of pressure difference and flow resistance. Airflow is driven by pressure differences caused by temperature differences (i.e. stack effect) and wind pressure gradients. The in service pressure difference is a function of roof geometry, roofing color and wind exposure. Total pressure differences are typically on the order of 1 to 10 Pa. Airflow resistance is a function of the ventilation gap construction. Larger, cleaner gaps (e.g. furred out spaces) have lower flow resistance while thinner, rough gaps (e.g. those created with drainage matts) have higher flow resistance.

Little has been done to document the flow resistance of ventilated gaps. In 2006, researchers at the University of Waterloo measured the airflow through ventilated gaps behind stucco cladding systems (Smegal, 2006). Figure 23 plots the measured airflow rates through 1.2 m (4 ft.) wide x 2.4 m (8 ft.) long ventilated gaps constructed using 19 mm (3/4 in.) thick strapping (the black line in the middle of the image) and using a 10 mm (3/8 in.) thick drainage matt as an 'air gap membrane' (the pink line in the lower middle part of the image).

Air change rates for the strapped cavity ranged from approximately 120 to 1200 ACH while air change rates for the air gap membrane were roughly an order of magnitude smaller, in the range of 30 to 150 ACH.

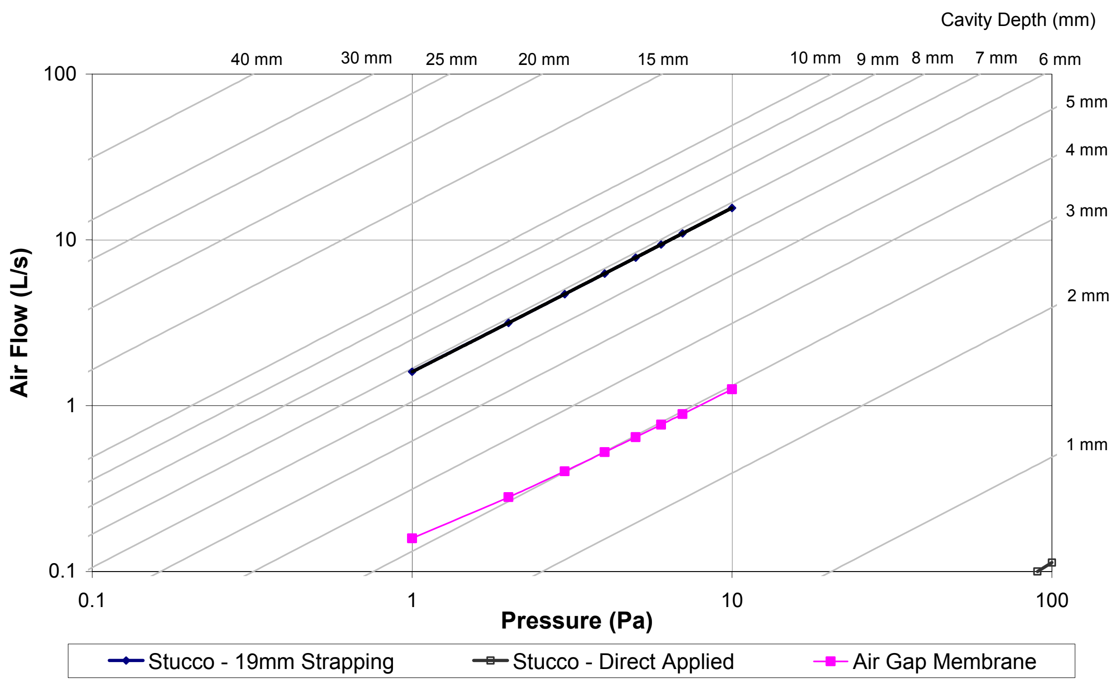


Figure 23 – Ventilation Gap Flow Rates and Equivalent Cavity Depths (Smegal, 2006)

Demonstrative hygrothermal simulations were prepared illustrate the effectiveness of the bottom-ventilated retrofit strategy. The reader should note that there has been little field research and forensic investigation into the long-term moisture durability of any of the approaches to bottom-ventilation of dense-packed assemblies so there is less experience available to calibrate hygrothermal simulations.

Figure 24 shows the biodegradation risk plot for a bottom-ventilated deck, dense-packed insulation retrofit assembly. The ventilated gap in the hygrothermal model is constructed using a 10 mm (3/8 in.) drainage mat and a vapor permeable WRB (e.g. Tyvek® HomeWrap®). A moderate ventilation rate of 30 ACH has been assumed for the purposes of this simulation.

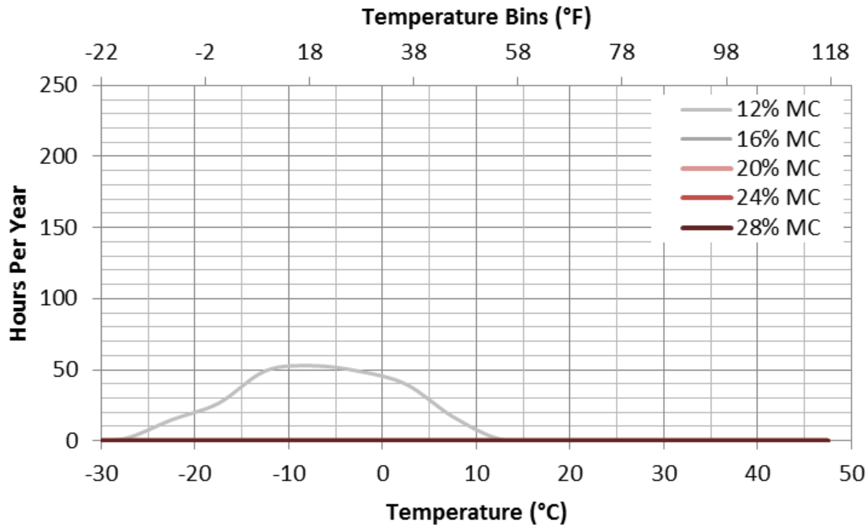


Figure 24 – Biodegredation Risk Plot for Bottom-Ventilated Retrofit Roof with Wintertime Indoor @ 40%RH (no air leaks)

Once again the predicted moisture performance of this assembly shows a significant improvement over the common retrofit assembly. The moisture performance of the bottom-ventilated dense-pack retrofit assembly is dependent on adequate ventilation rates hence it is important that designers and contractors pay special attention to the ventilation space and vent openings at the top and bottom of the assembly.

Dense-pack insulated roof assemblies with bottom-ventilated decks can survive some small air leaks provided that ventilation rates can keep up with moisture removal. There is a potential for the ventilation gap to draw indoor air through the ceiling plane and into the attic space. Ceiling plane air tightness is more critical when the bottom-ventilated deck strategy is employed to control moisture in dense-pack insulated roof assemblies.

The bottom-ventilated deck approach is best employed when there is no existing ceiling or the existing ceiling is to be replaced as part of a retrofit. Several contractors have expressed interest in using the bottom-ventilated deck approach to retrofit closed roof cavities where the existing roofing and ceiling materials are to be kept; however, no commercial solutions exist to create a ventilated gap in these assemblies. Some have proposed using cardboard tubes as vapor permeable ventilation ducts. Others have suggested encasing drainage mats in vapor permeable sleeves (e.g. of Typar®, Tyvek® or similar) that could be pulled up or down through an existing cavity and dense-packed in place against the underside of the roof deck. There are no known examples of either of these approaches in real-world applications.

3.4 Top-Ventilated Deck

Ventilated gaps can also be employed on the topside of the roof sheathing as illustrated in the concept drawing of Figure 25. Readers should note that this is the newest of the four dense-pack roof moisture management strategies discussed; only a few field installations are known to employ this strategy and there is no long-term field research into the moisture performance of these assemblies.

A number of low-rise residential roofing systems incorporate ventilated gaps between the roofing and the roof deck (e.g. clay roof tiles, concrete roof tiles & slate tiles installed on strapping; cedar shakes installed over drainage/ventilation matt). The top-ventilated deck strategy might be considered for dense-pack insulation retrofits where the existing ceiling must be kept but exterior insulation cannot be added (e.g. due to historical preservation considerations, spatial limitations or cost constraints). In these cases it must be clear that the insulation thickness will be limited to the depth of the existing assembly; it will often be impossible to meet current code requirements for minimum installed insulation.

When a ventilation gap is incorporated above the roof deck, the roofing can dry to the underside. If a vapor permeable underlayment is used, the roof sheathing can also dry to this ventilated gap; however, the rate of drying through the sheathing is limited by the vapor permeance of the sheathing and the drainage plane installed on top of the sheathing.

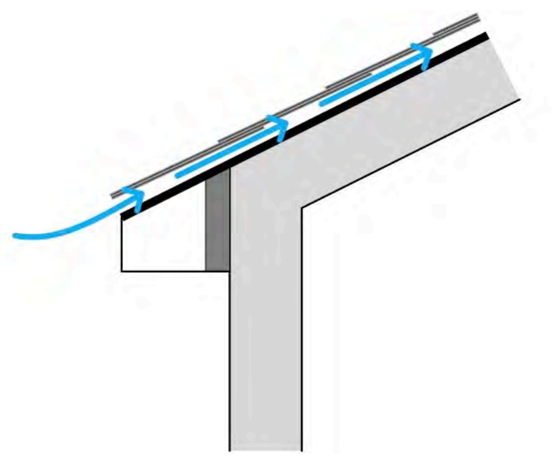


Figure 25 – Top-Ventilated Deck Concept

Hygrothermal simulations were prepared to demonstrate the performance of a top-ventilated deck retrofit to a north-facing roof with 2x6 rafters. The rafter space is dense-packed with 138 mm (5.5 in.) of CFI for an installed R-value of R21 (note this is not code-compliant level of insulation). Roof sheathing is 11 mm (7/16 in.) OSB and the roof employs an underlayment of #15 felt paper. The ventilated gap is constructed using a drainage / ventilation mat (e.g. Cedar Breather®). A moderate ventilation rate of 30 ACH was assumed for the ventilation space.

Figure 27 shows the biodegradation risk plot for the top-ventilated retrofit assembly when the wintertime indoor humidity is 40%RH and there is a very small air leak (0.006 lps/m^2 or 0.0012 cfm/ft^2). The predicted moisture performance is comparable to the common retrofit assembly with the air leak (originally presented in Figure 15 and reproduced here in Figure 26).

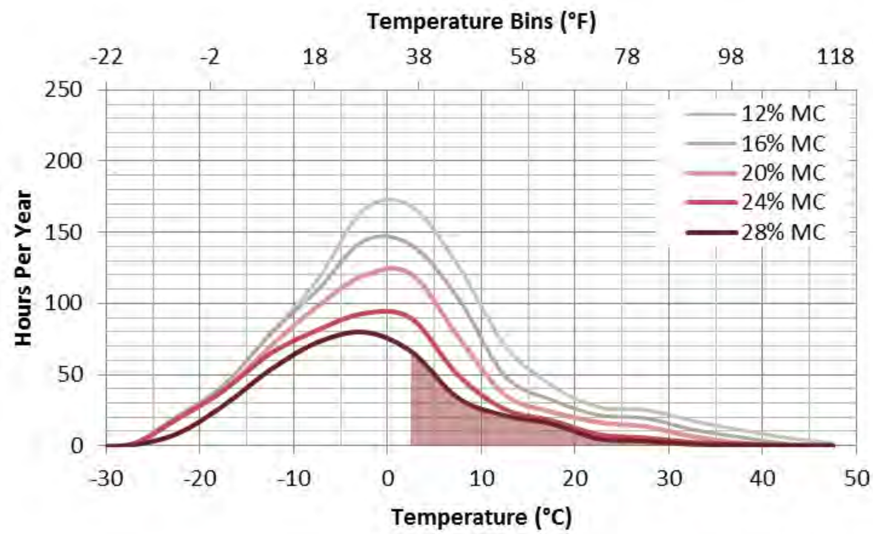


Figure 26 – Biodegredation Risk Plot for North-facing Common Retrofit Roof with Wintertime Indoor @ 40%RH and 0.0012 cfm/ ft^2 air leak

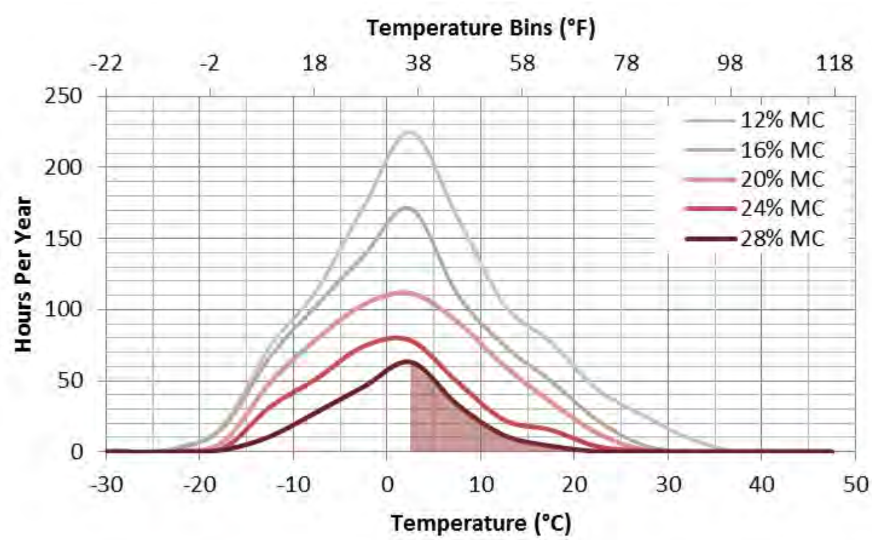


Figure 27 – Biodegredation Risk Plot for Top-Ventilated Retrofit OSB Roof w/ Wintertime Indoor @ 40%RH and 0.0012 cfm/ ft^2 air leak

In theory, top-ventilated deck dense-packed roof retrofits are prone to the same moisture sources as common (not recommended) dense-packed roof retrofits. The top-ventilated deck strategy seeks to dry moisture through the sheathing and underlayment to a ventilated gap that is created between the roofing and the underlayment material. Clearly moisture must move through the roof sheathing and underlayment before it can be removed by ventilation. At high RH levels plywood is more vapor permeable than OSB so it allows more moisture to pass. Table 5 provides a comparison of the vapor permeance of typical North American OSB and plywood sheathings at a range of different humidity levels.

Table 5 – Vapor Permeance of OSB & Plywood (ASHRAE HOF 2009)

RH (%)	11 mm (7/16 in.) OSB		12 mm (1/2 in.) Plywood	
	ng/Pa·s·m^2	US perms	ng/Pa·s·m^2	US perms
90	368	6.4	586	10.3
70	207	3.6	287	5.0
50	111	1.9	132	2.3
30	54	0.95	53	0.93
10	2	0.04	17	0.30

If the OSB roof sheathing of in the top-ventilated retrofit assembly is replaced with 12 mm (1/2 in.) plywood roof sheathing, moisture can more readily dry out of the assembly. Figure 28 show the biodegradation risk plots for the same top-ventilated roof assembly as the one depicted in Figure 27 but the OSB sheathing has been replaced plywood.

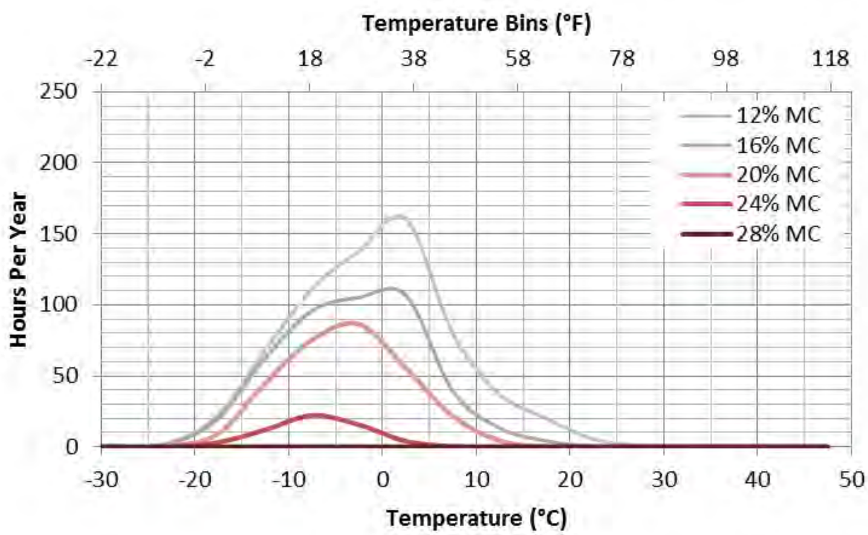


Figure 28 – Biodegredation Risk Plot for Top-Ventilated Retrofit Plywood Roof w/ Wintertime Indoor @ 40%RH and 0.0012 cfm/ ft^2 air leak

Field experience reflects the trends predicted by the demonstrative hygrothermal simulations: the predicted moisture performance for the top-ventilated roof with plywood sheathing is much better than that of the top-ventilated retrofit roof with OSB sheathing.

Top-ventilated retrofit roofs may provide better moisture performance than common retrofit roofs; however, further research is needed to better understand and establish the sensitivity to sheathing and underlay vapor permeance. At this point in time the likely moisture performance of top-ventilated retrofit roofs is not expected to be as good as the other three retrofit strategies: exterior insulated, hybrid-insulated and bottom-ventilated retrofits. Builders are encouraged to employ one of the first three strategies. If a top-ventilated retrofit must be implemented, it should be completed using plywood sheathing and high vapor permeance underlayment.

4 Measure Implementation Details

Figure 29 summarizes the dense-pack roof strategies that can be used in different retrofit situations. The circled numbers refer to the details presented in Figure 30 through Figure 33.

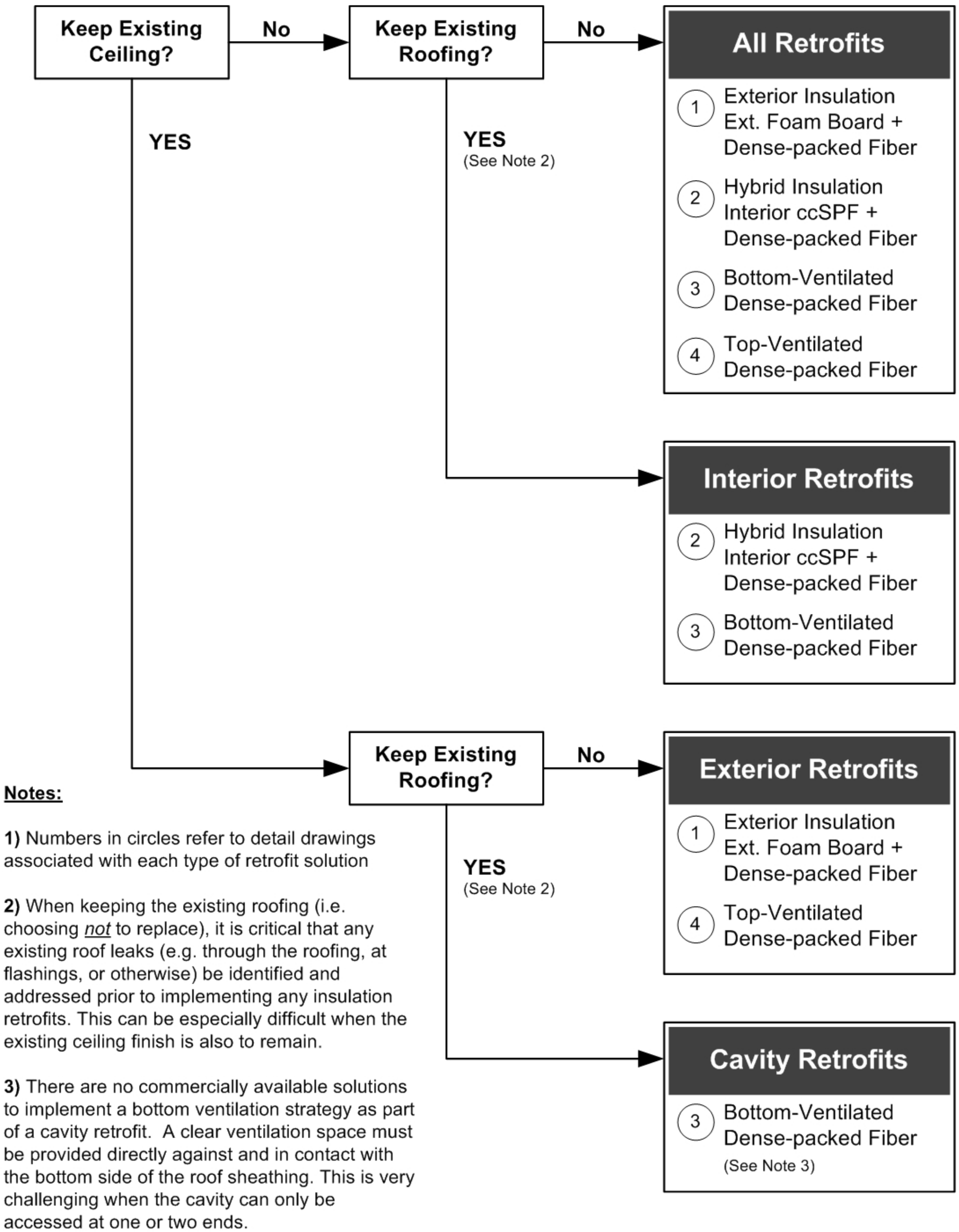
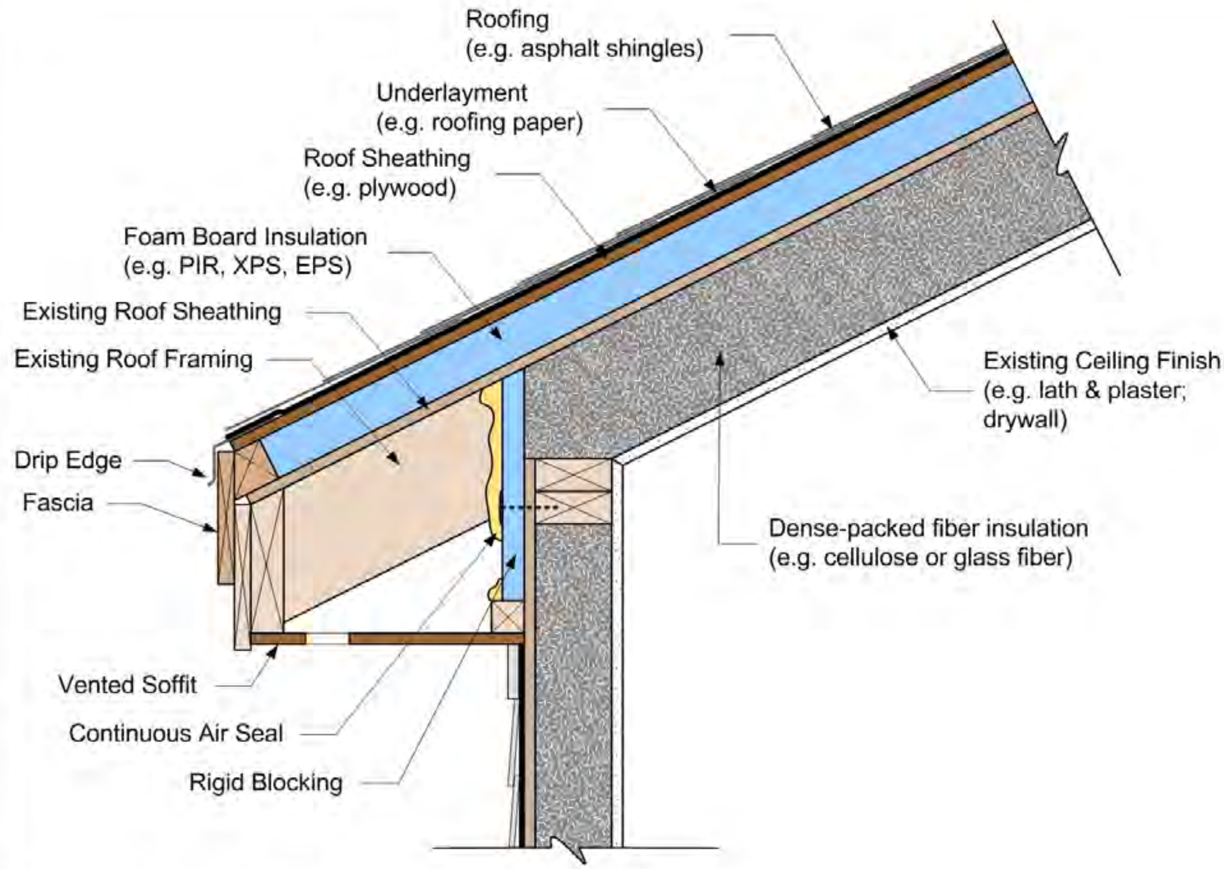


Figure 29 – Dense-Pack Roof Retrofit Options



Sequence of Retrofit:

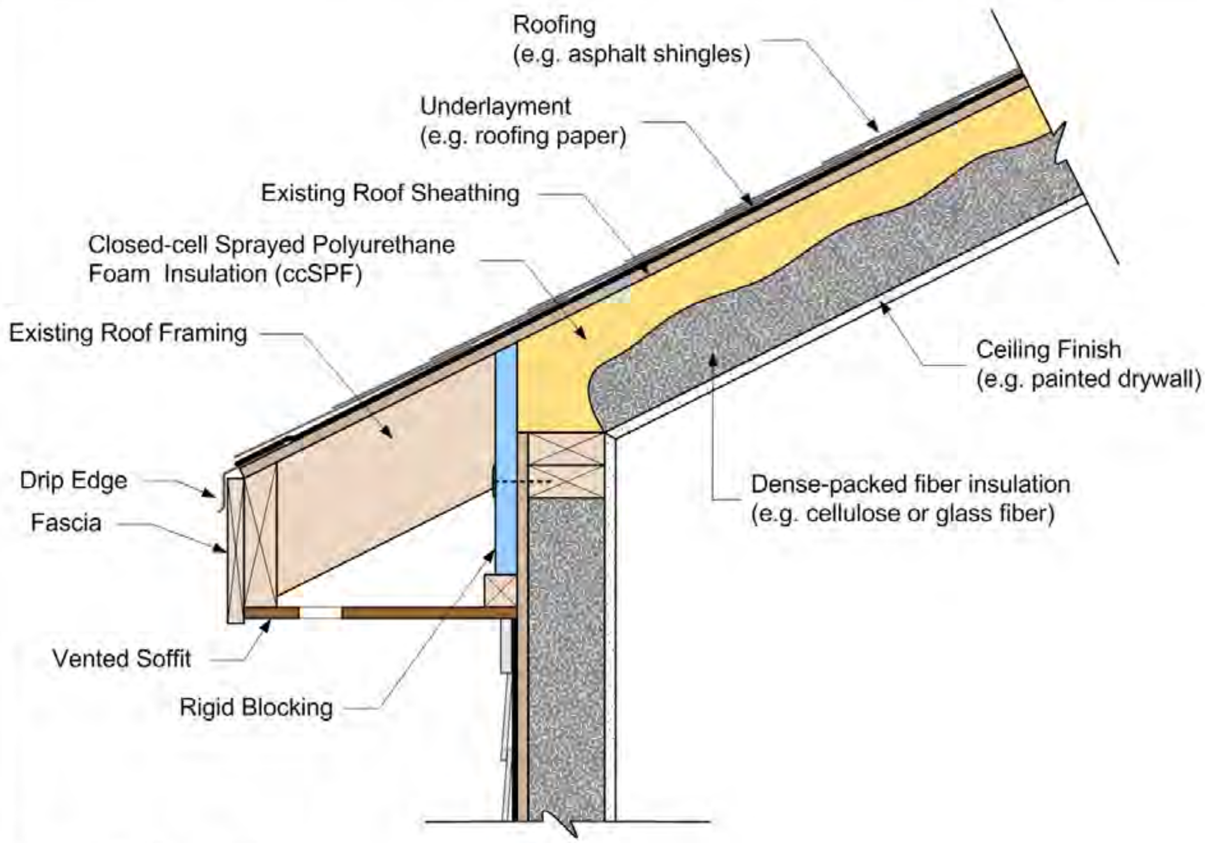
1) Remove existing roofing and underlayment; Inspect existing roof deck and framing and repair as necessary.

2) Install new exterior foam board insulation, roof sheathing, underlayment, flashings and roofing.

3) Remove existing soffit and install rigid blocking to prevent loose-fill fiber insulation from blowing into soffit; Install continuous air seal at all joints and interfaces in blocking; Replace soffit.

4) Dense-pack rafter cavities using approved cellulose or glass fiber insulation and following insertion tube techniques described in BPI RBE-WHALCI 2012.

Figure 30 – Strategy 1: Exterior-Insulated Dense-Packed Roof Assembly



Sequence of Retrofit:

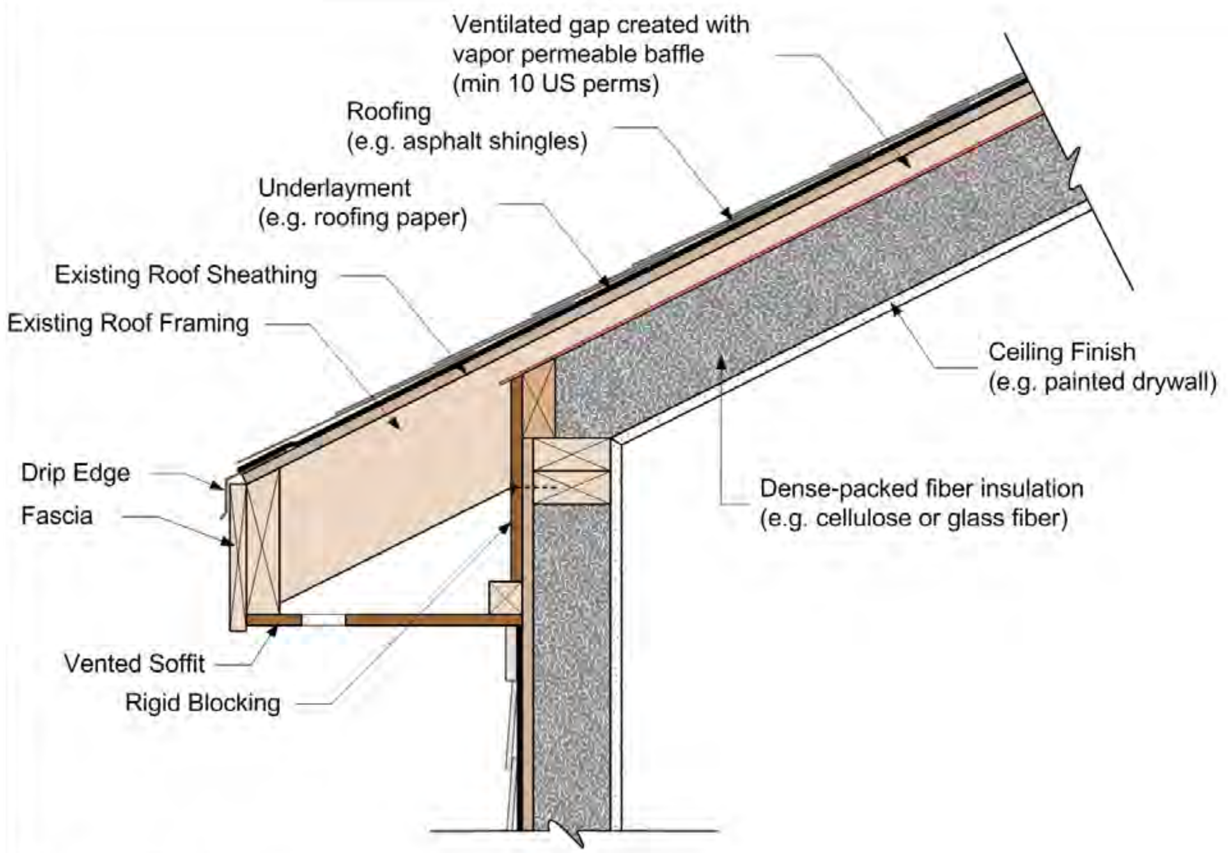
1) If keeping existing roofing, identify and repair any roof leaks prior to proceeding with retrofit; Otherwise, remove existing roofing and underlayment; Inspect existing roof deck and framing and repair as necessary.

2) Remove existing soffit and install rigid blocking to prevent loose-fill fiber insulation from blowing into soffit; Replace soffit.

3) Remove existing ceiling and insulation (if any) and install ccSPF insulation directly to underside of roof deck; Create air seal at bottom of cavity space by ensuring that foam seals to top plates, blocking, framing and roof deck.

4) Dense-pack rafter cavities using approved cellulose or glass fiber insulation and following insertion tube techniques described in BPI RBE-WHALCI 2012.

Figure 31 – Strategy 2: Hybrid-Insulated Dense-Packed Roof Assembly



Sequence of Retrofit:

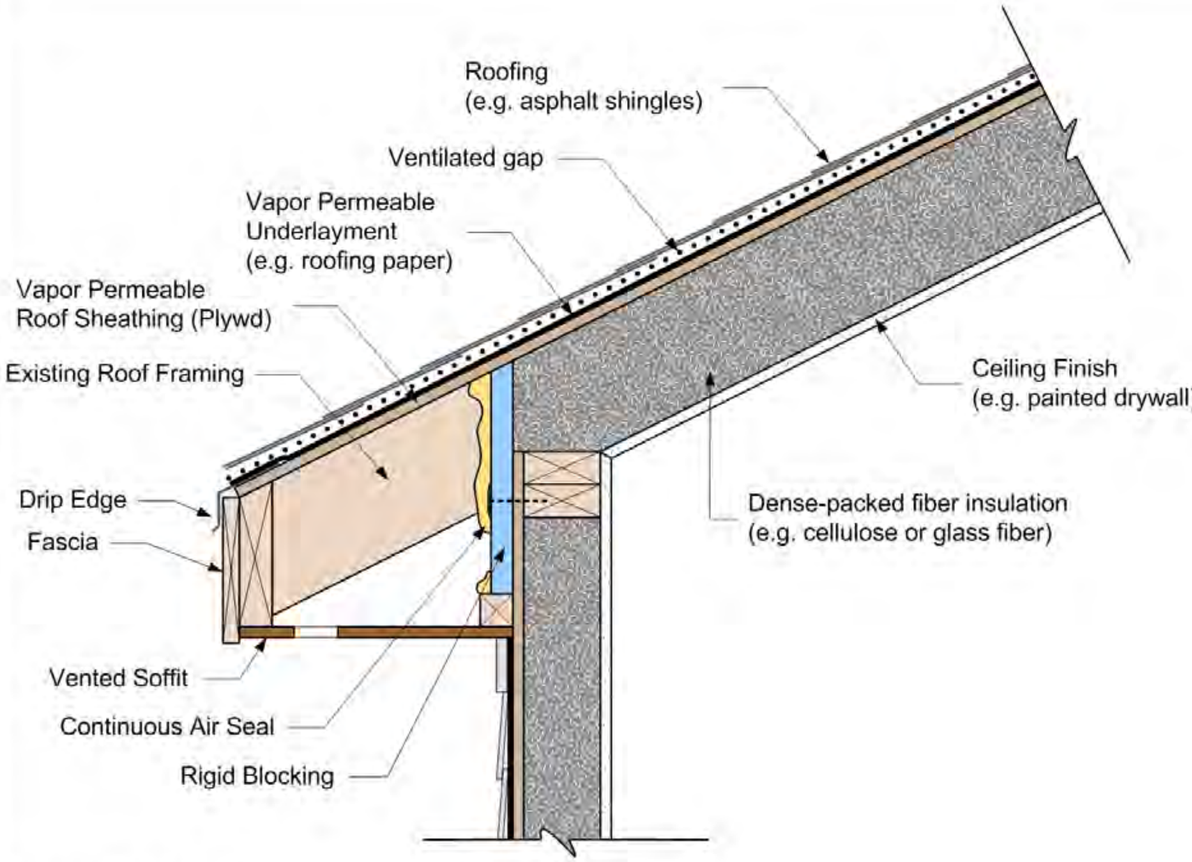
1) If keeping existing roofing, identify and repair any roof leaks prior to proceeding with retrofit; Otherwise, remove existing roofing and underlayment; Inspect existing roof deck and framing and repair as necessary.

2) Remove existing soffit and install rigid blocking to prevent loose-fill fiber insulation from blowing into soffit.

3) Remove existing ceiling and insulation (if any). Create ventilated gap directly against the bottom side of the roof sheathing- use vapor permeable baffle material (e.g. ¼ plywood on 1x furring). Replace soffit.

4) Dense-pack rafter cavities using approved cellulose or glass fiber insulation and following insertion tube techniques described in BPI RBE-WHALCI 2012.

Figure 32 – Detail 3: Bottom-Ventilated Dense-Packed Roof Assembly



Sequence of Retrofit:

1) Remove existing roofing and underlayment; Inspect existing roof deck and framing and repair as necessary. If existing sheathing is OSB, replace with Plywood.

2) Create drained, ventilated gap on top side of roof sheathing – install new, vapor permeable, underlayment as drainage plane then construct ventilation gap above using drainage matt (e.g. cedar breather) or strapping (if appropriate for selected roofing); Install new roofing.

3) Remove existing soffit and install rigid blocking to prevent loose-fill fiber insulation from blowing into soffit; Install continuous air seal at all joints and interfaces in blocking; Replace soffit.

4) Dense-pack rafter cavities using approved cellulose or glass fiber insulation and following insertion tube techniques described in BPI RBE-WHALCI 2012.

Figure 33 – Detail 4: Top-Ventilated Dense-Packed Roof Assembly

5 Key Conclusions and Recommendations

This Guideline addresses moisture control strategies for assemblies that are insulated with dense-packed insulation. It has been common to retrofit existing uninsulated and poorly insulated roof assemblies by dense-packing the empty framing space (e.g. rafter space) with loose fill insulations of cellulose or fiberglass. No measures are taken to provide ventilation (to remove moisture) or control condensing surface temperatures (to minimize moisture accumulation). Forensic building scientists suggest that two (2) assemblies in ten (10) fail as a result of moisture problems – typically within 10 years.

Many contractors and sales people falsely believe that dense-packed assemblies are 'airtight'. This has been shown not to be the case. Laboratory testing has confirmed the connection between small amounts of air leakage and dangerously high roof sheathing and framing moisture contents in roof assemblies that are dense-packed using the common (not recommended) retrofit approach. Field experience indicates a connection between moisture problems in dense-packed roofs and elevated indoor humidity levels.

Since dense-pack insulation always permits some air leakage, some amount of moisture accumulation is likely when indoor RH is in the range of 40% and higher, unless steps are taken to control the temperature of the condensation plane.

This Guideline identifies four strategies that the building industry has employed address the causes of moisture problems in dense-packed roof assemblies:

1. Exterior Insulation: Board Foam insulation installed on top of the roof deck to control the temperature of the condensation plane, control relative humidity levels at the roof sheathing and limit the moisture accumulation
2. Hybrid Insulation: Closed-cell Sprayed Polyurethane Foam (ccSPF) on the underside of the roof deck to control the temperature of the condensation plane and limit outward vapor diffusion to the roof sheathing
3. Bottom-Ventilated Decks: Provision of a ventilated gap between the bottom of the roof sheathing and the top of the dense-packed insulation to control the moisture deposition rate and promote drying of fiber insulation materials
4. Top-Ventilated Decks: Provision of a ventilated gap between the top of the roof sheathing and the underside of the roofing to promote drying of the roof sheathing.

The first two strategies are well developed, have a long history of performance in many houses over wide geographic regions and have been adopted by the code. The exterior insulation and hybrid insulation strategies are the preferred over other approaches. The 3rd and 4th strategies have a shorter history but have received significant attention in some regions. Builders should proceed carefully when applying the bottom-ventilated and top-ventilated deck strategies.

This Guideline provides annotated schematic drawings to summarize key concepts of each of the four strategies presented. These drawings are not intended to be used as construction details, but rather as tools for discussion between designers and builders of dense-packed roof assemblies.

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