Moisture-Safe Unvented Wood Roof Systems

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ABSTRACT

Wood-framed pitched roofs have traditionally constructed with fibrous insulation laid on the ceiling plane, and the large volume above this insulation well ventilated with exterior air. However, there is a growing trend toward insulating the underside of the sloped roof deck so that the volume between the ceiling plane and the sloped roof plane can be conditioned and contain HVAC systems, duct distribution, storage and even living space. In this insulation arrangement, ventilation below the deck is more difficult, expensive, and/or impractical to achieve, and so unvented solutions have attracted significant interest (i.e., unvented cathedralized attics).

The primary concern with the use of unvented roofs is the potential for moisture build up at the underside of the roof sheathing during cold weather. Rain leaks are just as dangerous. Research has shown that the good field experience with ventilated attics is due to the removal of moisture that passes through the ceiling plane by diffusion and accidental air leaks.

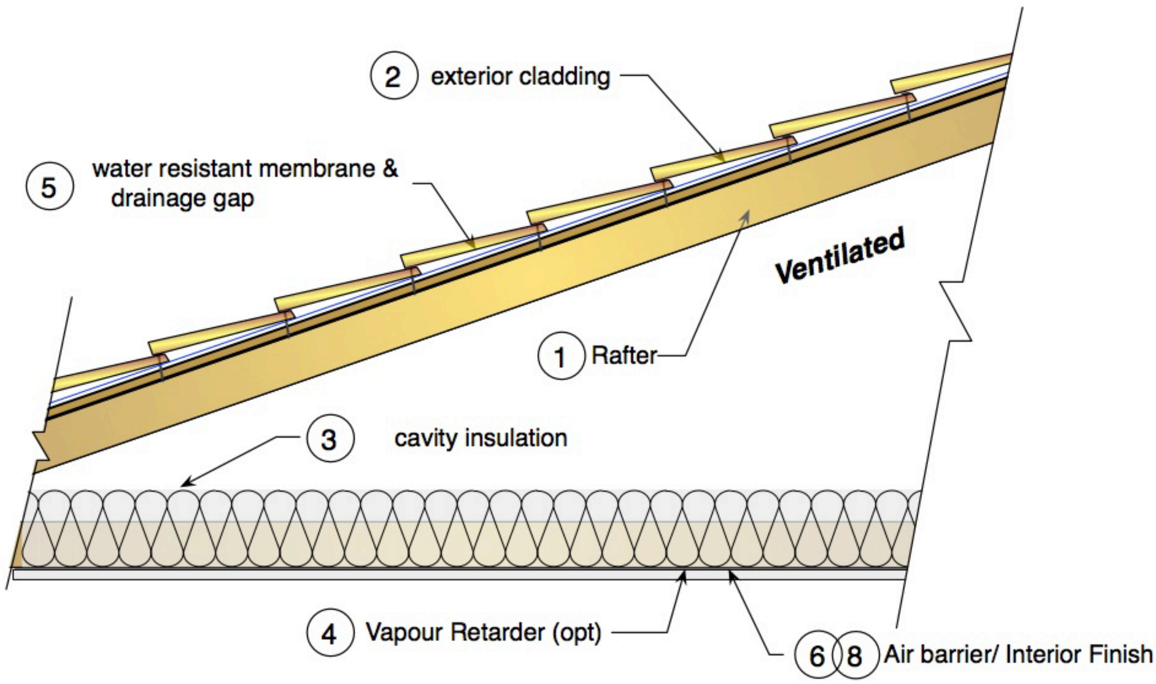
This paper describes a hygrothermal modeling study, including all of the US climate zones, a range of interior humidity levels and numerous arrangements and types of insulation. The results showed that so long as airtightness is provided, and wintertime humidity is controlled, numerous unvented solutions using either or both spray foam (open and closed cell) and fibrous insulation (cellulose and mineral fiber) can be successful. Climate, the solar properties and exposure of the roofing, the air and vapor permeance of the insulation (s) and interior humidity are the most important factors to be considered in the design of moisture-safe unvented roof systems.

INTRODUCTION

Wood-framed pitched roofs have traditionally been constructed with fibrous insulation laid on the ceiling plane, and the large volume above this insulation well ventilated with exterior air (Figure 1). However, there is a growing trend toward insulating the underside of the sloped roof so that the volume between the ceiling plane and the sloped roof plane can be conditioned and contain HVAC systems, duct distribution, storage and even living space. In this insulation arrangement (Figure 2), ventilation is difficult, expensive, and/or impractical to achieve, and so unvented solutions have attracted significant interest. This approach to insulated pitched wood-framed roofs is termed an unvented cathedralized attic.

The primary concern with the use of unvented cathedralized attics is the potential for moisture build up at the underside of the roof sheathing during cold weather. Research has shown that the good field experience with ventilated attics is due to the removal of moisture that passes through the ceiling plane by diffusion and accidental air leaks during cold weather. Despite common beliefs, field research and theoretical studies have shown that there is almost no impact on roofing temperatures by using an unvented roof approach.

A study was initiated to assist in the development of scientifically-based moisture control recommendations for installers of insulation products in unvented cathedralized attics. This paper describes this study, including its approach, results and interpretation.



Typical Construction Materials

1. Wood framed rafter and joist (shown) or wood truss
   Steel framed rafter and joist or truss
2. Cedar shakes (shown)
   Metal panels, standing seam
   Asphalt Shingles
   Exposed Membranes
3. Batt (shown)
   Blown-in cellulose, fiberglass, rockwool
   Spray foam
4. *Optional*
   Paint or vinyl wallpaper on drywall
   Polyethylene
   Foil-backed drywall
   Kraft facing on batt
5. Asphalt impregnated felt
   Asphalt impregnated building paper
   Permeable polymer housewrap
   Impermeable self-sealing membrane
6. Drywall (shown)
   Spray-foam on substrate
   Membrane (supported)
8. Painted drywall
   Wood paneling
   Vinyl wallpaper on drywall
   Textured coating

Figure 1: Typical Ventilated Attic Insulated at Ceiling Plane

APPROACH

A series of detailed computer simulations were conducted of the moisture performance of unvented cathedralized-attic wood roofs. Several different insulation products, ranging from highly vapor and air permeable fibrous insulation to air impermeable vapor retarding foam insulation were considered. The influence of different types of roofing materials and interior environments were considered alongside the primary variable of climate zone.

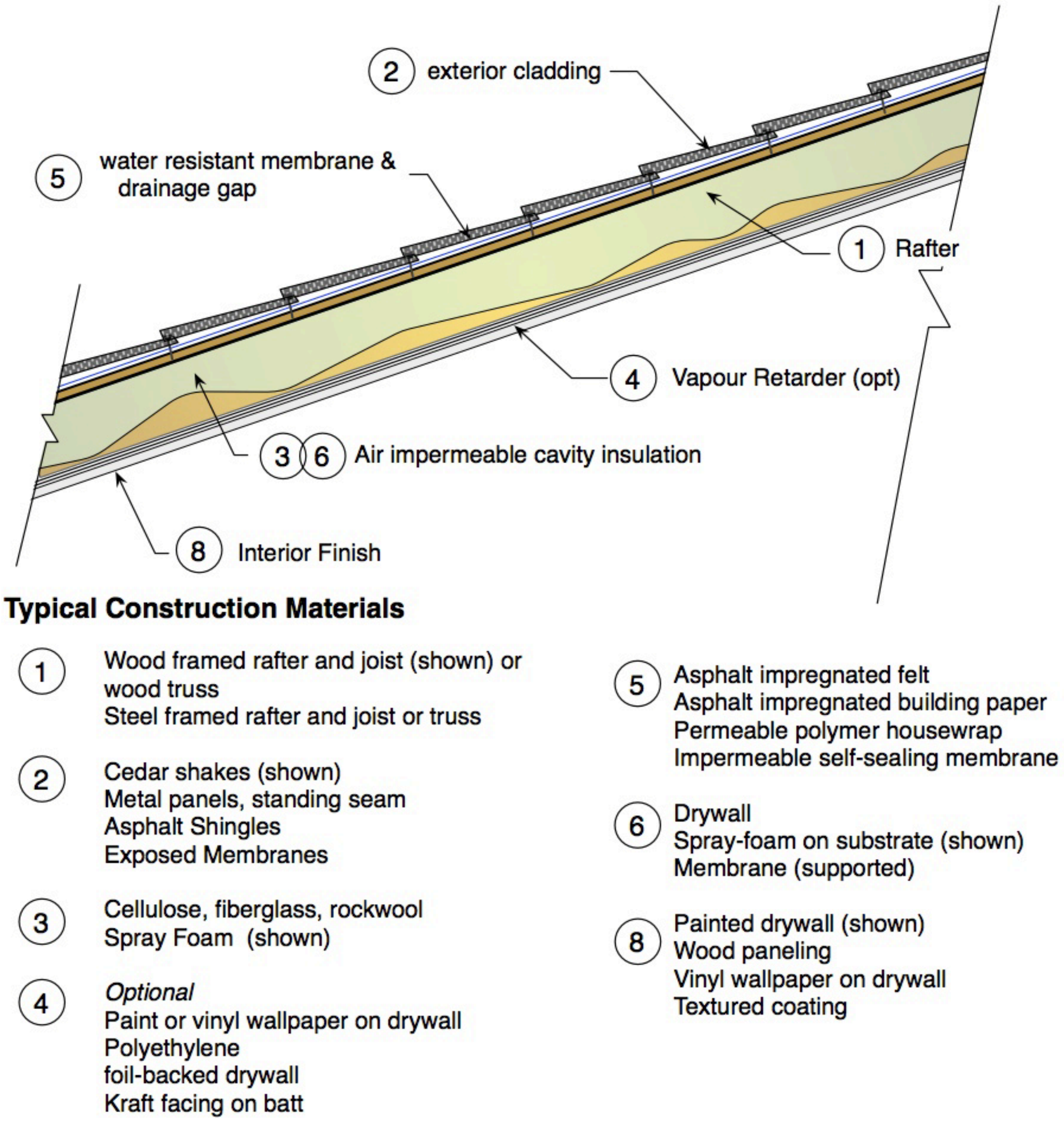


Figure 2: Typical Unvented Cathedralized Attic

The study focused on the worst-case scenarios to define the upper limit of application for each combination of materials. Hence, the results are intended to be conservative guidance for practitioners. Nevertheless, homes may sometimes be operated at higher moisture levels than recommended in the Boundary Conditions section (see later in this paper) and this may result in moisture failures.

The WUFI Pro 4.0 hygrothermal computer model was used [Kuenzel & Kiessl 1997, Kuenzel 2006] with special enhancements [Kuenzel *et al* 2002] that allowed us to model back ventilation of the concrete tiles and the impact of night-sky radiation in some of the southwestern climates where this is quite important.

Roof Topology

The roofs modeled were comprised of a roofing material (either concrete tiles, wood shakes, light-colored membrane or steel, or composite shingles depending on the market) over OSB sheathing on 2x8, 2x10, or 2x12 rafters depending on climate zone. The roof was a 3-in-12 pitch roof oriented to the north for most cases. This is the worst-case scenario, as little solar radiation warms the roof during cold weather. South-facing orientations are always warmer in the northern hemisphere. Snow accumulations will add insulation values to the exterior of the sheathing and hence tend to warm the roofs, resulting in safer cold weather results. The worst-case situation would be a very thin layer of snow (little insulation) that remains on the north-facing roof: this would be similar to the case of light-colored metal roofing.

The roofing materials were chosen to cover the range of those with high solar absorption (granulated, dark colored asphalt shingles, absorptance=0.85) to those with low (smooth light colored materials such as a metal roof, light beige in color, absorptance=0.30). Because of the very different amounts of solar radiation absorbed by different roof claddings, the difference in performance can be significant, even though the chosen orientation was north-facing.

At least one set of simulations was run for each of seven climate zones in the continental United States and Alaska. These zones also cover most of the populated areas of Canada: Vancouver and area is in Zone 4C, southern Ontario (including Toronto) is in Zone 6 and most of the rest of Canada is in Zone 7. Large urban centers with available weather data were chosen for simulation.

DOE Zone & City (12)	**Code Required R-value**	**Roofing Type (4)**	**Insulation Type (8)**
1 Miami	30	Dark asphalt	Spray fiberglass (1.8 pcf)
2A Houston	30	Tile (ventilated)	1" ocSPF + spray fiber glass
2B Phoenix	30	Light metal	1" ccSPF + spray fiber glass
3A Atlanta	30	Cedar shakes	2" ccSPF + spray fiber glass
3B San Francisco	30		Full-depth ocSPF
4A Kansas City	38		Full-depth ccSPF
4A Boston	38		Kraft-faced batt
4C Seattle	38		Full-depth cellulose
5A Chicago	38		
5B Denver	38		
6A Minneapolis	49		
7 International Falls	49		

Table 1: Matrix of Climate Zones, Roofing, R-value, and Insulation Types Modeled.

Note: ocSPF is ½ pound per cubic foot open cell spray polyurethane foam, ccSPF is 2 pound per cubic foot closed cell polyurethane foam

The roof rafter space was assumed to be filled with sufficient insulation to meet the 2009 IRC code values based the DOE Zone (listed in Table 1). It was further assumed that a large enough rafter space was provided for the insulation used. In the case of Zones 6 and higher, well over 12” (300 mm) of space would be required for all insulations except the ccSPF (which can achieve R49 in a 2x10 rafter space). This places practical limits on the technologies that can be employed. The simplicity of an all closed-cell foam solution may outweigh the costs of using 14” I-joists, counter-strapping on top of 2x12 rafters, or the use of top-side rigid foam to achieve the required high R-values using fibrous or ocSPF.

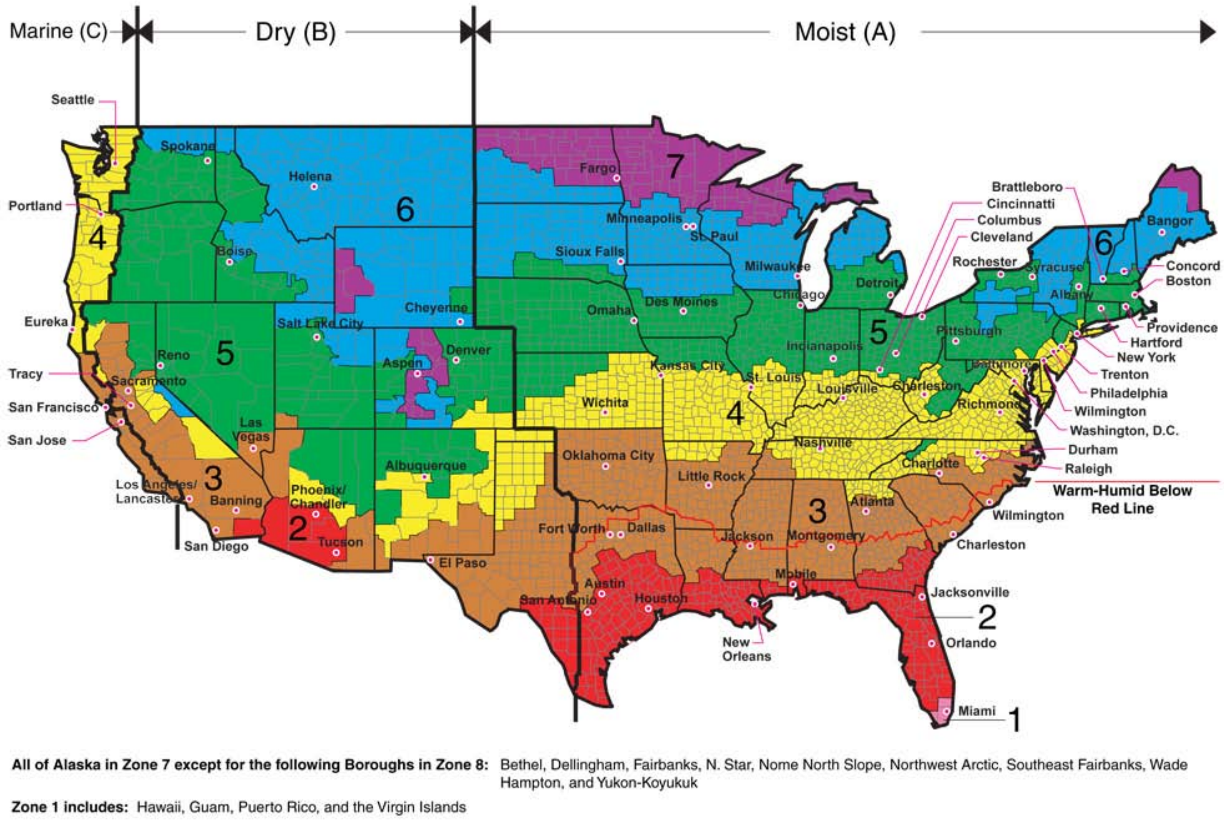


Figure 3: DOE Climate Zone Map

Material Properties

Most of the material properties were chosen from the WUFI database. However, some properties were specifically developed for this project.

Spray fiberglass of 1.8 pcf density was used in several of the roof designs. The properties were provided by the manufacturer [Johns Manville 2007]. Lower density applications will not change the results of the study provided the same R-value is achieved (i.e., the vapor permeance does not change appreciably with density in such a product).

The permeance of the ½ pcf open-cell spray polyurethane foam (ocSPF) was taken from two manufacturers’ datasheets. This same permeance was also built into the WUFI database (R3.8/inch and 23 US perms for a 1” thickness). The permeance and R-value of closed-cell 2 pcf spray polyurethane foam (ccSPF) was based on the current range these products provide (R6.2/inch and 1.2 US perms per inch). Newer foams with a range of densities (between 0.5 and well over 2 pcf) and open cell content have different properties and these may change the results of the simulations.

The RH-dependent permeance of Kraft-facing on batts was taken from the literature [Gatland 2005]. The material properties from this research showed that although a Kraft-facing had a perm rating of less than 1 under the dry-cup test, the permeance increased significantly with increasing RH. The dry cup test procedure in the ASTM E96 standard imposes an average RH of 25%. In more humid climates, e.g. Seattle, the interior RH is much higher (e.g., around 50%) during the winter and the Kraft-facing becomes more permeable for most of the winter under these conditions.

Boundary Conditions

Boundary conditions are critical to the results of any simulation. In all cases we used hourly weather files with full solar, temperature, rain and RH data. For this work we used the 10% cold year (that is 90% of years from 1960 to 1990 have been warmer) for the exterior conditions. It is worth noting that we have previously observed that climates in North America have been warming (the most recent decade is the hottest on record), and the 10% cold year now appears to have a probability of occurrence in any given year of less than 10%. For specific situations the local heating degree days should be compared to the closest large city in Table 1.

Interior RH conditions can dominate the performance of vapor open insulated systems. In fact, it is our recommendation that safe operating RH limits be provided on a tag attached to the inside of each roof that is insulated. The interior conditions were varied in the simulation from medium to high interior moisture levels. We chose the EuroNorm Standard 15026 [Euronorm 2007] to predict interior conditions. This model considers the outside temperature and adjusts the interior RH (e.g., Figure 4).

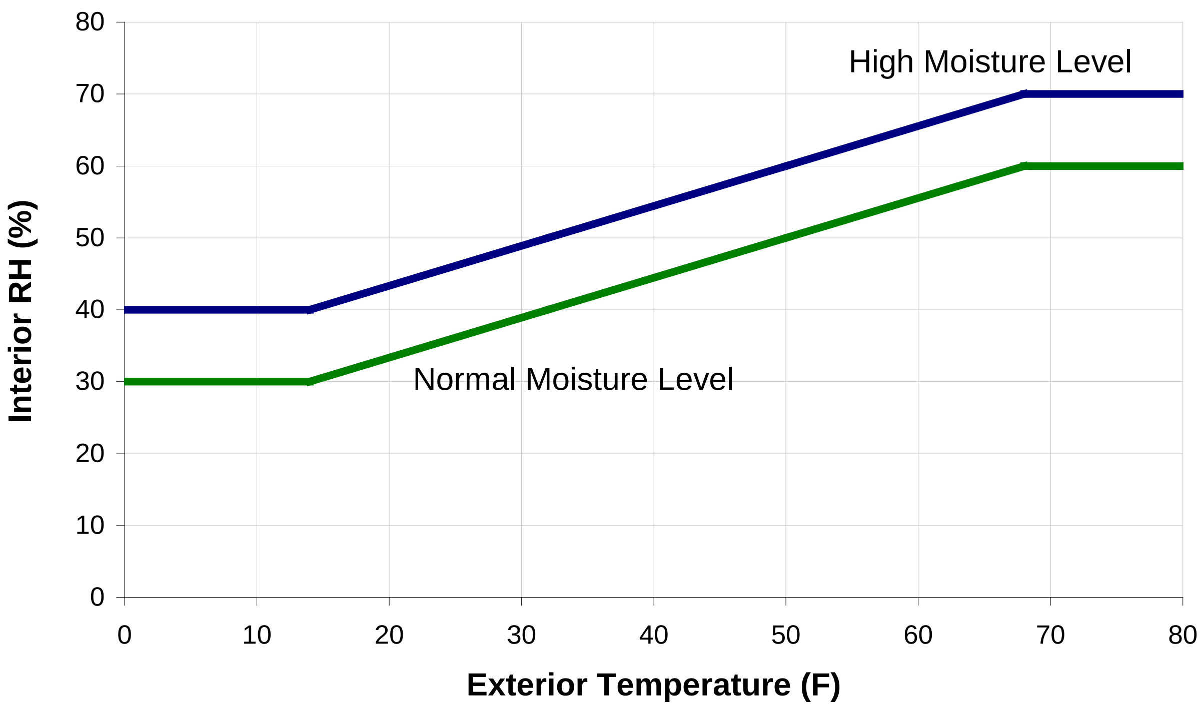


Figure 4: EuroNorm Standard 15026 Model for Interior RH Levels

We have found that this represents how many homes behave (provided that a ventilation system according to ASHRAE 62.2 is installed and operated), although there is also a small effect of exterior air moisture content that is not temperature-dependent. For example, Chicago air in winter is noticeably drier than San Francisco (Figure 5). To assess the risk of the worst house, we also investigated the high moisture load condition shown in Figure 4. This level of moisture should be avoided in practice but could occur if the home were not properly operated (i.e., not ventilated while also airtight). High moisture level homes would experience persistent condensation on typical residential windows.

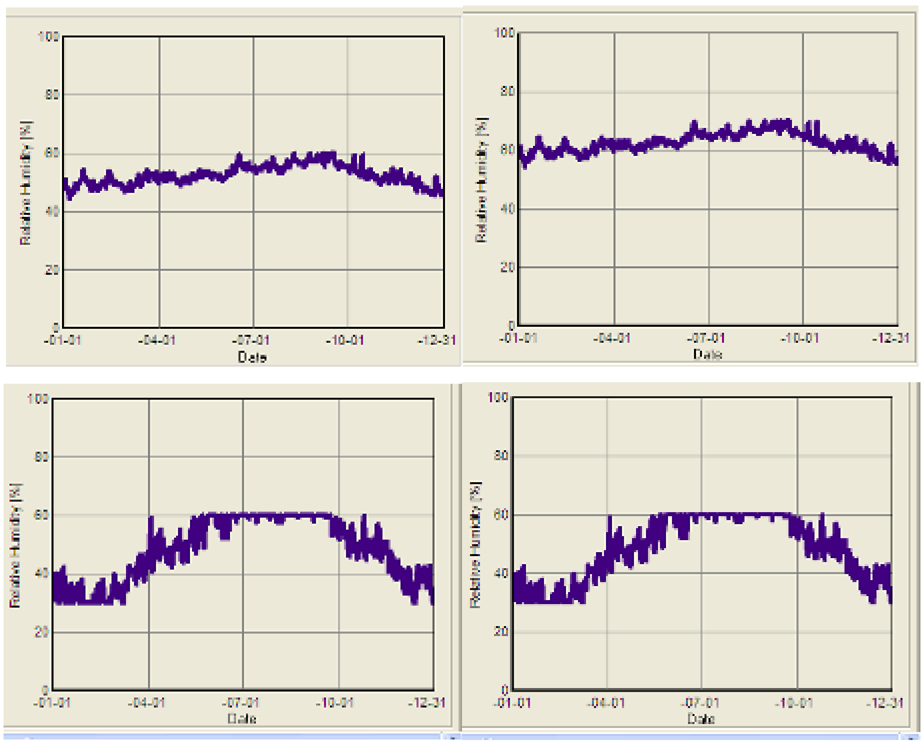


Figure 5: Interior RH conditions for San Francisco (top) and Chicago (bottom) for both Normal (left) and High (right) Moisture Conditions

The combination of the 10% cold year and high moisture conditions means that the indoor conditions are rather severe, and unlikely to be experienced in more than a few percent of homes.

Interpretation

The performance of the roofs was ranked based on the moisture content of the innermost 1 mm (less than 1/16”) of the OSB. This is under the assumption that the critical failure mode is mold or decay of the roof sheathing during cold weather conditions as water vapor is driven through vapor permeable and vapor semi-permeable insulations by diffusion. We are confident that this is the correct failure mode on which to focus. Uncontrolled air movement can also cause condensation on the roof deck or on the interior surfaces of air impermeable insulations. This second transport mechanism is addressed in the next sub-section and has, in practice been the source of many cathedral ceiling moisture problems.

It has been our experience that wood moisture contents of more than 28% for more than four weeks are routinely experienced by open cell spray foam roofs in colder climates (we have experience or reports from Zones 4, 5 and 6), and that visual inspections shows no mold or damage after one or two years of such exposure. However, the ASHRAE 160P standard recommends a maximum monthly average moisture content of 16% (equilibrium with 80%RH) to prevent mold growth. As this is a rather conservative level, we used this as the very safe level.

To provide more information about the level of performance we chose to report the results in terms of four performance classes (Table 2). This is of course, a highly simplified view of wood moisture durability, but a manageable and practical set of categories is necessary to generate engineering solutions.

Class	**OSB MC Conditions**
0	Below 16% all year
1	Above 16% 1 week or more
2	Above 16% 4 weeks or more Or above 28% 1 week or more
3	Above 28% 4 weeks or more

Table 2: Chosen Performance Classes

Class 1, exceeding 16% moisture content for one week, is very unlikely to cause any problems.

Class 2 is the region where some mold, but no decay, may begin to grow if temperature conditions are optimal and the cycle of wetting repeats for several years. Hence, this is the level at which mold is incipient, and would be considered by some (e.g. ASHRAE 160P) as a dangerous level. In other research [Black & Straube 2007] OSB moisture contents of above 16% (and below 28%) were measured for more than 4 weeks at 25 C, with no mold growth visible.

The moisture content of 28% is the lowest level at which decay can begin [Morris 1998] and represents the start of some irreversible thickness swelling in OSB. Generally decay will not occur unless levels above 28% are held for many months with warm (over 10 C) temperatures. In this study, Class 3, moisture content above 28% for more than 4 weeks, was considered likely to cause visible mold and potentially decay after several years of cycling.

Air movement

The WUFI simulation considered moisture and heat movement by diffusion and equivalent conduction respectively through properly constructed roof assemblies. If air is driven through an air permeable insulation layer both additional heat and moisture can be transferred. Insulations such as mineral fiber (kraft-faced batt or sprayed) and cellulose allow air to move through them if not protected by an air impermeable layer. The roof deck is typically quite airtight (because of the sandwich provided by the roofing, underlayment, and sheathing) but can allow air to pass through at penetrations (such as plumbing vents).

For roofs with fibrous insulation (mineral fiber or cellulose), airflow is a serious moisture risk in an unvented assembly. If simulations show that diffusion is a risk for these highly vapor permeable insulations, then air movement through them will also cause sheathing moisture contents to rise. To deal with airflow through the enclosure, an air barrier system is required somewhere within the assembly. In practice an air impermeable layer is required on the inside and outside of the air permeable insulation to control moisture movement. For the roofs insulated with partial-depth spray foam fills, air leakage through the insulation is effectively stopped, as the foam seals all the joints and cracks in the roof deck. It cannot seal the airflow through wood-to-wood joints: these require alternate air sealing treatment and are not considered by the analysis in this paper.

To assess the implications of airflow from the interior causing condensation within the roof it is conventional to compare the dewpoint of the interior air to the surface temperature of the condensing plane. In roof systems with air-permeable fibrous insulation, the condensing plane is the underside of the roof deck. For roofs with partial-depth SPF, the condensing plane is the underside of the air-impermeable foam. For full-depth SPF roofs, the temperature of the interior face of the foam is approximately equal to the interior air temperature, and so no condensation risk exists.

As this failure mode is the result of accidental and unintended air flows, it is difficult to estimate the volume of air leakage that occurs from hour to hour and therefore one cannot know what rate of moisture flow is to the condensation surface. It is not possible to measure performance based on the moisture content of the OSB without knowing the moisture flux. Hence, performance was assessed and compared by counting the number of hours during the year when condensation would occur if air were allowed free access to the condensation plane. If condensation occurred for more than about one month (1000 hours) the roof design was considered unsafe. Note that the failure mode of air leakage condensation will always be more critical than failure due to diffusion only, as diffusion is always retarded by passing through materials where air is assumed to flow unimpeded.

Note that 1000 hours of condensation also means that many hours of re-evaporation of condensate occurs during the winter, and airflow during warmer periods (e.g.., when the sun is shining) also allows drying. The month-long time period has been chosen based on experience and could be significantly longer or slightly shorter in some situations. For example, consider the plots in Figure 7 and Figure 8 for Minneapolis with a high interior moisture load, and Denver with a normal moisture load. If airflow within insulation were to occur, far too many hours would result in condensation (3454 hrs per year). In Denver, only about 800 hours occur, and it can be seen that these condensation hours are interspersed with non-condensation (drying) hours.

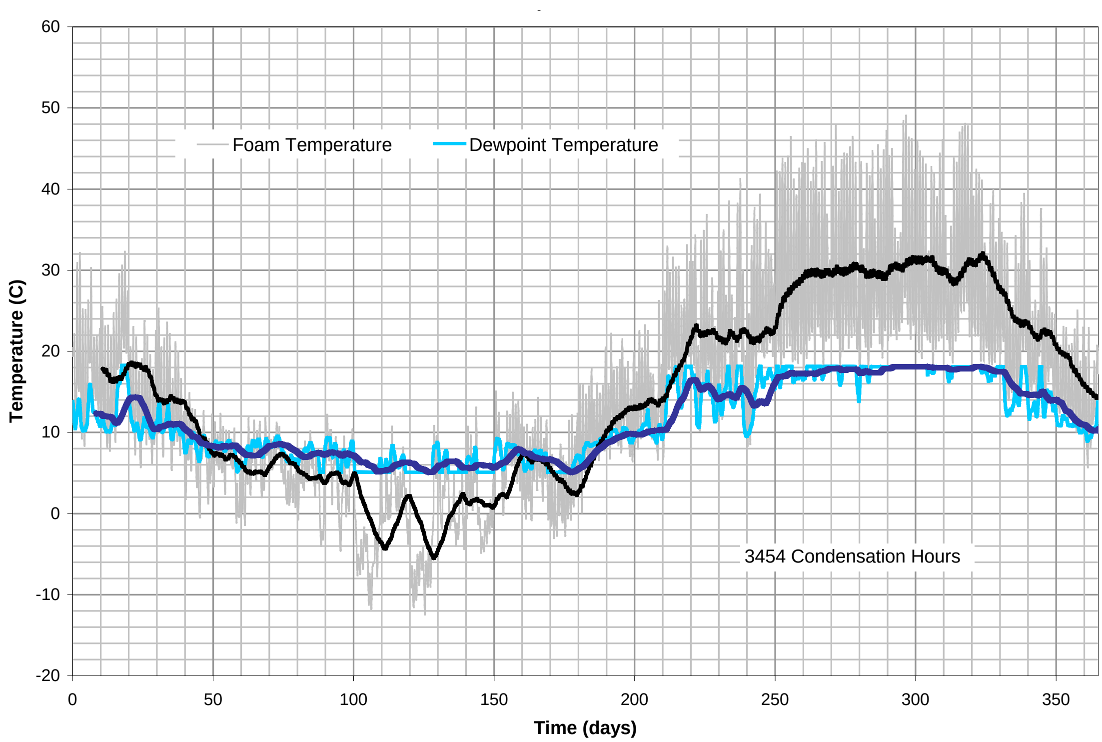


Figure 7: Plot of Interior Dewpoint vs. Foam Temperature for Minneapolis (high moisture load)

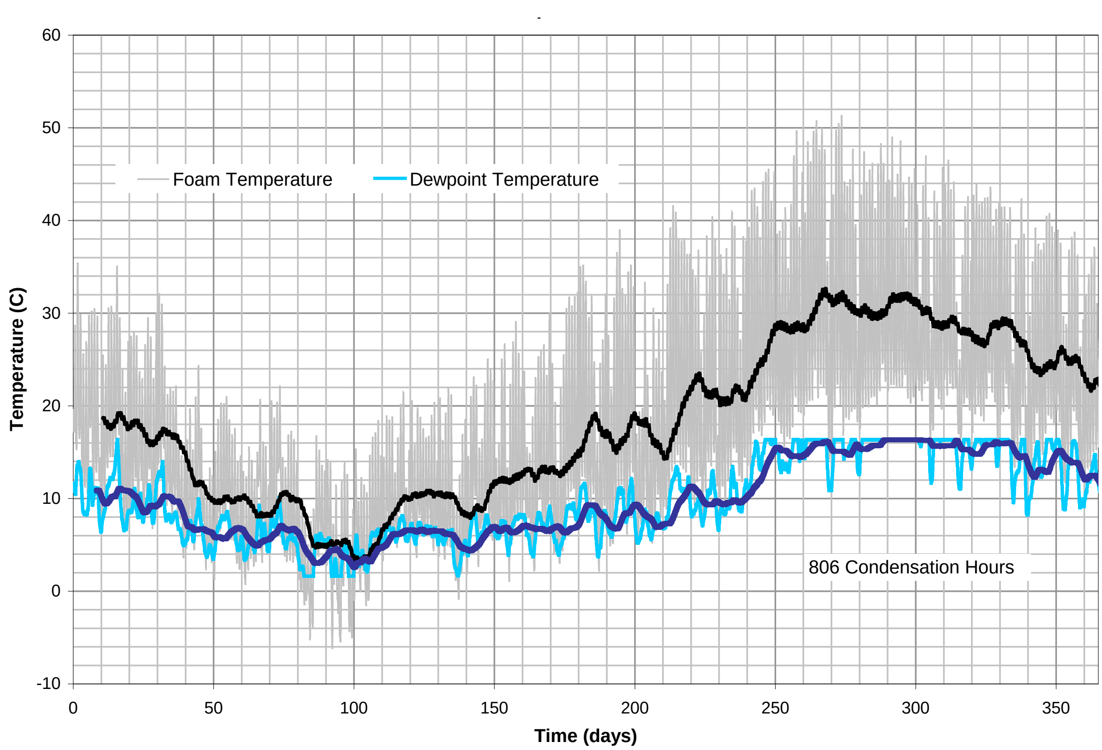


Figure 8: Interior Dewpoint vs Inside Foam Temperature (Denver, Normal Moisture Load)

RESULTS

The results generated by the preceding set of assumptions are summarized in the Tables 3 and 4.

The results can be simplified to some general conclusions:

1. The full-depth ocSPF system works problem free in Zones 1 and 2. The lower permeance of the ocSPF compared to fibrous insulation results in slightly lower moisture content for the foam roofs in most simulations, but not sufficiently to change the class. The open cell foam has the very significant practical advantage of acting as an excellent air barrier system in these climates, thereby stopping the waste of energy and condensation problems caused by air movement.
2. The ccSPF roofs performs well in all locations except under light-colored metal roofs in Zones 7 and higher. However, for dangerous levels to be reached, the interior RH must be maintained at high levels in these cold climates. In practice, residential occupancies will have lower RH and thus will be safe. From a practical standpoint, for the roof OSB moisture content to reach unsafe levels, interior RH levels would need to be so high that even good quality windows would experience persistent and copious condensation.
3. The combination of ocSPF and spray fiberglass fill provides little benefit to the moisture performance (although the air sealing will save energy) in Zones 5 and higher, and the performance of this arrangement is marginal in Zones 3-4 with high interior RH conditions.
4. The 1” ccSPF plus fibrous fill combination performed well up to Zone 5B, with light-colored metal roofs failing in colder (above Zone 4C) climates. However, this approach does not solve the potential for air leakage condensation from air flowing through insulation in Zones 4 and higher (see Table 4).

For North-facing 3:12 pitch wood roof				Spray fiberglass (1.8 pcf)	Cellulose	1" ocSPF + spray fiberglass	Full-depth ocSPF	Kraft-faced fiberglass batt	1" ccSPF + spray fiberglass	2" ccSPF + spray fiberglass	4" ccSPF + spray fiberglass	Full-depth ccSPF
DOE Zone	**City**	**R-value**	**Roof Type**									
1A	Miami	30	Tiles	0	0	0	NA	0	NA	NA	NA	0
			Lt Metal	0	0	0	NA	0	NA	NA	NA	0
2A	Houston	30	Dk. Asphalt	2	0	0	0	0	NA	NA	NA	0
			Tiles	3	2	0	NA	0	NA	NA	NA	0
2B	Phoenix	30	Tiles	0	0	0	NA	0	NA	NA	NA	0
		30	Lt. Metal	2/0	0	0	0	0	NA	NA	NA	0
3A	Atlanta	30	Dk. Asphalt	2/1	2/0	2	1/0	0	NA	NA	NA	0
3C	San Francisco	30	Tiles	2	1	2	2	0	NA	NA	NA	0
			Dk. Asphalt	1	0	0	0	0	NA	NA	NA	0
			Lt. Metal	3	2	3	3	0	NA	NA	NA	0
4A	Kansas City	38	Dk. Asphalt	3/3	3/2	3/3	3/2	1/0	0	NA	NA	0
			Lt. Metal	3/3	3/3	3/3	3/3	2/1	0	NA	NA	0
4C	Seattle	38	Dk. Asphalt	3/3	2/1	3/2	3/0+	0	0	NA	NA	0
			Lt. Metal	3/3	3/2	3/3	3/2	3/0+	3/0	NA	NA	2/0
			Cedar Shakes	3/3	2/2	3/3	3/2	0	0	NA	NA	0
4A	Boston	38	Dk. Asphalt	3/3	3/2	3/3	3/2	0+	0	NA	NA	0
			Lt. Metal	3/3	3/3	3/3	3/3	3/1	2/0	NA	NA	0
5A	Chicago	38	Dk. Asphalt	3/3	3/2	NA	NA	NA	0	0	0/0	0
			Lt. Metal	3/3	3/3	NA	NA	NA	2/0	0	0/0	0
5B	Boulder	38	Dk. Asphalt	3/3	2/1+	3/2	NA	0/0	0	0	0/0	0
			Lt. Metal	3/3	3/2	3/3	NA	3/0	2/0	0	0/0	0
6A	Minneapolis	49	Dk. Asphalt	3/3	2/2	NA	NA	NA	0/0	0/0	0/0	0/0
			Lt. Metal	3/3	3/3	NA	NA	NA	3/0	3/0	2/0	2/0
7A	Int. Falls	49	Dk. Asphalt	3/3	3/2	NA	NA	NA	0/0	0/0	0/0	0/0
			Lt. Metal	3/3	3/3	NA	NA	NA	3/1-	3/0	3/0	3/0

Legend OSB Moisture Content, Inner layer

0 - Below 16% all year	Results are for High moisture interior conditions if a single number is given
1 - Above 16% 1 week	Results are for High/Normal moisture interior conditions if reported as X/Y.
2 - Above 16% 4 weeks	Color represents performance under High interior moisture conditions
- Above 28% 1 week	NA means simulations were not conducted - color represents estimated extrapolation
3 - Above 28% 4 weeks	See paper for definitions of High/Normal moisture loads
(red box)	Indicates danger of convective-air-movement-induced condensation at normal moisture level

Table 3: Summary Results Table (Diffusion only, High Humidity)

			1" ccSPF		2" ccSPF		Kraft-faced batt		3" ccSPF	
Zone	**City**	**Roofing**	**Normal**	**High**	**Normal**	**High**	**Normal**	**High**	**Normal**	**High**
4A	Kansas City	Dk Asphalt	2058	3217	825	2114	3530	3530	34	666
		Lt Metal	2564	3857	1041	2754	2912	4855	58	886
4A	Boston	Dk Asphalt	1889	3297	528	1989	3608	5100	12	344
		Lt Metal	2368	4055	647	2656	3005	3949	14	471
4C	Seattle	Dk Asphalt	1059	3233	9	1245	3397	5673	0	0
		Lt Metal	1282	4111	12	1655	3043	4368	0	0
									4" Closed Cell Foam	
5A	Chicago	Dk Asphalt	2491	3686	924	2477	N/S	N/S	0	0
		Lt Metal	3083	4352	1192	3249	N/S	N/S	0	0
5B	Boulder	Dk Asphalt	2487	3651	806	2347	N/S	N/S	0	0
		Lt Metal	2916	4443	986	2980	N/S	N/S	0	0
6A	Minneapolis	Dk Asphalt	3149	4320	2050	3454	N/S	N/S	182	773
		Lt Metal	3728	4964	2528	4200	N/S	N/S	234	956
7	International	Dk Asphalt	3980	4869	2980	4085	N/S	N/S	777	1738
	Falls	Lt Metal	4508	5556	3400	4975	N/S	N/S	875	1919

Legend	Less than 100 hrs per year	N/S - not simulated
	Less than 1000 hrs per yr	Over 1000 hrs per year

Table 4: No of Hours per Year of Condensation Potential if Air Moves through Fibrous Insulation Layer

5. The hybrid 2" ccSPF and spray fiberglass or batt insulation performed well in all locations except Zones 6 and 7 under light colored metal roofs. Again, the high interior moisture load is somewhat unrepresentative as it is an extreme test. Airflow through the spray fiberglass (unlikely) or batt would limit the application of this system to Zone 5 or lower (see Table 4).

6. The 3” ccSPF plus spray fiberglass or batts performed well even if some airflow occurred, up to Zone 4, and even with high interior moisture levels.
7. The 4” ccSPF plus spray fiberglass or batts performed well up to Zone 6 with high interior moisture levels and can even perform in Zone 7 if normal moisture levels are maintained.
8. Spray fiberglass and batt insulation systems in unvented roofs will only work in Zones 1 and 2B if wintertime humidities are kept low. Any airflow into or within these roofs, even with kraft-facing, will risk condensation in Zones 2A, 3 and higher. These results are also backed by years of forensic experience.

Note that the very high insulation levels in Zones 6 and 7 mean that the proportion of R-value provided by a 2” layer of closed-cell spray foam is less than ¼ that required by code. Hence, a more practical application might use 2 passes (2 or 2” each) of ccSPF (about R24) followed by 6” of spray fiberglass (about R25) in a reasonably-sized space (eg., a 2x12 rafter). This solution would also generally solve most air leakage related moisture issues. Hence, for Zone 6 and 7, a system with about 4” of ccSPF plus fibrous insulation would be moisture safe and would have practical benefits.

It should also be noted that field experience has reported some examples of high moisture content roof sheathing with full-depth ocSPF roofs in climates in Zone 6, with occasional reports in Zone 5 and Zone 4C. However, Zone 4A should be a safe location for such a system except for high interior humidity or low solar heating of the roofing.

Other Performance Issues

As noted above, the issues of proper airsealing (generally solved if spray foam is used, but it can be provided by detailing the roof deck properly) and control of airflow through the insulation itself (in the case of fibrous) is very important. In practice, the worst failures are precipitated by poor airflow control.

Workmanship is also a consideration. Proper application of spray foam (so that it does not shrink away from the wood framing and allow air movement), and batt insulation (so that it fills the space) is required.

The fire resistance, flame spread, and smoke-produced properties of the different strategies must also be evaluated.

Conclusions

Computer-modeling can provide designers a useful guide to the selection of different products for the control of moisture problems. As with all such cases, it is important to chose the correct interior conditions, exterior climate zone, and material properties.

So long as airtightness is provided, and wintertime humidity is controlled, numerous unvented solutions using either or both spray foam (open and closed cell) and fibrous insulation (cellulose and mineral fiber) can be successful. Climate, the solar properties and exposure of the roofing, the air and vapor permeance of the insulation (s) and interior humidity are the most important factors to be considered in the design of moisture-safe unvented roof systems.

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