AVOIDING CONDENSATION IN LOW SLOPE ROOFING ASSEMBLIES

By

Karim Allana, PE, RRC, RWC
2018 33rd RCI International Convention and Trade Show

Today's paper will focus on the causes and prevention of condensation in low slope roofing assemblies. Within the last 30 years, the increased use of cool roof assemblies has increased condensation problems – both in new construction and renovation. I will examine the causes of roof condensation (specifically in low-slope roofs) and the debilitating effects it can have on system performance and lifespan. Finally, I will demonstrate how to prevent and remediate roof condensation through proper design methodology and construction.

CONDENSATION

Condensation is the conversion of a gas into a liquid. It occurs when warmer, humid air contacts cool surfaces and water vapor in the air condenses into liquid water (similar to a cold soda fresh out of the fridge on a hot day). The "dew point" is the temperature at which condensation occurs. The warmer the air temperature, the more water vapor it holds as humidity.

CONDENSATION IN ROOFING ASSEMBLES

Roofing systems may be divided into two classifications - steep-sloped and low-sloped roofs. The National Roofing Contractors Association (NRCA) defines a steep-sloped roof as a roof covering installed on a slope exceeding 3:12 (14 degrees). Condensation is rarely a problem in steep-sloped roofs with an attic, since they typically have ventilated attic spaces. Proper ventilation of the attic (required by code) allows moist air in the attic space to be replaced with fresh outside air, which cannot condense at outside temperature. For this reason, steep-sloped roofing assemblies with attic spaces have been excluded from this paper. Steep sloped cathedral ceiling roofs however, do require ventilation or vapor barrier and insulation.

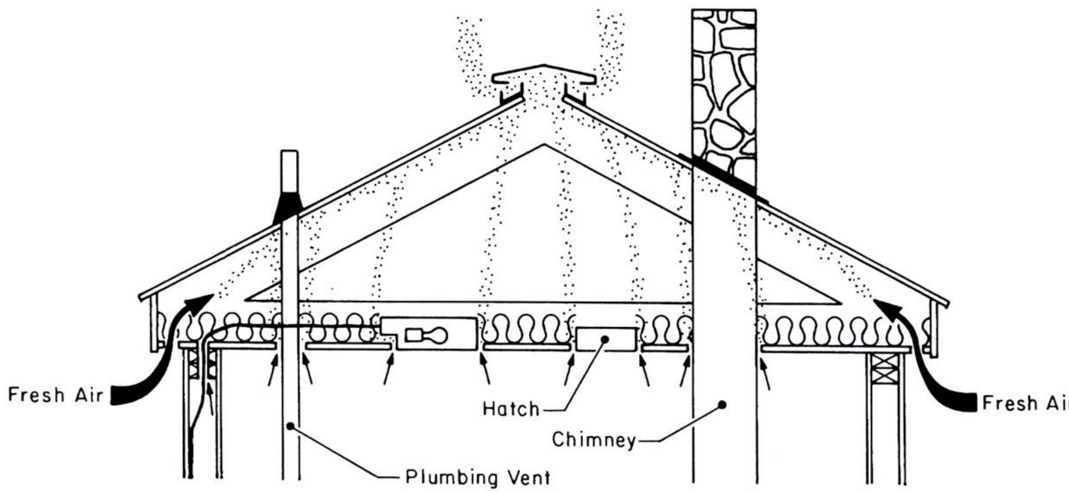


Figure 1: Typical Low Sloped Roof with Attic Ventilation

The NRCA defines a low-sloped roof as a roof covering installed on a slope equal to or less than 3:12 (14 degrees). Low-slope roofing assemblies are comprised of the roof deck, vapor barrier (if necessary), roof insulation, cover board, and roof membrane. In our experience, the majority of commercial and industrial roofing systems tend to be low-sloped.

Condensation occurs in roofing assemblies when warm, moisture-laden air inside a building contacts cool surfaces such as cool piping or a roof deck. When the water vapor in the air reaches a surface at dew point temperature, it condenses on that surface and begins to collect in the roof cavity. Interstitial condensation occurs when water vapor permeates the various layers of the roof assembly and condenses within the roof.

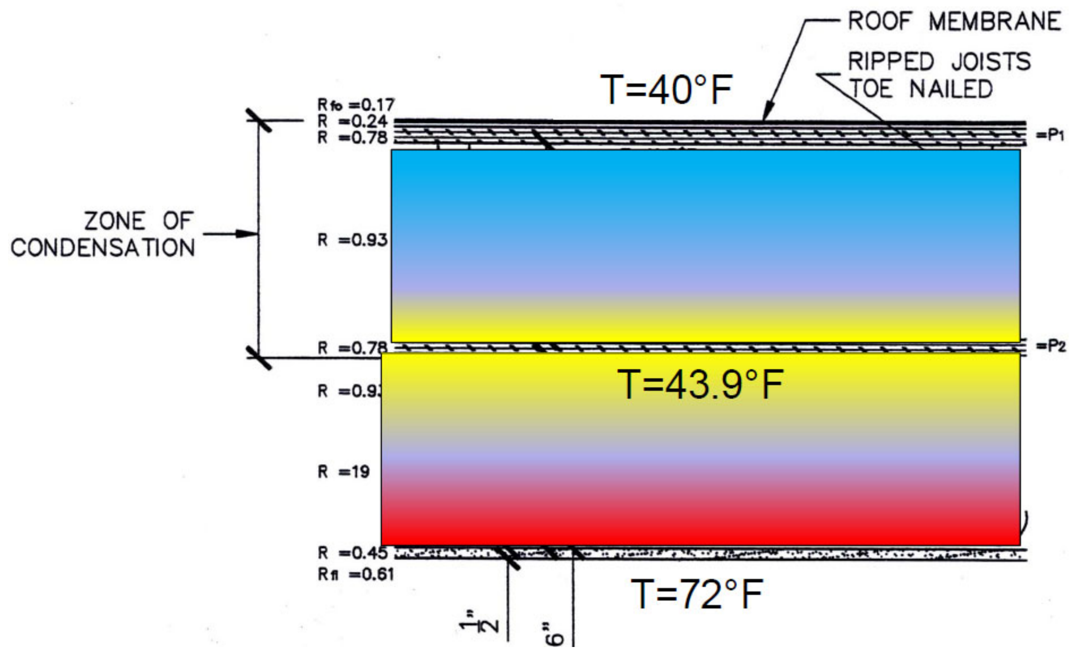


Figure 2: Condensation Occurs when Interior Water Vapor Permeates Past the Dew Point Location

Condensation in low-sloped roofs can be exacerbated by a variety of factors including temperature levels, indoor and outdoor humidity levels, and changes to heating or air conditioning use inside the building. A building's occupancy use can also affect condensation levels. For example, multi-family residential structures, data centers, areas with an indoor pool, or other buildings that generate or maintain higher indoor humidity and/or temperature levels and typically have more condensation damage related issues.

Other major condensation factors include hygrothermal climate zones, the type of roofing assembly, and improperly treated roof penetrations.

CLIMATE ZONES

While condensation can be problematic in any climate, areas with naturally high humidity (such as Florida or Hawai'i) and cold climates (such as Maine or New York) are at higher risk. Warm humid climates naturally hold more water vapor in the air. Cooler climates lower the dew point temperature allowing water vapor to condense at a lower point within the roofing assembly.

THE CONCEPT OF SELF-DRYING ROOFS

The most common method of preventing condensation in roof assemblies is to either ventilate the roof or install vapor barriers. A vapor barrier is generally installed on the "warm side" of the roof. In climates like Hawai'i this means it would be installed closer to the exterior surface, outside of the insulated spaces. In North Eastern United States climates such as Wisconsin or Michigan, the vapor barrier would be installed on the interior surface, inside of the insulated areas. In moderate climates such as California, vapor barriers are rarely installed at all.

In my estimation, only 10% to 20% of roofs in the US had vapor barriers prior to the introduction of "cool roofs". According to the NRCA, a cool roof is defined as "a roof system that uses products made of highly reflective and emissive materials for its top surface. Cool roof surfaces can remain at markedly lower temperatures when exposed to solar heat in service than surfaces of roofs constructed with traditional non-reflective roofing products." The absence of vapor barriers did not mean there was no condensation. On cold nights, moisture would still condense under the roof. However, during the day the sun's energy creates heat, vaporize the condensed water, and drives it back in to the building. This concept of condensing and drying is known as "self-drying roofs".

As a roofer in my teenage years in Northern California, vapor barriers were almost never installed on low slope commercial buildings. I remember tearing off built up roofs early in the morning and the bottom of the roof membrane would be covered with condensed water. I would commonly observe rusty nails backing out and plywood sheathing delaminating from this wetting and drying cycle. In the afternoon, the same BUR roof assembly would be completely dry, even in the winter, due to the solar heat gain and elevated roof surface temperatures. This phenomenon is defined as "self-drying roofs". One of the most common modes of self-drying roof failure is when rusty nails back out and puncture the roof membrane, plywood delamination and rusted fasteners and plates and damage to metal pan roof decks. Often, the level of condensation in a "self drying" roof did not rise to failure in less than 15 or 20 years. Every 15-20 years, most roofs with plywood substrates would require some level of replacement and re-nailing due to condensation damage.

Despite the inefficient manner in which self-drying roofs worked, the use of vapor barriers in states like California was very rare. While self-drying roofs did result in damage, the damage was generally limited and most roofs could last more than 20 years of wetting and drying cycles.

COOL ROOFS TRENDS

Over the past several decades, the building code and industry has been moving towards more energy efficient products and construction methods. One of the most popular trends is the Energy Star-compliant cool roof. A cool roof is a highly reflective roof capable of high reflectivity and high emissivity. Cool roofs can reflect up to 90% of the sunlight and UV radiation. This lowers the roof's surface temperature, which reduces heat gain. While this can result in lowering cooling costs in the summer, cool roofs stay cold (rather than heat up) during the winter and do not self-dry.

While cool roofs successfully reduce internal roof assembly temperatures, they are reportedly experiencing more condensation than their traditional dark counterparts. Less heat and radiation is absorbed into the roofing components so they fall below the dew point more quickly and remain below the dew point for longer periods of time. This provides greater opportunity for condensation to form under the membrane and for substrates to remain wet longer and the roofs don't self dry. Accumulated moisture in cool roofs can potentially remain for weeks or months at a time, causing severe damage within 2-5 years.

Condensation build-up is common when new cool roofs and re-roofs or cool roof coatings installed over older traditional roofing assemblies. There have been reports of cool re-roofs experiencing condensation where it was previously undetected for decades. In one of our cases, an apartment building roof had been performing for over 20 years as a traditional BUR, self-drying but when recovered with a cool TPO roof, there was significant condensation damage within six years.

Figure 3: Condensation Damage under a Cool Roof

ROOF-MOUNTED ACCESSORIES

Roof-mounted accessories, or roof penetrations, are another factor that can contribute to condensation. Penetrations like solar panel integrations, roof drains, vents, etc., represent gaps in the roofing structure and vapor barrier; they are inherently cooler due to outdoor exposure and can promote condensation within the roof assembly. If poorly sealed and/or insulated, the gaps from penetrations allow humid air into the roofing assembly, which can condense under the roof.

Figure 4: Roof Drains and Other Penetrations Leave Gaps That Can Allow Humid Air to Bypass the Roof Deck

CONDENSATION DAMAGE

Humid environments like a moisture-laden roof that stay moist for days and weeks at a time are ideal for dry rot and mold, which can make roofs unsafe to walk on. If left unaddressed, damage from condensation can destroy an entire roofing structure. Excess moisture can lead to unseen roof decay and structural damage. In freezing temperatures, the interstitial water vapor condenses within the roof layer. Condensed water expands when frozen, which can cause further structural damage.

Figure 5: Damage Directly Under Roofing

DETECTING EXISTING CONDENSATION

I have seen several cases of condensation damage misdiagnosed as water intrusion damage. In many cases, signs of condensation damage can mimic signs of water intrusion. A trained eye can differentiate condensation from water intrusion by the location, size, and shape of the damaged areas. Roof leaks, as opposed to condensation, are often precipitated from a source of water intrusion and damage often spreads outwards, diminishing from the point of water intrusion. Condensation on the other hand, is often located in the "ridge" or high parts of the roof, and damage can often be uniformly across.

A typical moisture investigation would begin with a nuclear gauge, electronic impedance, or infrared survey to map the locations of roof moisture. Nuclear density gauges use small amounts of radiation to detect hydrogen atoms (moisture) underneath or within the roofing assembly. The hydrogen atoms slow the reflection of radiation allowing the mapping of moisture densities in a grid pattern. This allows investigators to select areas for roof cuts to confirm the presence of moisture. Infrared imaging can also be used to map internal roof condensation through the temperature differential between dry and moist roofing materials.

Once potentially moist areas have been identified, they can be confirmed with roof core cuts from various locations.

Figure 6: Nuclear Density Gauge Roof Survey Results

DESIGNING ROOFS TO MITIGATE CONDENSATION

A properly designed roof will prevent ever-present water vapor from reaching dew point temperatures within the roofing assembly. This is most commonly done through the incorporation of either ventilation and/or a vapor barrier. However, designing for a specific roofing assembly and a specific hygrothermal climate is key.

The concept behind designing a vapor barrier is to locate the vapor barrier below the dew point temperature. In a heating climate, properly designed vapor barriers can be installed in the ceiling space under the insulation or on top of the roof substrate with additional insulation above it and under the roofing membrane. How much insulation you need above the vapor barrier varies with design interior and exterior temperatures and humidity.

With the relatively recent conception of WUFI analysis, selecting the proper roofing design configuration to prevent condensation is not guesswork anymore. WUFI stands for Wärme-Und Feuchtetransport Instationär (translated from German as transient heat and moisture transport) and is a series of computer programs used for hygrothermal modeling.

WUFI assists designers with anticipating system performance by calculating differential equations for heat and moisture flow to anticipate probable thermal and moisture conditions for specific roofing assemblies. WUFI analysis can determine if a new roofing assembly will propagate mold and/or fungal growth and perform simulations of accumulating moisture content in each roofing layer over time. It allows a designer to test combinations of roofing materials and design configurations to ensure optimum hygrothermal conditions that will inherently discourage condensation.

VENTILATION

Ventilation is the process of introducing fresh air into a building and cycling out stale air. It decreases condensation by removing humid, moist air from the building before it reaches the dew point. Building ventilation falls into two categories – mechanical ventilation and natural/air pressure ventilation.

In most commercial and industrial buildings, mechanical ventilation is achieved through a heating, ventilation, and air conditioning (HVAC) system. HVAC systems control indoor temperature, humidity levels, and air quality. While HVAC units successfully remove water from the air, they can also increase the temperature differential. In Georgia for example, a building will typically be heavily air conditioned for comfort. However, if any humid, outdoor air is able to penetrate the roofing assembly, it will condense more quickly and will be less likely to evaporate.

Air pressure ventilation relies on the indoor and outdoor vapor pressure differential to self-circulate fresh air into the roof cavity while allowing stale air to escape. As the warmer indoor air rises and escapes through vents towards the ceiling, it draws in fresh air from outside creating a convective loop. Intake vents are required on the lower part of the roof and exhaust vents are required at the high points to create a stack effect.

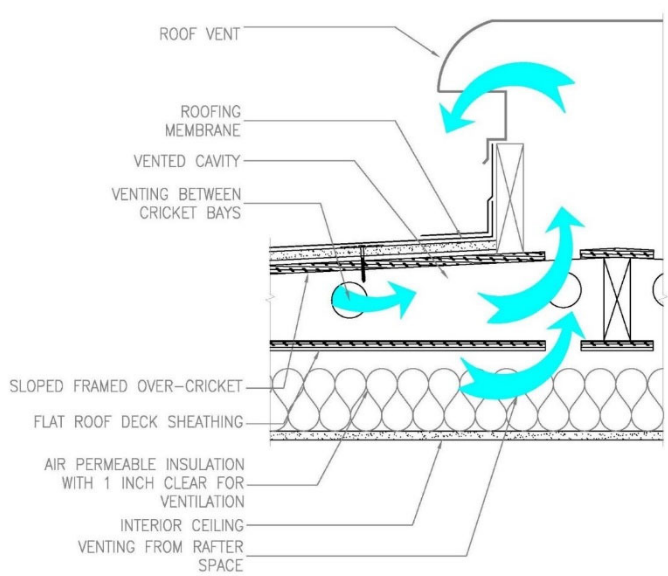


Figure 7: Venting Double Roof Deck with Sloped Framing

Naturally ventilating a low-sloped roof is more difficult than ventilating a sloped roof because there is no attic space to gain the height difference between intake and exhaust vents. When designing ventilation for low-sloped roofs, it is important that all areas exposed to humid indoor air are ventilated. In the case of a wood-framed roof assembly, cross ventilation is required. It is also imperative that all roof penetrations (including some vents) are properly insulated. Since ventilation allows water vapor past the dew point, no cold surfaces (like pipe penetrations) can contact that water vapor.

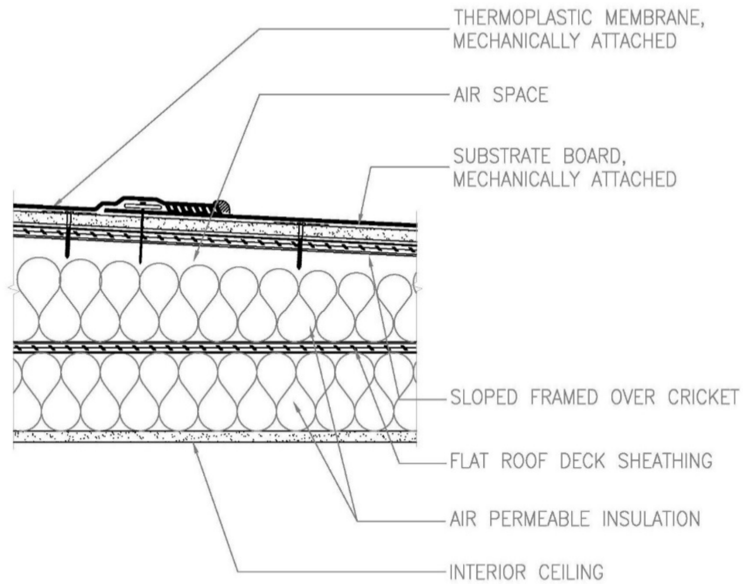


Figure 8: Venting Double Roof Deck with Sloped Framing

While ventilation can prevent humid indoor air from reaching the roof cavity and condensing, it cannot prevent humid outdoor air from entering. This requires a vapor retarder.

VAPOR RETARDERS

A vapor retarder is a membrane installed to impede water vapor from permeating through the barrier. There are three classes of vapor retarders: Class I, Class II, and Class III. Class III vapor retarders have a permeance level between 1.0 perm and 10 perms and are considered semi-permeable. Class II vapor retarders have a permeance level between 0.1 perm and 1.0 perm and are considered semi-impermeable. Class I vapor retarders (sometimes referred to as vapor barriers) have a permeance level of 0.1 perm or less and are called "impermeable".

A well-designed vapor retarder can prevent water vapor from reaching the dew point and condensing. If improperly designed or if there are holes and unsealed laps, a vapor barrier can exacerbate condensation problems as opposed to mitigating them. Instead of keeping moisture out, they allow moisture in and can prevent it from drying

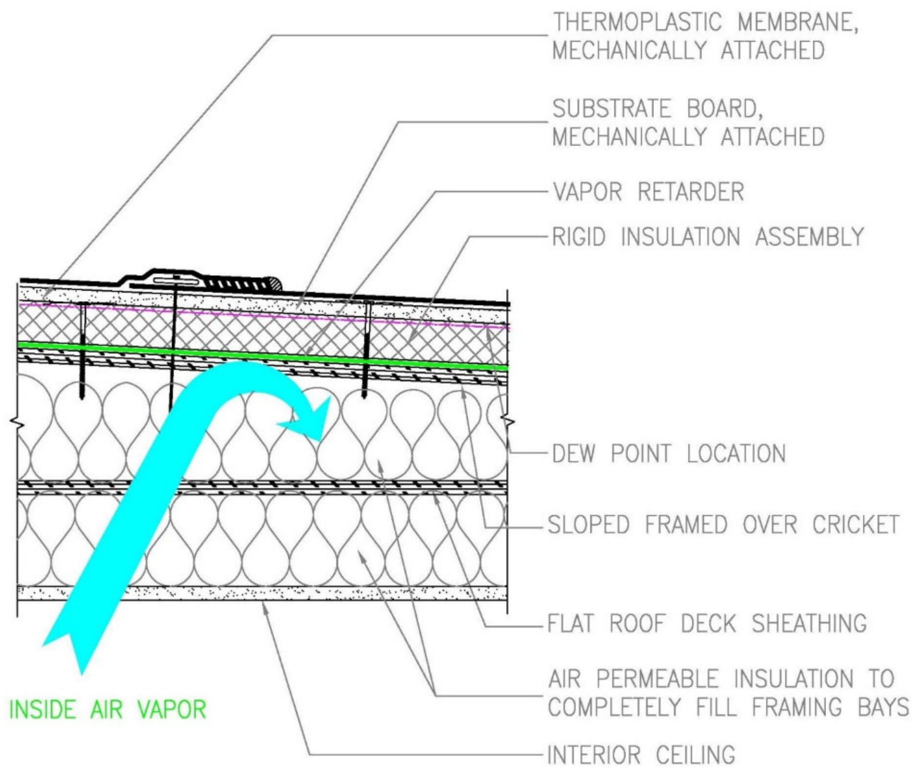


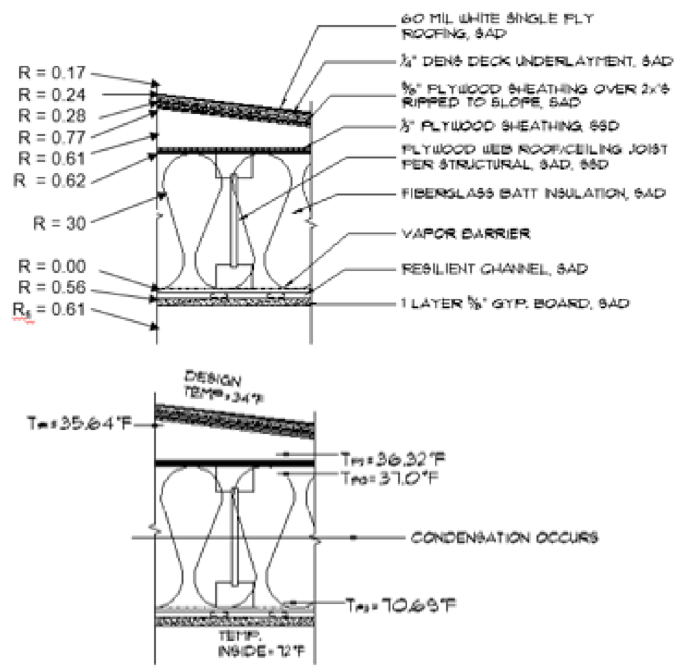
Figure 9: Vapor Barrier Prevents Water Vapor from Condensing in the Roof Assembly

In a low-sloped roof assembly insulation is often installed in the ceiling. The simple and obvious place to add a vapor barrier is below the insulation on the ceiling joist. However, installing a vapor barrier on the warm side of ceiling (below) insulation is the worse place to put it. Vapor barriers in the ceiling are difficult to install and almost always result in failures. This is because ceilings have many penetrations like canned lights, vents, pipe penetrations, demising walls, etc. Vapor barriers installed in the ceiling due to the number of complex conditions require high degree of skill and quality control which is often lacking. Instead, it is better to install the vapor barrier on the roof deck, under insulation and the roof where the conditions are more controlled. In these cases the vapor barrier is typically installed by the roofing contractor as opposed to thermal insulation or sheet rock contractor who does the work in the ceiling.

The first step to designing a condensation-free roof is to determine the dew point temperature. The designer must ensure that the temperature of the vapor barrier remains higher than that dew point. Once the dew point has been calculated the insulation thickness can be varied to keep the vapor barrier above the dew point. The formula used to calculate dew point temperature is as follows. The designer must determine the interior/exterior temperatures, the R-value (building materials' resistance to heat flow) of roofing construction below the vapor retarder, and the R-value of overall roofing construction.

$$T_{vr} = T_i - [(\frac{\sum R_i}{\sum R})(T_i - T_o)]$$

T_{vr} = Temperature (F) at the vapor retarder
T_i = Design inside (interior side) temperature (F)
T_o = Design outside (exterior side) temperature (F)
$\sum R_i$ = R-value (F•ft.²•h/Btu) of construction below (to the interior side) the vapor retarder
$\sum R$ = R-value (F•ft.²•h/Btu) of the overall roof construction



Winter conditions, heat flow upwards,

R_{total} = (0.61 + 0.56 + 30.0 + 0.62) + 0.61 + 0.77 + 0.28 + 0.24 + 0.17)

R_{total} = 33.86

Assume outside temperature 34°F

Assume inside temperature 72°F

$\sum R_i$ = (0.61 + 0.56 + 30.0 + 0.62) = 31.79

Temperature at P_i

$$T_{P2} = T_i - \left[\left(\frac{\sum R_i}{\sum R}\right)\left(T_i - T_o\right)\right]$$

$$T_{P1} = 72 - \left[\left(\frac{32.4}{33.86}\right)\left(72 - 34\right)\right] = 35.64F$$

$$T_{P2} = 72 - \left[\left(\frac{31.79}{33.86}\right)\left(72 - 34\right)\right] = 36.32°F$$

$$T_{Po} = 72 - \left[\left(\frac{31.2}{33.86}\right)\left(72 - 34\right)\right] = 37.0°F$$

$$T_{P3} = 72 - \left[\left(\frac{1.17}{33.86}\right)\left(72 - 34\right)\right] = 70.69°F$$

Figure 10: Calculating Dew Point Temperature of a Roof Assembly

The placement of the vapor retarder within the roofing assembly is critical. Vapor retarders cannot be installed on the interior ceiling because there are too many penetrations (fans, lights, mounted accessories, etc.) with too many potential gaps for the vapor retarder to perform properly. If there is not enough insulation on top of the vapor retarder, it will allow the vapor retarder to cool below the dew point and will not prevent condensation.

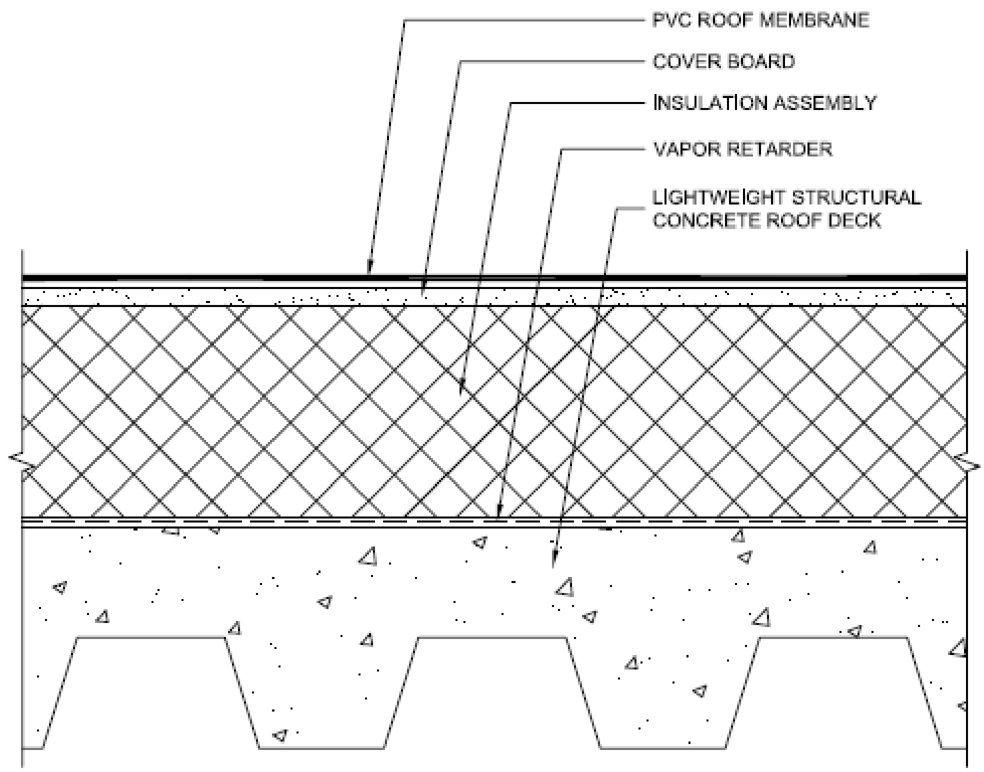


Figure 11: Vapor Barrier Placement on a Lightweight Structural Concrete

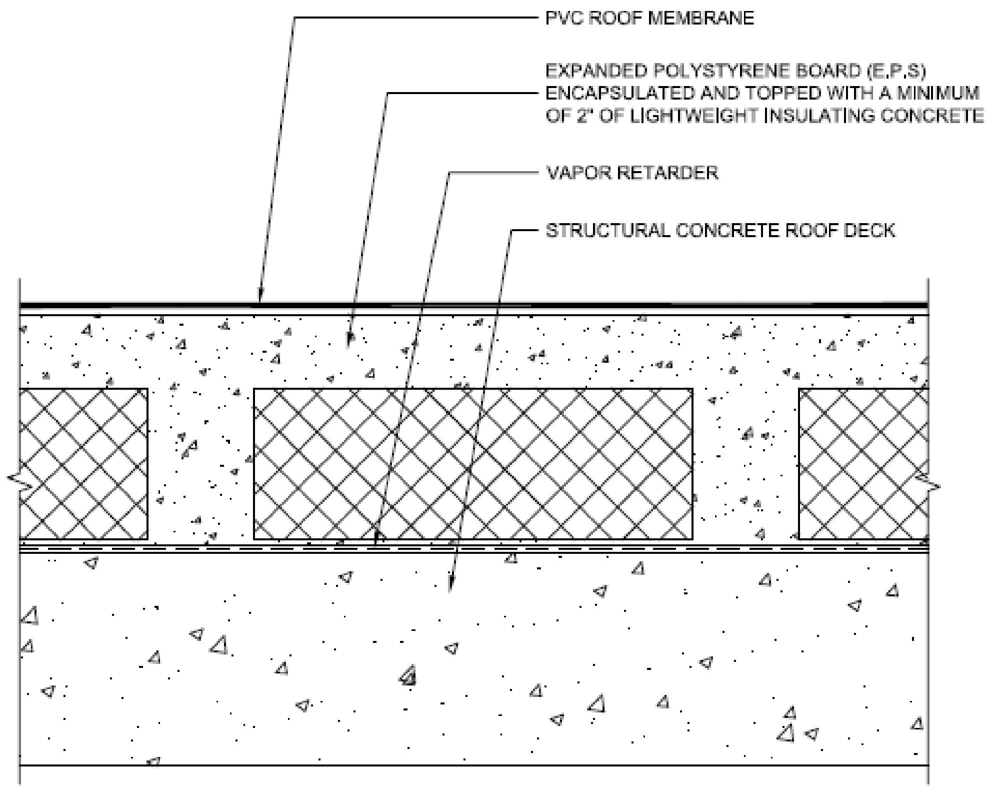


Figure 12: Vapor Barrier Placement on a Lightweight Insulating Concrete Deck

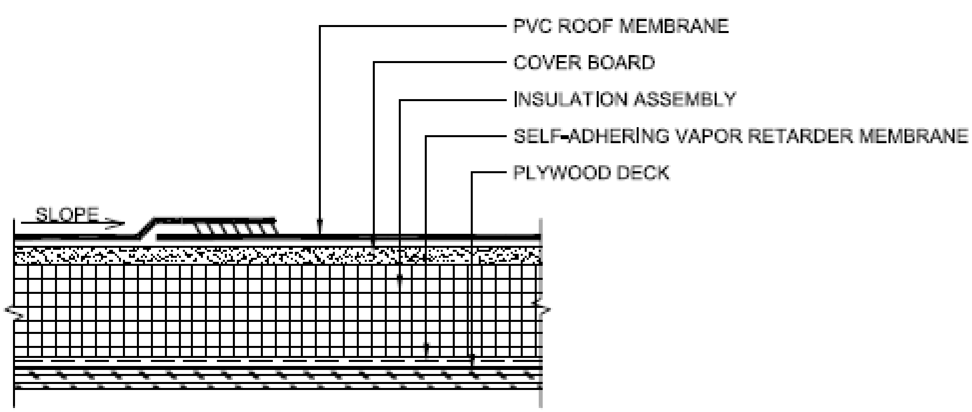


Figure 13: Vapor Barrier Placement on a Wood Deck

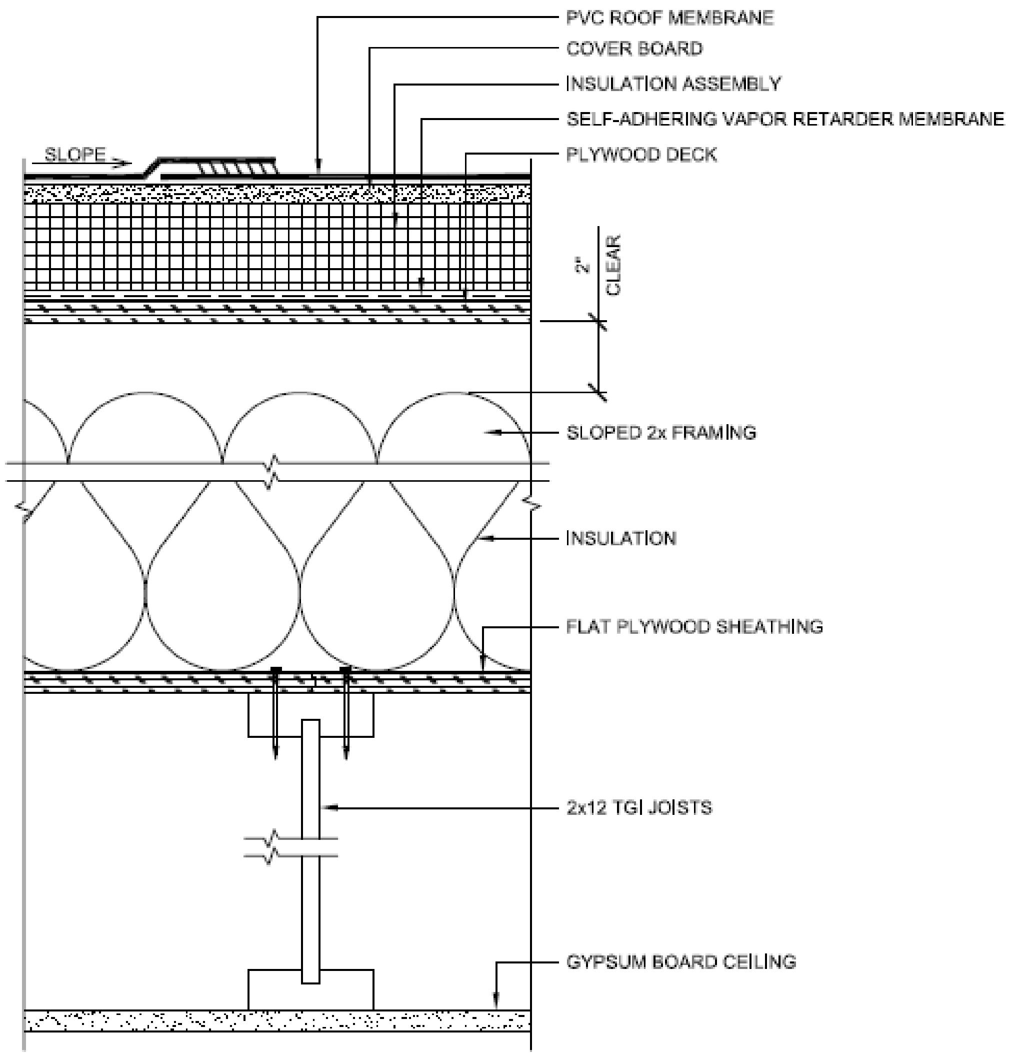


Figure 14: Vapor Barrier Placement on a Wood Double-Framed Deck

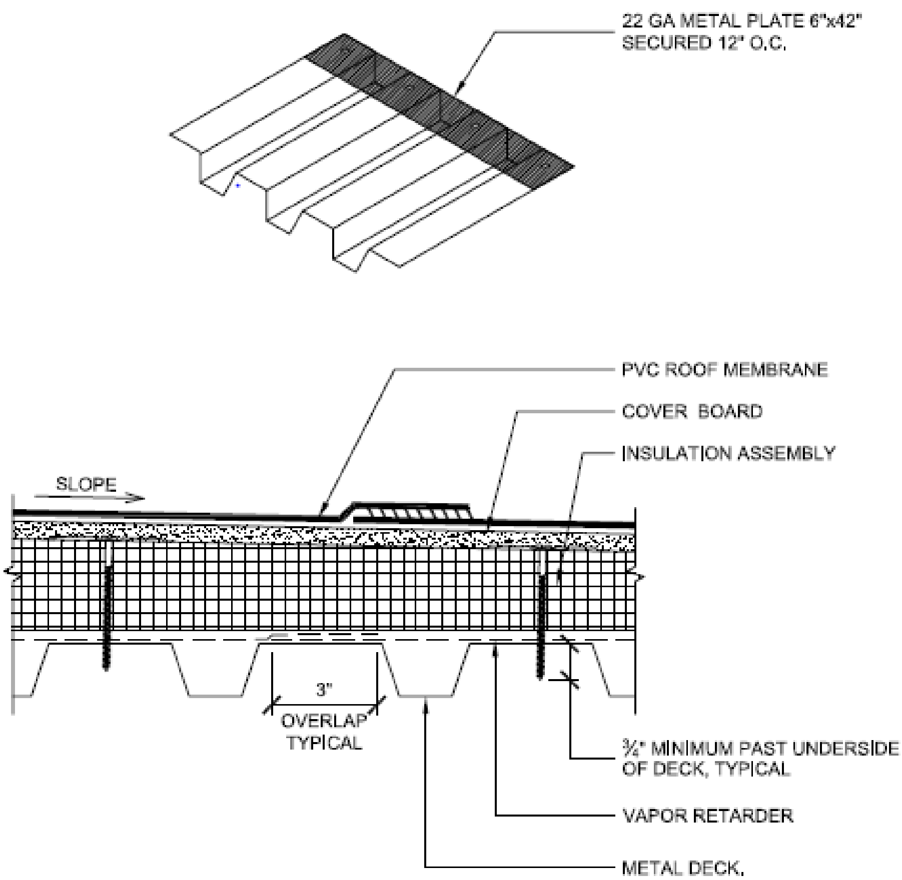


Figure 15: Vapor Barrier Placement in Metal Deck

It is imperative that vapor barriers continue uninterrupted (or properly sealed) over the roof and down both exterior and party walls. If the vapor barrier is improperly terminated at the roof, water vapor can penetrate through the gaps and condense. If the vapor barriers do not continue down structural and party walls, water vapor can still permeate through interior and exterior walls and contact surfaces cool enough for condensation.

LESSONS LEARNED

Even a perfectly designed roof might still incur condensation. The only true way to prevent condensation in roofing assemblies is through conscientious design. Ventilation and vapor barriers must be designed for existing, realistic conditions. Roofing designers must take hygrothermal climate and specific roofing assemblies into account. What works for an ice cream shop in Hawai'i will not work for an indoor health spa and sauna in the Midwest.

Building owners should be aware of rising humidity levels that can affect condensation. While cool roofs can appear problematic, they are no more problematic than other roofing membranes or coatings. Cool Roofs encounter problems when they are designed without considering these factors. Designing appropriate ventilation, using a vapor barrier that properly terminates at all walls, and ensuring properly sealed and insulated, can mitigate condensation.

There are currently no concrete guidelines for determining whether specific roofing assemblies should include a vapor barrier/retarder or not. Code requires that the design professional take condensation into account and design assemblies to prevent it. The NRCA recommends that a vapor retarder be used when outside temperatures reach below 40 degrees Fahrenheit and where the internal relative humidity is 45 percent or greater. Any roof replacement or new roof project with a cool roof should include a vapor retarder if exterior temperatures can dip below 45 degrees.

Some of the top debated questions for projects receiving a new cool roof are:

1. If replacing a roof, without a roofing design consultant, is the roofing contractor responsible for designing and installing a vapor barrier?
2. If a new cool re-roof is causing condensation damage, when the old traditional roof did not, should the roofing manufacturer require a vapor barrier?
3. Should a cool roof manufacturer automatically provide warnings to owners and contractors regarding potential for condensation?
4. Should an Architect designing a new cool roof on a new building be required to design a vapor barrier?