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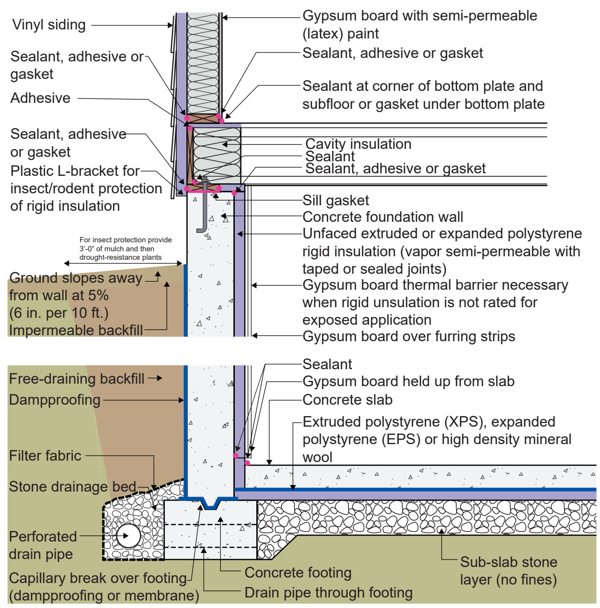
Moisture Control for Residential Buildings



Principles and Practices

Joseph Lstiburek
Building Science Corporation

September 30, 2020

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OAK RIDGE NATIONAL LABORATORY
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Moisture Control for Residential Buildings

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Contents

Preface

This handbook is an update of the original Moisture Control Handbook that was published in 1991. Thirty years ago, we had already recognized that the control of moisture was the critical path to designing energy efficient, durable, and healthy buildings. The Abstract of the original handbook states that moisture is "viewed as one of the single largest factors limiting the useful service life of a building," that "very little consensus on moisture control existed, and that "a need to develop a document which presented moisture from a building science or systems approach existed."

Why update the handbook? The laws of physics have not changed; air, moisture, and heat still flow in and out of buildings according to the laws of thermodynamics. However, building materials, equipment, and construction practices have changed substantially over the last thirty years and changing consumer expectations about comfort have transformed the way modern buildings are constructed and perform. Examples of these requirements include:

- Innovative labor-saving building materials have changed the way building envelopes behave. Market introduction of new materials that reduce air infiltration have also contributed to the reduced drying potential of building assemblies. Even new homes not considered energy efficient by today's standards are tighter and less forgiving to moisture intrusion than older homes.

- The dramatic increase in central air conditioning, especially in colder climates, has significantly changed the thermal conditions inside homes throughout the United States. These relatively new operating conditions have fundamentally changed the thermal, air, and moisture dynamics in homes.

- Compared to 1991, the latest building energy codes require significantly increased airtightness and insulation levels. When designed and installed properly, these new requirements are cost effective and improve comfort and energy efficiency. However, design and installation problems persist leading to increased risk of durability problems.

Modern building envelope assemblies are much less tolerant of design and installation flaws. They must be better designed and constructed to control the thermal, air, and moisture flows in and out of the structure.

To ensure that constructing or retrofitting energy efficient building envelopes is not jeopardizing their service life, moisture design must be conducted.

The objective of this handbook is to provide updated information to designers, builders, and building owners that will lead to the construction of energy efficient building envelopes. The handbook clearly illustrates that an energy efficient airtight building envelope and a durable structure are not mutually exclusive and that both requirements can be obtained with thoughtful design. By considering the moisture conditions and moisture performance in the design, the building envelope service life can exceed those typically seen in existing buildings. Hopefully this handbook can provide a roadmap and become your resource for achieving this goal.

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Abstract

Moisture problems are prevalent all over North America, almost independent of climate. They are viewed as one of the single largest factors limiting the useful service life of a building. Elevated levels of moisture in buildings also can lead to serious health effects for occupants. A need to develop a document that presents the issues relating to moisture from a building science or "systems" approach exists. This document attempts to fill that need.

The first three chapters of the handbook present the basic principles of moisture movement and control. Chapter 1 addresses changes in construction and energy flow. Chapter 2 deals with materials. Chapter 3 deals with moisture movement including rain, ground water, air flow and interaction of air flow with mechanical systems and finally diffusion. Chapters 4, 5, 6, and 7 deal with wall assemblies, roof assemblies, foundation assemblies and ventilation systems respectively. Chapters 8, 9, and 10 deal with climate-specific assemblies and case studies. Chapter 11 addresses common problems.

Acknowledgments

This handbook is an update of the original Moisture Control Handbook published by the U.S Department of Energy and Oak Ridge National Laboratory in October, 1991. Although the fundamental physics and principles have not changed in the almost three decades that have passed since the publication of the original handbook a great deal of understanding in building performance and materials has taken place. This handbook is intended to memorialize this new understanding.

The original handbook was the brainchild of Sam Taylor, now retired from the U.S. Department of Energy. Major technical advice to the original handbook came from the late Gustav Handegord, formerly of the National Research Council of Canada. Professor John Timusk, retired from the University of Toronto and Professor George Tsongas, retired from Portland State University also provided major technical advice to the original handbook.

The handbook "redo" is the brainchild of Andre Desjarlais of Oak Ridge National Laboratory. Support has been provided by Eric Werling of the U.S. Department of Energy. Don Gatley provided technical advice on HVAC systems, Dr. Mark Bomberg provided technical advice on materials science and the late Dr. Don Onysko provided technical advice on wood science.

Professor John Straube of the University of Waterloo; Chris Schumacher, RDH Laboratories; Foster Lyons of Foster Lyons Building Science, Mike Steffen of Walsh Construction, Mikael Salonvaara of Oak Ridge Laboratory, Sam Rashkin of the U.S. Department of Energy, Michael Kramer of RDH Building Science, Peter Baker, Betsy Pettit, Kohta Ueno and Christine Williamson of Building Science Corporation provided guidance, advice and review to this update of the handbook.

The impressive graphics and layout are by Ashley Owens of [RE]Architect.

Joseph Lstiburek
September, 2020

Moisture Control Handbook

"The three biggest problems in buildings are moisture, moisture and moisture…."

Gustav Handegord

"Don't do stupid things…."

Anton TenWolde

"Water, water, everywhere,
And all the boards did shrink;
Water, water, everywhere,
Nor any drop to drink."

Samuel Taylor Coleridge,
The Rime of the Ancient Mariner

CHAPTER 1

Introduction

Water is one of the three principal degradation mechanisms affecting building materials and assemblies. The other two are heat and ultra-violet radiation. Arguably water is the most significant.

If the goal is for buildings to last a long time build them dry, keep them dry, and let them dry if they get wet. Not complicated in principle. It shouldn't be complicated in practice, but often is. It didn't used to be. What changed?

Three big things have changed in our lifetimes:

- We don't build out of rocks and hundred-year-old trees anymore;
- We have very little energy exchange from the inside to outside and vice versa; and
- We have heating, cooling, and ventilation systems that condition the inside almost year-round.

First, the materials that buildings are constructed from have changed dramatically. The newer materials are by and large more sensitive to water damage than the older traditional materials. We used to go to forests and take big trees down, cut them into boards, build boats out of them, and sail them around the world. Try doing that with oriented strand board (OSB). We have paper-faced gypsum in place of plaster and lath. We have engineered wood "I-joists" in place of dimensional framing.

Second, thermal insulation was added to wall assemblies, roof assemblies, and foundation assemblies. The function was to keep the heat inside during the heating season and keep the heat outside during the cooling season. We added more and more and more. We have reached the point where very little energy exchange happens across building assemblies. This is both good and bad. The good is that buildings are very comfortable and consume very little energy. The bad is that the ability of building assemblies to dry - should they start out wet or get wet during service - has been reduced. Drying is an energy exchange process. Less movement of energy yields less drying. When we had poorly insulated buildings the energy exchange was great and we were not very concerned about "incidental water". For example, windows have always leaked. Not a lot, but a little. When they leaked into wall assemblies that were uninsulated or poorly insulated they were able to dry due to the exchange of energy across the wall assembly. We called this water leakage "incidental water" and didn't worry much about it as it did not lead to damage. Today, we can't ignore "incidental water" as energy is not available to promote drying. This "no longer incidental water" has led to fundamental changes in how we install windows and doors, how we flash service penetrations and how we install claddings.

Third, heating has been around for a long time. Cooling is a more recent development. Today, except in very limited circumstances, buildings are heated and cooled year-round. Buildings are also now mechanically ventilated. Buildings no longer rely on operable windows for an exchange of air between the interior and exterior. These changes are also both good and bad. Again, the good news is that buildings are very comfortable and consume very little energy. With controlled mechanical ventilation we can control the quality and the quantity of the air buildings exchange with the exterior. The bad news is that during cooling periods interior surfaces are colder and relative humidity adjacent interior surfaces is higher, which can lead to moisture problems. The bad gets worse if we do not bring in sufficient exterior air. We can create indoor environmental issues. The opposite is also bad. If we bring in too much exterior air we can create indoor environmental issues such as excessive interior surface wetting in hot-humid and mixed-humid climates or excessive interior dryness in cold climates leading to discomfort and material damage to hygroscopic interior trim and finishing materials. It gets even more complicated with ducted and fan- driven heating, cooling and ventilation systems. Buildings are significantly more airtight, so moving large quantities of air within them can lead to unacceptably high negative and positive air pressure differences. And we are not done yet. Because of the huge improvements in efficiency typical air conditioning systems no longer run long enough to sufficiently dehumidify the interior of buildings. On top of that, modern high efficiency air conditioning systems provide less dehumidification than old, inefficient units.

Over time the moisture sensitivity of assemblies has gone up as well as the "dwell time" for water in these building assemblies. Building assemblies are staying wetter longer and the modern materials are unable to tolerate the moisture stress. This is coupled with heating, cooling, and ventilation systems that have to address air change, air pressure, and interior humidity control. Things are much more complicated than they used to be.

Wetting and Drying of Buildings

Ideally, buildings would always be built with dry materials under dry conditions, and would never get wet from imperfect design, poor workmanship, or occupants. These conditions rarely exist. Most of the time we build outside out of wet materials. Concrete comes in a big truck and we pour it. We fill our joints in gypsum board with "mud." Construction is an inherently wet process. Wet happens.

Building assemblies get wet from the outside, get wet from the inside, and start out wet. We must control wetting from the outside, control wetting from the inside, and let assemblies dry to the inside, or to the outside, or to both sides.

Moisture accumulates in the building enclosure when the rate of moisture entry into an assembly exceeds the rate of moisture removal. When moisture accumulation exceeds the ability of the assembly materials to store the moisture without significantly degrading performance or long-term service life, moisture problems result. The moisture storage capacity of a material depends on time, temperature, and material properties.

This moisture storage capacity is significant in determining performance. Consider three examples: a wood frame wall, a steel stud wall, and a masonry wall.

In an exterior wood frame wall sheathed with wood boards or plywood, the wood can safely store moisture until the moisture content by weight exceeds 16 percent (the "surface mold limit for wood"). The equilibrium moisture content of wood exposed to a relative humidity of 80 percent is 16 percent. In most climates most wood materials come to equilibrium at around 10 percent moisture content by weight. The difference between the surface mold limit and the typical average condition in an exterior wood frame wall is approximately 6 percent moisture content by weight. In other words, the moisture storage capacity or hygric buffer capacity of most exterior wood frame walls sheathed with wood-based sheathings is approximately 6 percent. If moisture accumulates beyond about 16 percent by weight, wood surfaces are likely to develop mold.

Note that the surface mold limit is different than decay. There are "decay fungi" and there are "mold fungi" – they are not the same. Decay can be initiated when the moisture content by weight exceeds the fiber-saturation point. The fiber-saturation point for most wood species used in construction is approximately 28%. However, once decay has begun, stopping decay requires reducing the fiber-saturation point below 20%. The "on switch" for decay is 28%. The "off switch" is 20%. The reason for this difference is that one of the byproducts of decay is free water, which further supports the decay process. This leads to interesting issues. The fiber-saturation point cannot be reached by exposing wood to high relative humidity – only liquid water can initiate decay. The liquid water can come from rainwater, groundwater, condensation, plumbing leaks, or the initial moisture content of "green" wood. Freshly cut lumber has a moisture content well above the fiber-saturation point. However, once decay is occurring a high enough relative humidity can keep the decay process going. Time of wetness is also significant. Brief spikes above 28% are not often an issue. Brief in this context is several days.

In the average home constructed in the 1960's with wood framing and plywood approximately 4,000 to 5,000 pounds of wood is found in the exterior walls. This yields a hygric buffer capacity of approximately 250 to 300 pounds of water or approximately 30 to 35 gallons. From a performance perspective, the average 1960's home can easily accommodate 30 to 35 gallons of water via hygric redistribution. Many water leaks are not a problem because of this large capacity to store water. Now change out the plywood for OSB. This results in a huge reduction in hygric buffer capacity – roughly 2/3 depending on assumptions – to approximately 10 gallons.

Matters are considerably different when the exterior walls are constructed with steel studs and paper-faced gypsum sheathing. There is no water storage capacity in the steel studs and the paper-faced gypsum sheathing can store approximately 1 percent moisture content by weight before mold colonization occurs. Constructing the average home with steel studs and gypsum sheathing yields a hygric buffer capacity of

5 gallons. In this type of an assembly, even the smallest leak can lead to problems.

In contrast, consider a similar-sized home built with masonry exterior walls and masonry cladding. That construction yields a hygric buffer capacity of approximately 500 gallons.

As mentioned earlier the quantity of accumulated moisture in assemblies is affected by the energy flow through the assemblies. In general, more thermal insulation increases the dwell time of moisture in the assembly. Dwell time – or drying time – should be as short as possible to avoid moisture problems.

Moisture Control

Various strategies can be implemented to minimize the risk of moisture damage. The strategies fall into the following three groups:

- Control of moisture entry
- Control of moisture accumulation
- Removal of moisture

These are best used in combination. Strategies effective in the control of moisture entry, however, are often not effective if building assemblies start out wet - and in fact can be detrimental. If a technique is effective at preventing moisture from entering an assembly, it is also likely to be effective at preventing moisture from leaving an assembly. Conversely, a technique effective at removing moisture may also allow moisture to enter. Balance between entry and removal is the key in many assemblies.

The most significant wetting mechanism is liquid flow with rainwater and groundwater as the main moisture sources. Controlling rainwater entry above grade and groundwater entry below grade is the single most important issue, to address with respect to moisture damage and have been the preoccupation of generations of builders and designers. Air transport and vapor diffusion are not such obvious contributions to the wetting of building assemblies with air transport being much more significant than vapor diffusion. All of these mechanisms are capable of leading to moisture-related building problems.

Hygric Buffer Capacity for 2,000 ft^2 Home	
Steel frame with gypsum sheathing:	approximately 5 gallons
Wood frame with wood sheathing:	approximately 10 gallons
Masonry wall with masonry cladding:	approximately 500 gallons

All moisture movement - and therefore any moisture-related problem - comes from one or more of these mechanisms.

Historically successful approaches to moisture control usually incorporate the following strategies:

- Control the wetting of building assemblies and surfaces from the exterior
- Control the wetting of building assemblies and surfaces from the interior
- Should building assemblies or surfaces get wet, or start out wet, allow them to dry to either the exterior or the interior or both.

Building assemblies, in all climates, can get wet from the exterior by liquid flow (rainwater, dew, and groundwater as moisture sources) and capillary suction (rainwater, dew and groundwater as moisture sources). Accordingly, techniques for the control of liquid flow and capillary suction are similar in all climates and are interchangeable.

However, building assemblies get wet by air movement and vapor diffusion in different manners depending on climate and time of year. Accordingly, techniques for the control of air movement and vapor diffusion are typically different for each climate and are seldom interchangeable between the different geographical locations.

Both air movement and vapor diffusion move moisture from both the interior and exterior of a building envelope/ building enclosure. The rates depend on both climatic and interior conditions. This fact is often overlooked by designers and builders. It is not unusual to find "cold" climate building envelope/ building enclosure designs employed in "warm" climate regions. Even more confusing to the builder and designer are conditions where both heating and cooling occur for extended periods.

Climate Dependence of Moisture Control

Buildings should be suited to their environment, both exterior and interior. It is not desirable to construct the same manner of building in Montreal, Memphis, Mojave, and Miami. It's cold in Montreal, it's humid in Memphis, it's hot and dry in Mojave, and it's hot and wet in Miami. And that's just the outside environment. It is also not desirable to construct the same manner of building to enclose a warehouse, house, school, office, health club with a swimming pool, hospital, or museum. The interior environment clearly influences the design of the building envelope and mechanical system.

Environmental Loads

Hygro-thermal regions, rain exposure zones, and interior climate classes are defined as environmental loads. These loads can be used in the design, construction, operation, diagnosis, and understanding of building enclosures and mechanical systems.

Not much rainfall in Las Vegas as compared to Seattle. It gets pretty hot in Las Vegas, not so hot in Seattle.

It gets pretty cold in Minneapolis, not so cold in St. Louis. Not many problems occur when you build a warehouse pretty much anywhere. It's pretty risky when you put a swimming pool inside a house pretty much anywhere.

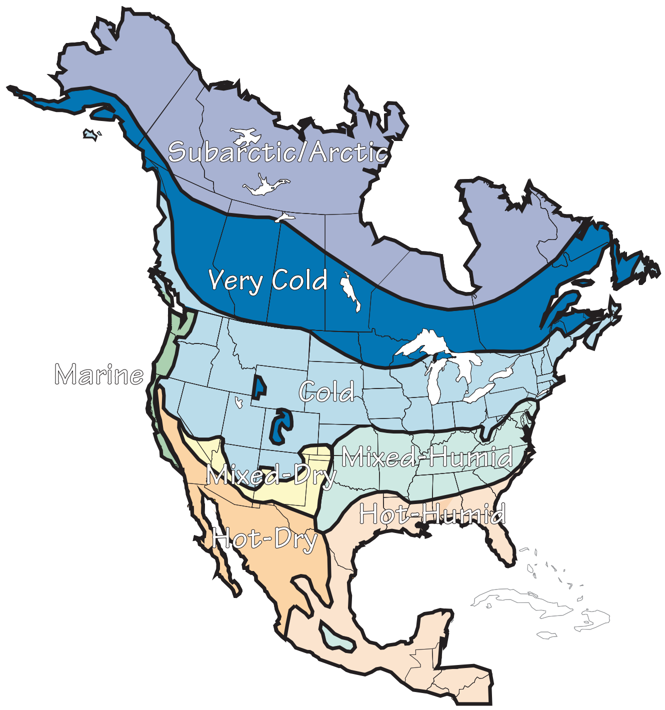


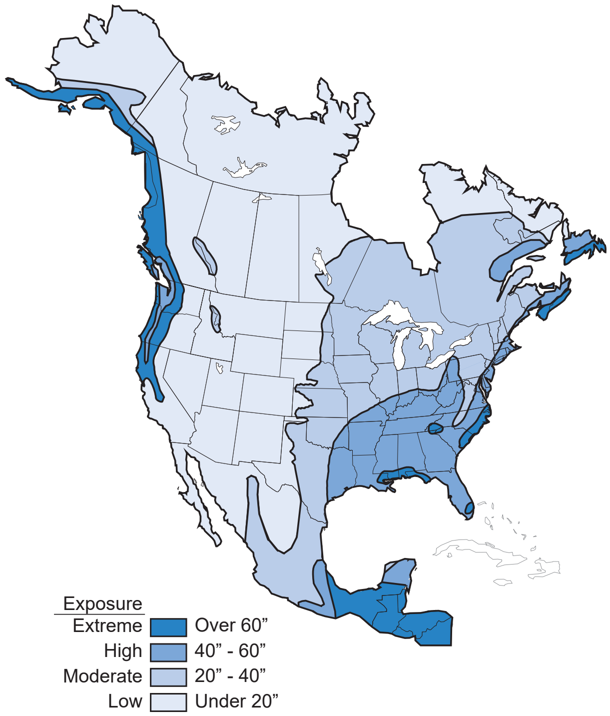
Figure 1.1: Hygrothermal Regions - Based on Herbertson's Thermal Regions and Köeppen climate types.

Where the building is located determines the external environmental load, temperature, relative humidity, rainfall, and snowfall (precipitation). What is going on inside determines the internal environmental load…temperature, relative humidity, and air pressure.

The hygro-thermal regions defined in **Figure 1.1** are loosely based on Köppen climate types. The rain exposure zones defined in **Figure 1.2** are based on annual precipitation. The model building codes further subdivide the hygro-thermal regions into climate zones where building code requirements are specified on a climate zone basis (**Figure 1.3**). The building code climate zones also account for annual rainfall. Moist (A) and Marine (C) climate zones are regions where annual precipitation exceeds 20 inches and the Dry (B) climate zone is where annual precipitation is less than 20 inches. The interior climate classes are based on temperature control, vapor pressure control, and air pressure control.

Hygro-Thermal Regions (**Figure 1.1**)

- Very Cold
- Cold
- Mixed-Humid
- Hot-Dry/Mixed Dry
- Hot-Humid



* Based on information from the U.S. Department of Agriculture and Environment Canada

Figure 1.2: Rain Exposure Zones - Based on annual precipitation

General Strategy

Building assemblies need to be protected from wetting via rainwater, groundwater, air transport and from vapor diffusion. The typical strategies use water control layers, air control layers, vapor control layers, thermal control layers (“insulation”), air pressure control, and control of interior moisture levels through ventilation, dehumidification, and source control. Climate location, season, and interior loads determine the strategies.

Rain Exposure Zones (**Figure 1.2**)

Extreme (above 60 inches annual precipitation)

High (40 to 60 inches annual precipitation)

Moderate (20 to 40 inches annual precipitation)

Low (less than 20 inches annual precipitation)

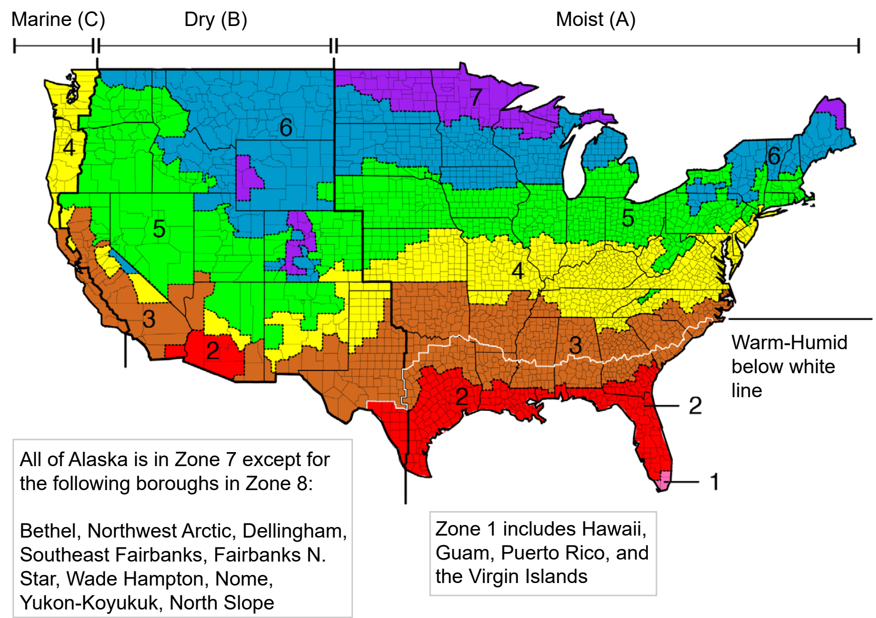


Figure 1.3: International Energy Conservation Code (IECC) Climate Zones - The building code climate zones take into account annual rainfall. Moist (A) and Marine (C) climate zones are regions where annual precipitation exceeds 20 inches and the Dry (B) climate zone is where annual precipitation is less than 20 inches.

Interior Climate Classes

I – Temperature moderated
Vapor pressure (relative humidity) uncontrolled

Air pressure uncontrolled (warehouses, garages, storage rooms)

II – Temperature controlled
Vapor pressure (relative humidity) moderated

Air pressure moderated (houses, apartments, offices, schools, commercial and retail spaces)

III – Temperature controlled
Vapor pressure (relative humidity) controlled

Air Pressure controlled (hospitals, museums, swimming pool enclosures and computer facilities)

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CHAPTER 2

The Water Molecule, Materials and Mold

Many molecules have a positive electrical charge area and a negative electrical charge area on their perimeter. If those areas always remain fixed in place, they are called dipoles. Water is a molecule with one oxygen and two hydrogen atoms held together with a covalent bond at an angle of 104.5 degrees (**Figure 2.1**) resulting in a permanent dipole (**Figure 2.2**). The polar nature of the water molecule governs its interaction with other materials and with itself.

Water likes to stick to itself and stick to other things. Hydrogen bonding, among other forces, causes the water molecule to cling to other molecules resulting in adsorption. Many materials "can capture water molecules from the air and localize them on their surfaces…such water is said to be in the adsorbed state".

Adsorbed water is considered by some a 4th state of matter (**Figure 2.3**). Adsorbed water is not quite a liquid. But it is a liquid… sort of. It has unusual properties. It sticks to surfaces in "monolayers" (**Figure 2.4**). The number of monolayers is directly related to relative humidity. Why is this unusual? Relative humidity is not absolute humidity or vapor pressure. The sheer number of water molecules in the air adjacent a surface is not as important as the relative amount of water molecules in the air adjacent the

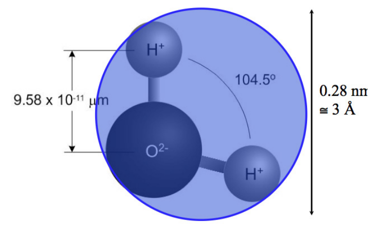

Figure 2.1: The Water Molecule – A permanent dipole.

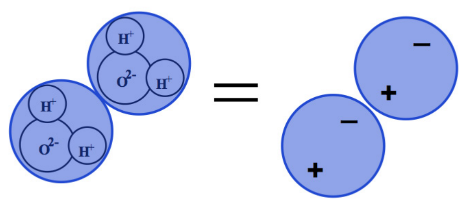

Figure 2.2: Sticky Stuff – Because it is a polar molecule water likes to stick to itself and to other things.

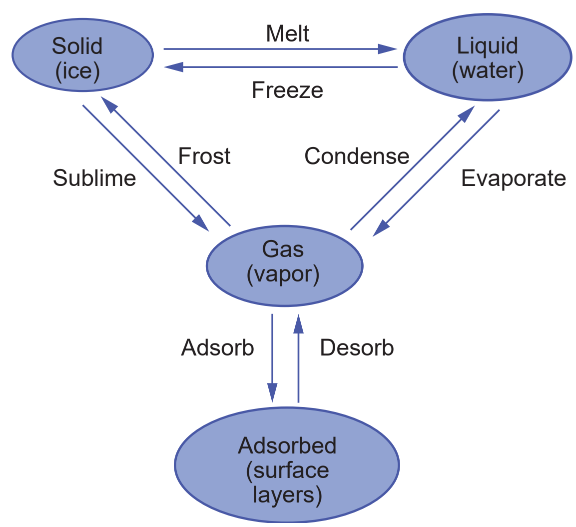

Figure 2.3: Four "Phases" of Water – Adsorbed water is not quite a liquid. But is sort of like a liquid. This is adapted from Kumaran, 2002.

surface, compared to the total amount of molecules that can be in the air adjacent the surface. This is unusual….but it is so.

According to "theory" no more than five monolayers of water molecules can stick to a surface. The first monolayer of water is really, really stuck to the surface. The second monolayer is not as stuck, because it has to stick "through" the first monolayer. The third has to stick "through" two monolayers and so on. Until you get to the fifth monolayer which is pretty weak. This is the basis of multilayer sorption – the BET theory – named after Brunauer, Emmet and Teller.

This adsorbed water layer tends to move along a surface following a concentration gradient….from more to less…(**Figure 2.5**). The process is called surface diffusion. The molecules of water flow along the surface according to the concentration gradient from more to less….but they don't get to the surface necessarily because of a concentration gradient and they change their behavior once they get to the surface.

Most of our building materials are porous in nature. Seemingly solid building materials typically have networks of openings or pores – concrete, brick, paper-faced gypsum, and wood. This, of course, is obvious. What is also obvious is that the pores are not all of uniform size. Some pores are big. Some are small. Some are in between. Yes, this is obvious as well. As the relative humidity goes up the number of monolayers of adsorbed water go up as previously mentioned.

This means that the small pores have a larger proportion of their volume filled compared to the large pores (**Figure 2.6**). This is also obvious. What comes next is not. As the open volume in the very smallest pores gets smaller and smaller the forces between the water vapor molecule still bouncing around in this extremely confined space changes. They get more attractive to each other due to a phenomenon called van der Waals interactions. This phenomenon leads to condensation and the complete filling of these very small pores, even though the vapor pressure in that small space and the

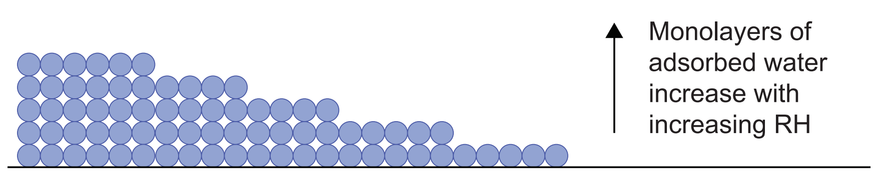

Figure 2.4: Monolayers of Water – The number of monolayers is directly related to relative humidity. Note that surfaces are never "flat" as shown…

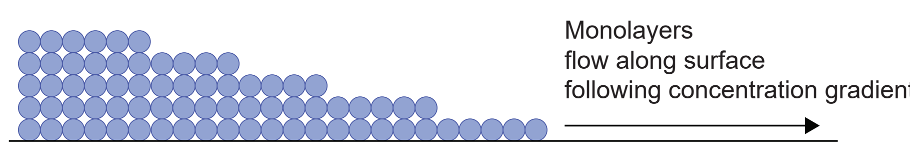

Figure 2.5: Surface Diffusion – Adsorbed water moves along a surface following a concentration gradient. Note that reality does not have such clean straight surfaces…..

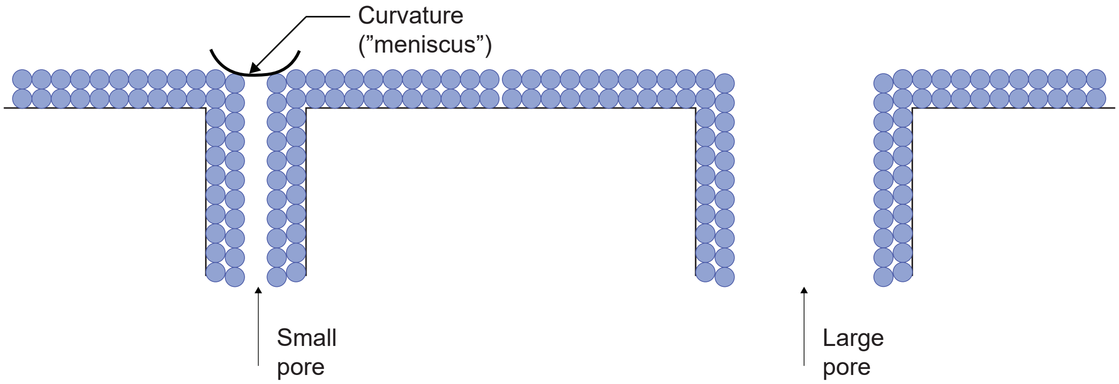

Figure 2.6: Capillary Condensation – Small pores get filled before large pores. A reduction in vapor pressure over a curved surface results in capillary condensation. Thank Lord Kelvin for this. Once again the real world is not as "crisp" and "clean" as drawn.

adjacent, larger pores is still relatively low and below the condensation vapor pressure. Further, this newly condensed water does not evaporate back into the larger pores because the vapor in that larger pore "sees" a depression….a curvature at the entrance to the smaller pore or at any point along its own length that is vanishingly narrow. We call this curved surface a "meniscus" … after the Greek meaning "crescent-shaped" moon. Now we need help from Lord Kelvin. The Kelvin equation (**Equation 2.1**) shows that equilibrium vapor pressure over a curved meniscus is lowered. This reduced equilibrium vapor pressure prevents the evaporation of this condensed water in the smaller pore and brings about more condensation – the water vapor in the space above the meniscus condenses, even though its vapor pressure is below its saturation vapor pressure. In this way the pores fill up with condensed liquid from smallest to largest. The practical implications are significant. This means we can get condensation on porous surface materials at relative humidities less than 100 percent. The condensation occurs in the pores.

$$\ln \frac{p}{p_0} = \frac{2\gamma V_{\mathrm{m}}}{rRT}$$

Equation 2.1 – Kelvin Equation

p = vapor pressure
p_0 = saturated vapor pressure
γ = liquid/vapor surface tension
Vm = molar volume of the liquid
R = universal gas constant
r = radius of the droplet
T = temperature

Mold needs liquid phase water to grow. Mold typically can grow on paper faced surfaces at 80 percent relative humidity. The liquid phase to support this mold growth comes from capillary condensation. At 80 percent relative humidity liquid phase water occurs in the pores of the paper faced gypsum due to capillary condensation.

The affinity of a material for water vapor is described by the sorption curve. More formally the moisture content of a material in equilibrium with moist air is referred to as a sorption isotherm.

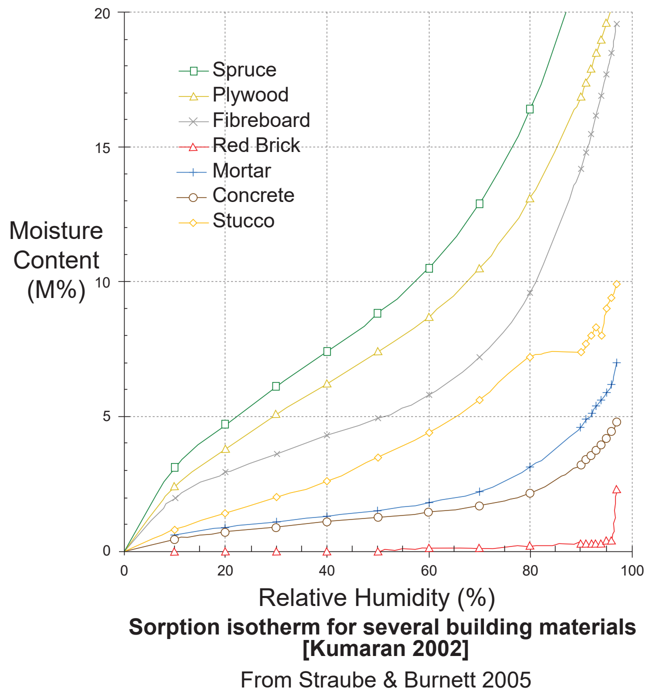

Figure 2.8: Sorption Isotherms - Common building materials sorption isotherms– courtesy of Kumaran by way of Straube and Burnett (2005).

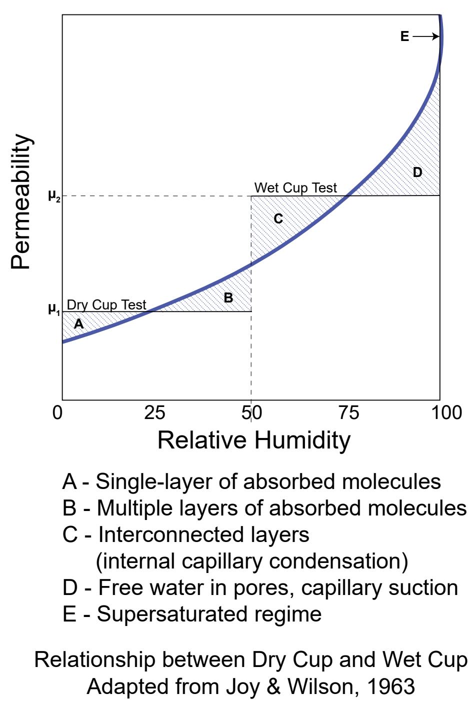

Figure 2.9: Dry Cup vs Wet Cup - The zones described as A, B, C, D and E in Figure 9 represent the moisture transport processes involved. As relative humidity goes up the material goes from single layer adsorbate transport to multiple layer adsorbate transport to internal capillary condensation to free water capillary suction and finally to supersaturated flow.

Figure 2.8 shows sorption isotherms for common building materials. Note that the horizontal axis is relative humidity, and the vertical access is moisture content. If the vertical axis is replaced with vapor transmission (permeability) the shape of the curve is somewhat similar (the sorption curve is a "s-curve" – the permanence curve is "exponential"). For many materials as relative humidity increases so does vapor transmission. There can be a significant change in vapor permeability with relative humidity due to adsorbate transport, capillary transport and liquid transport. This can have major implications when we use such materials in assemblies.These transport properties are typically measured using: "dry cup", "wet cup" and "inverted wet cup" tests (**Figure 2.9**).

For a dry cup test the material to be tested is placed over a "cup" that has a desiccant in it. The material is sealed with wax to the edge of the cup. The cup is placed in an environmental chamber maintained at room temperature and 50 percent relative humidity. One side of the material – the "cup side" - "sees" 0 percent relative humidity and the top side "sees" 50 percent relative humidity. Water molecules migrate from the environmental chamber through the material into the cup and are adsorbed by the desiccant. The cup gains weight over time and this increase in weight over time determines the "dry cup" vapor permeability of the material.

For a wet cup test the desiccant is replaced with liquid water, and we use the same environmental chamber. The "cup side" of the material now "sees" 100 percent relative humidity and the top side – the environmental chamber side "sees" the same 50 percent relative humidity as before. The water molecules now move in the opposite direction and the cup loses weight over time and this determines the "wet cup" vapor permeability of the material.

For the inverted wet cup test turn the wet cup upside down – "invert" it. Liquid water on the "cup side" of the material is now in direct contact with the material. Note that the inverted wet cup test is strictly a liquid water, not water vapor, transport test.

The zones described as A, B, C, D and E in **Figure 2.9** represent the moisture transport processes involved. As relative humidity goes up the material goes from single layer adsorbate transport to multiple layer adsorbate transport to internal capillary condensation to free water capillary suction and finally to supersaturated flow.

Traditional wood frame wall assemblies historically were insulated with fiberglass batt cavity insulation that had an integral "asphalt coated kraft paper" adhered to one side – typically the interior side. **Figure 2.10** graphs the permanence of interior wall assembly linings vs relative humidity. The kraft facing has a "dry cup" value of 1 perm and a "wet cup" value of 15 perms. In most of the United States and Canada buildings in the winter have low interior relative humidity – around 25 percent - and high interior relative humidity during the summer – 60 percent and higher. The kraft facing works much like a "valve"….closed in the winter and open in the summer. It reduces wetting from the interior during the winter but allows inward drying during the summer. In an air-conditioned building it is a bad idea to have an interior vapor barrier. The kraft facing is not an interior vapor barrier during cooling periods as its valve is open. During the winter the kraft facing is a vapor retarder throttling the outward flow of vapor from the interior. Kraft facing is often referred to as a "first generation smart vapor control layer" - a half-century old "smart" membrane.

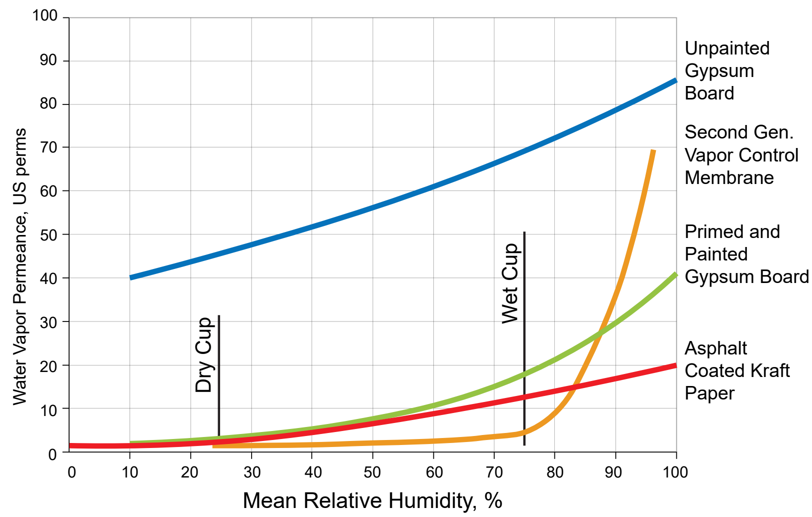

Figure 2.10: Permeance of Interior Wall Linings - The kraft facing has a "dry cup" value of 1 perm and a "wet cup" value of 15 perms. In most of the United States and Canada buildings in the winter have low interior relative humidities – around 25 percent and high interior relative humidities during the summer – 60 percent and higher. The kraft facing works much like a "valve"….closed in the winter and open in the summer.

Today we have extremely "smart" vapor control layers – "second-generation smart control layers". To understand their significance and therefor underlying performance both dry cup and wet cup properties need to be appreciated. And in some cases inverted wet cup properties. Dry cup properties by themselves are not sufficient to understand the performance of modern materials. The shape of the water vapor permanence curves of these layers are "engineered" to provide control that otherwise would not be possible. In this case "inflection points" translates into "valve" opening and closing. "Smart vapor barriers" on the interior are truly smart. In many cases insulating the interior of mass walls would not be possible without this type of technology.

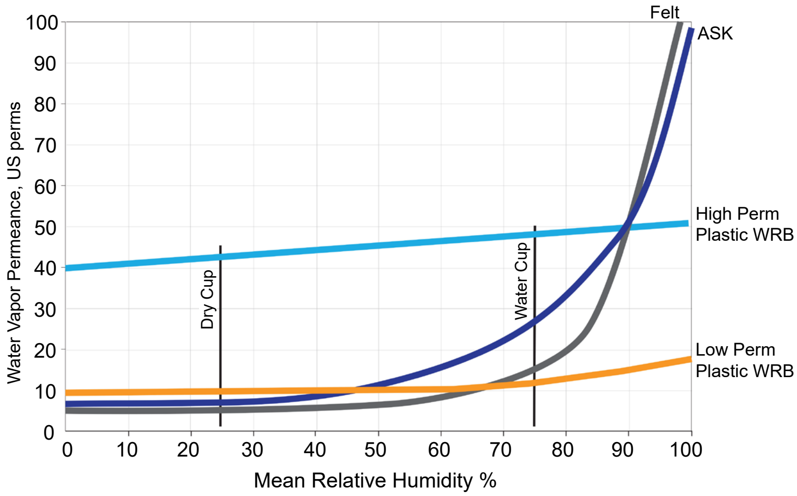

Figure 2.11: Permeance of Exterior Wall Layers - Look at the shape of the curves for the traditional materials: impregnated felt and asphalt saturated kraft (ASK). Notice how the bend upward past 50 percent relative humidity. Hard to knock the old materials. They were pretty darn "smart".

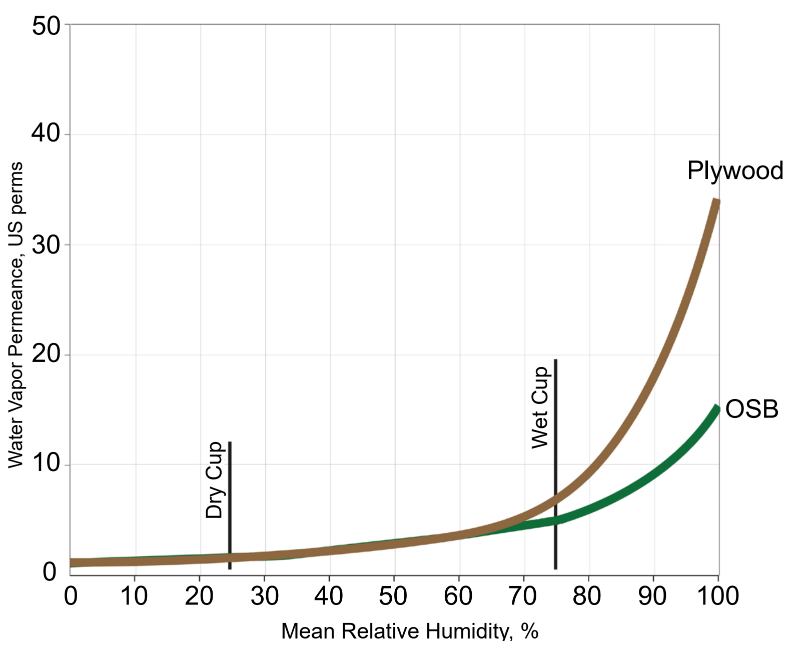

Figure 2.12: Vapor Transmission of Plywood and Oriented Strand Board (OSB) - What makes them work is the wet cup performance not the dry cup performance. Lots of walls would be rotting if they stayed at their dry cup value regardless of the relative humidity and their respective moisture contents.

Figure 2.11 shows the vapor permenance of materials commonly used on the exterior of wall assemblies. Notice how the curves for the traditional materials - impregnated felt and asphalt saturated kraft (ASK) bend upward past 50 percent relative humidity. Some of the traditional materials were pretty darn "smart". Trouble was they tended to blow off and were hard to put up…. but what made them "better" than most appreciated was their wet cup properties. Again, the dry cup by itself does not tell the story.

Figure 2.12 shows the vapor transmission of plywood and oriented strand board (OSB). The performance of these materials is usually determined by the wet cup performance not the dry cup performance because they are placed on the exterior of a building. Many walls would rot if they stayed at their dry cup value regardless of the relative humidity and their respective moisture contents.

When we start looking at composite materials and assemblies such as OSB covered with fluid applied water resistive barriers (WRB's) or gypsum board or OSB with integral water resistive barriers all three characteristics need to be considered: dry cup, wet cup, and inverted wet cup. The shape of the curve matters. Where the inflection point occurs matters. The direction of vapor and water flow matters. Relative humidity matters to materials more than is typically appreciated.

Relative Humidity and Vapor Pressure

Air is capable of containing moisture in the vapor, or gas, phase. The amount of moisture contained in air is referred to as absolute humidity. More precisely, the absolute humidity is the ratio of the mass of water vapor to the mass of dry air. The absolute humidity is also referred to as the humidity ratio.

Air is a mixture of several gases, the most notable being oxygen, nitrogen, argon, and water. Since water vapor is a gas, air containing moisture is, therefore, a mixture of several gases including water vapor. The total air pressure exerted by a volume of air in a given container on that container is the sum of the individual or partial pressures of the constituent gases which make up the air, including water vapor. The vapor pressure is the partial pressure of the water vapor gas on the container.

The terms absolute humidity, humidity ratio, and vapor pressure refer to the same concept: air contains varying amounts of moisture in the gas or vapor form, depending on several factors. The amount of moisture contained in air - the air's vapor pressure, or absolute humidity - is dependent on temperature. The warmer the temperature, the greater the amount of moisture the air mixture can contain; the cooler air is, the less moisture the air mixture can contain. Air is said to be saturated when it contains the maximum amount of moisture possible at a specific temperature, or 100 percent relative humidity. Air holding half the maximum amount of moisture has a relative humidity of 50 percent. Relative humidity is defined as the amount of moisture contained in a unit of air relative to the maximum amount of moisture the unit of air can hold at a specific temperature.

Figure 2.13 illustrates the concepts of relative humidity, vapor pressure, and the influence of temperature and vapor pressure on relative humidity. Two containers, each containing the same mass and composition

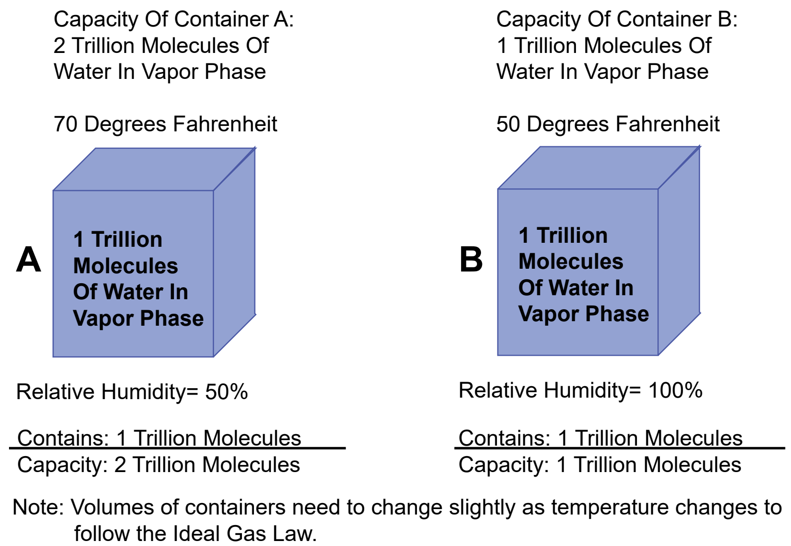

Figure 2.13: Relative Humidity Increases as Temperature Decreases - The concept of relative humidity, vapor pressure, and the influence of temperature and vapor pressure on relative humidity.

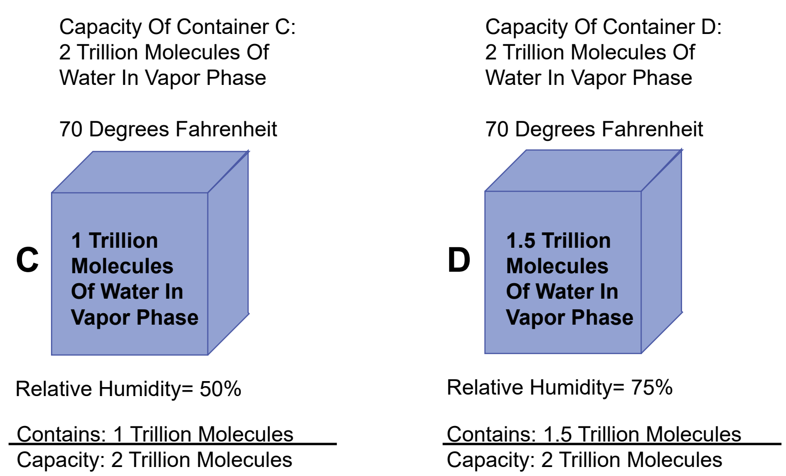

Figure 2.14: Relative Humidity Increases as Vapor Pressure or Moisture Content of Air Increases - The concept of relative humidity, vapor pressure, and the influence of temperature and vapor pressure on relative humidity.

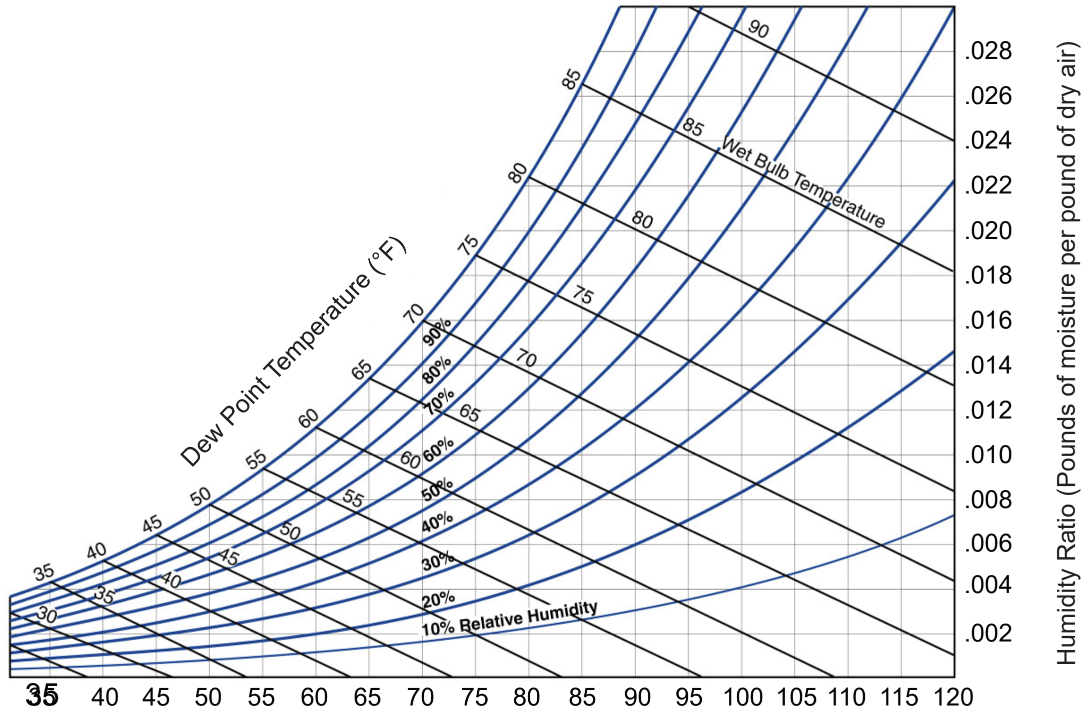

Figure 2.15: Psychrometric Chart - The relationship between temperature, relative humidity and vapor pressure is presented graphically on a psychrometric chart.

of air, are sealed. The containers are assumed to be airtight, watertight, and vapor tight. The amount of moisture in each container is identical – 1 trillion molecules of water in the vapor form.

Container A is maintained at 70° Fahrenheit, and container B is maintained at 50° Fahrenheit. Recall that the warmer the temperature, the more moisture that can be contained in the air mixture. Assume that the maximum amount of moisture the air mixture in container A can hold is 2 trillion molecules of water in the vapor phase. Because the air mixture in this container actually contains only 1 trillion molecules of water, the relative humidity is 50 percent. In contrast the air in container B is maintained at 50° Fahrenheit and the air mixture can only contain a maximum of 1 trillion molecules of water so the relative humidity of the air in container B is 100 percent.

Both containers hold precisely the same amount of moisture. Therefore both have identical vapor pressures, yet one container (the warmer container) has a relative humidity of 50 percent and the other container has a relative humidity of 100 percent. In fact, the relative humidity of the warmer container can be increased by cooling the container, and not necessarily by adding moisture (increasing vapor pressure). In other words, relative humidity can be changed merely by altering temperature, not necessarily by changing moisture content.

In **Figure 2.14**, two additional sealed containers are provided, each containing the same amount of air as the previous two containers. These containers are also assumed to be airtight, watertight, and vapor tight. However, unlike the previous two containers, the temperature of these containers is identically maintained at 70°

Fahrenheit. Therefore, being consistent with the previous example, the maximum amount of moisture these containers can contain in the vapor phase is 2 trillion molecules. However, assume that one of these containers contains 1 trillion molecules of water in the vapor phase and the other contains 1 ½ trillion molecules.

The air in the container containing 1 trillion molecules of water vapor is at 50 percent relative humidity, and the air in the container containing 1 ½ trillion molecules of water vapor is at 75 percent relative humidity.

In the first pair of containers, relative humidity was increased by maintaining a constant vapor pressure, or amount of moisture in each container, and changing the temperature (the capacity of the container to contain moisture).

In the second pair of containers, relative humidity was increased by maintaining a constant temperature in each container and increasing the vapor pressure (the amount of moisture present).

The confusion surrounding relative humidity is because it is often forgotten that relative humidity can be altered two ways – by changing vapor pressure (moisture in the air) or by changing temperature. Also, the relationship between temperature, relative humidity, and vapor pressure can often be counterintuitive. For example, cold air cannot contain much moisture, so cold air is "dry" in the absolute sense and has a low vapor pressure. Although cold air contains little moisture, the moisture that is present is often close to the maximum amount of moisture that can be contained at that temperature, so the relative humidity is high. It is not uncommon for exterior air in heating climates during heating periods to be cold and dry (in an absolute sense), with a low vapor pressure - but a high relative humidity. Since the capacity of the air to contain moisture is reduced as temperature is decreased, only a very small addition of moisture is required to bring it to saturation.

A relative humidity reading taken inside an enclosure will not give a useful indication of the actual amount of moisture present unless a temperature reading is taken at the same time. There is a great deal of difference between 50 percent relative humidity at 70° Fahrenheit and 50 percent relative humidity at 50° Fahrenheit. The relationship between temperature, relative humidity and vapor pressure is presented graphically on a psychometric chart in **Figure 2.15**.

To further complicate matters, relative humidity often varies across a room, since temperature also often varies across a room. For most intents and purposes the vapor pressure in a room can be assumed to be uniform. However, one side of a room may be warm and the other side may be cool. The warm side of the room will therefore have a lower relative humidity than the cool side. If accurate measurements of moisture levels in enclosures are desired, temperature and relative humidity readings need to be taken at both the same place and at the same time.

Mold

Molds are fungi - primitive (simple) life forms that grow on the surfaces of objects. Mold that grows on fabrics is typically referred to as mildew. Mold can discolor surfaces, lead to odor problems, deteriorate building materials, and lead to allergic reactions, or other potential health problems in susceptible individuals as well as other potential health problems. The following conditions are necessary and sufficient for mold growth to occur on most surfaces:

- Mold spores must be present.
- A nutrient base must be available (most surfaces contain nutrients).
- Temperatures at surfaces range between 40 and 100° Fahrenheit.
- Relative humidity adjacent to most surfaces is greater than 80 percent.
- Oxygen is available (above the waterline).

Of these conditions, relative humidity adjacent to surfaces is the most practical to control. Spores are almost always present in outdoor and indoor air. Almost all the commonly used construction materials can support mold growth, so control of available nutrients is limited, and human comfort constraints limit the use of temperature control. Where relative humidity adjacent to surfaces is maintained below 80 percent, mold growth can be controlled. Since relative humidity is dependent on both temperature and vapor pressure, mold control will be dependent on controlling both the temperature and vapor pressure adjacent to surfaces.

Mold Due to Surface Temperature

A classic example of mold occurring in a heating climate is that of an exposed closet on an exterior wall (**Figure 2.16**). The closet, by virtue of its geometry, has a higher surface area of heat loss, relative to room volume, than the other conditioned spaces. In addition, the exterior closet surfaces are more exposed to wind. Its heat loss is likely to be high, and it is not surprising that the closet is likely to be colder than the bedroom it is attached to. If the vapor pressure in the bedroom is the same as the vapor pressure in the closet, and the closet is colder, then the relative humidity in the closet will be higher than the relative humidity in the bedroom. If the closet experiences mold, it is apparent that the relative humidity in the closet is greater than 80 percent. However, the key question is this: is the relative humidity above 80 percent because the closet is too cold, or is it because there is too much moisture present (high vapor pressure) in the closet? Is this a surface temperature mold problem, or is this a vapor pressure mold problem – or a combination of the two?

To answer this question, the vapor pressure in the conditioned space needs to be determined. This can be done by measuring both the temperature and relative humidity in the bedroom at the same place and same time. Assume that in the first instance a relative humidity of 25 percent at a temperature of 70° Fahrenheit is measured. This indicates a low amount of moisture in the conditioned space. In other words, a relatively low vapor pressure exists in the bedroom. In heating climates during the three coldest months, relative humidity in residential occupancies is considered "low" when they are less than 25 percent, relative humidity is considered "typical" or "moderate" when it is between 25 percent and 40 percent; and considered "high" when it is above 40 percent.

Further assume that the amount of moisture (vapor pressure) in the air in the closet and the air in the bedroom is the same (a reasonable assumption, since the closet door is neither airtight nor vapor tight). Therefore, we can conclude that since the amount of moisture in the closet (vapor pressure) is low, we can conclude that the reason for the high relative humidity exists (over 80 percent since mold is present) is because the closet is too cold. This can be confirmed by taking a temperature reading in the closet.

The temperature of the closet can be increased by increasing the heat flow to the closet or decreasing the heat flow out of the closet to the exterior. Increasing the heat flow to the closet can be as simple as leaving the closet door open or replacing the closet door with a louvered door thereby promoting air circulation. The air circulation will carry heat into the closet, warming the closet and reducing its relative humidity.

Heat flow out of the closet can be reduced by better insulating the exterior walls. Exterior continuous insulation has had a significant effect on reducing closet mold.

The best solution is not to locate closets on exterior walls.

Mold Due to Vapor Pressure

Considering the same closet described in **Figure 2.16**, now assume a relative humidity of 50 percent at a temperature of 70° Fahrenheit in the bedroom. This indicates a high amount of moisture present in the conditioned space. In other words, a high vapor pressure exists in the bedroom. Also assume, as before, that the amount of moisture in the closet and the bedroom are the same. Therefore, we can conclude that since the amount of moisture in the closet (vapor pressure) is high, the reason the high relative humidity exists is that there is too much moisture in the house.

To control the mold in the closet, the relative humidity must be reduced, and since the relative humidity is high because the vapor pressure in the closet is too high, the vapor pressure in the closet and the house must be reduced. The vapor pressure or moisture levels in the closet in the house can be reduced using two methods: source control and dilution. Dehumidification is not likely to be effective in heating climates during heating periods as dehumidifiers are not effective at reducing relative humidities much below 50 percent. Dehumidifiers are very effective in mixed-humid climates and hot-humid climates during cooling periods and the spring and fall. They are also effective in cold climates in basements during the summer months.

Source control, the most energy-efficient of the two approaches, involves controlling interior airborne moisture levels through the control of moisture sources. Common examples of source control are the direct venting of bathrooms and kitchen ranges/stoves to the exterior. Other strategies include the construction of dry foundations and the storage of firewood outdoors rather than indoors. Unvented space heaters and gas fireplaces should never be installed.
Dilution involves the use of air change, or the exchange of moisture-laden interior air with dry exterior air. If the exterior

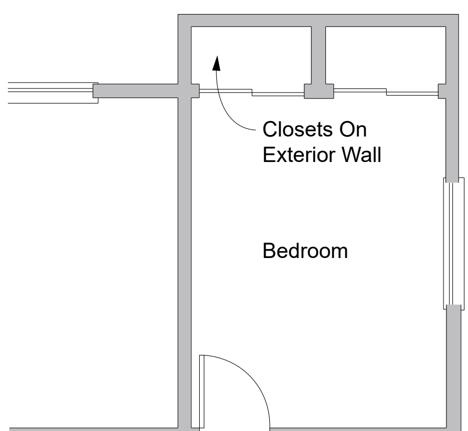

Figure 2.16: Partial Plan of House - Exposed closet on an exterior wall.

air is drier than the interior air, the greater the air change, the greater the dilution of interior airborne moisture levels. Dilution can occur through natural air change (uncontrolled infiltration and exfiltration) or through controlled air change (mechanical ventilation). Note that dilution by air change is only possible where the exterior air is drier than the interior air. In mixed humid and hot humid climates or during cooling periods this is often not the case. As such dilution of interior airborne moisture levels utilizing air change is typically limited to heating climates and during heating seasons.

Dehumidification involves the removal of moisture from a space and usually involves the cooling of warm, moisture-laden air to reduce its ability to hold moisture, thereby forcing the moisture to condense. Air conditioners are de facto dehumidifiers. However, they only dehumidify when they are running. In many cases dehumidification is necessary when cooling is not necessary such as in highly efficient buildings constructed in hot humid and mixed humid climates. The reduced thermal loads from exterior thermal gain – and the use of highly efficient interior lighting – result in very low cooling loads. However, interior moisture loads are high enough to require dehumidification, due to the requirements for mechanical ventilation. Although mechanical ventilation is necessary to control interior contaminants, air change with the exterior brings exterior humid air into the building enclosure. In such cases a separate dehumidifier is necessary.

Common Examples of Mold

Most mold problems are either surface temperature related or vapor pressure related, or some combination of both. A surface-temperature related mold problem may not be eliminated by increasing ventilation or air change, whereas a vapor-pressure related mold problem may not be eliminated by increasing temperatures.

Understanding which factor dominates – surface temperature or vapor pressure – will limit the choice of effective strategies. An example of this would be an old, leaky, poorly insulated home in a heating climate which is suffering from mold. Since the house is leaky, it has a very high natural air change that dilutes interior airborne moisture levels and therefore maintains a very low interior vapor pressure. Providing mechanical ventilation in this house to attempt to control interior mold will likely not be effective since the interior moisture levels are already low. Increasing surface temperatures by insulating exterior walls, thereby reducing relative humidities adjacent exterior wall surfaces, would be a better strategy to control mold. Other common examples of mold follow.

Exterior Corners

Exterior corners are common locations for mold in heating climates due to the higher relative humidities found adjacent to exterior corner surfaces, compared to other exterior enclosure surfaces. The higher relative humidities are due to the corners being colder than other surfaces. The corners are often colder for the following reasons:

- Poor circulation
- Wind blowing through corner assemblies (“wind washing”)
- Lack of insulation because of framing
- Greater surface area of heat loss
- Thermal bridging through built-up wood corners

Lack of airflow at corners due to poor air circulation and obstructions such as furniture results in less heat being carried to corner surfaces, making them colder. Homes with forced-air heating systems or room ceiling fans have lower incidences of mold than homes with low levels of air movement.

Wind typically has higher velocities at corners, increasing heat loss at corner surfaces. If wind enters corner assemblies and blows through, or short-circuits the thermal insulation ("wind-washing"), the interior surfaces (gypsum board) can be cooled significantly. (**Figure 2.17a**)

Corner lumber framing practices often result in more wood than insulation in a corner. The resultant lack of thermal insulation leads to colder corner surfaces (**Figure 2.17b**). Better framing ('two-stud corners") reduce heat loss at corners, and reduces quantities of framing material required (**Figure 2.17c**). The advent of continuous exterior insulation has also significantly reduced the incidence of corner mold.

Corner geometry also results in greater exterior surface area of heat loss per unit of interior surface area than at other wall surfaces (**Figure 2.17d**).

Exterior Roof/Wall Intersections

Cool interior surfaces in heating climates also can occur where exterior walls intersect roofs. Ceiling thermal insulation is often thinner at building perimeters due to roof geometries, resulting in greater heat loss at perimeters, and thus cool spots (**Figure 2.18a**). The cool spots lead to higher relative humidities adjacent surfaces and mold. The use of "high-heel" or "raised-

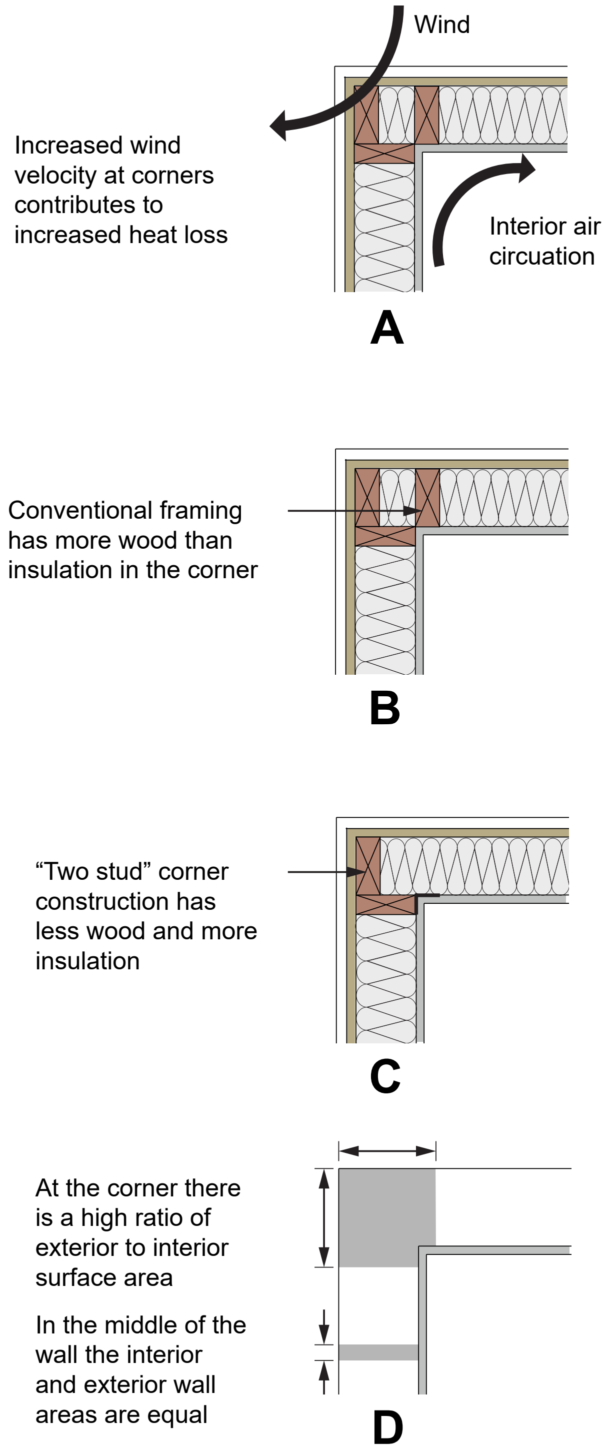

Figure 2.17: Heat Loss Effects at Building Corners - Exterior corners are common locations for mold in heating climates due to the higher relative humidities found adjacent exterior corner surfaces than at other exterior enclosure surfaces. The higher relative humidities are due to the corners being colder than other surfaces.

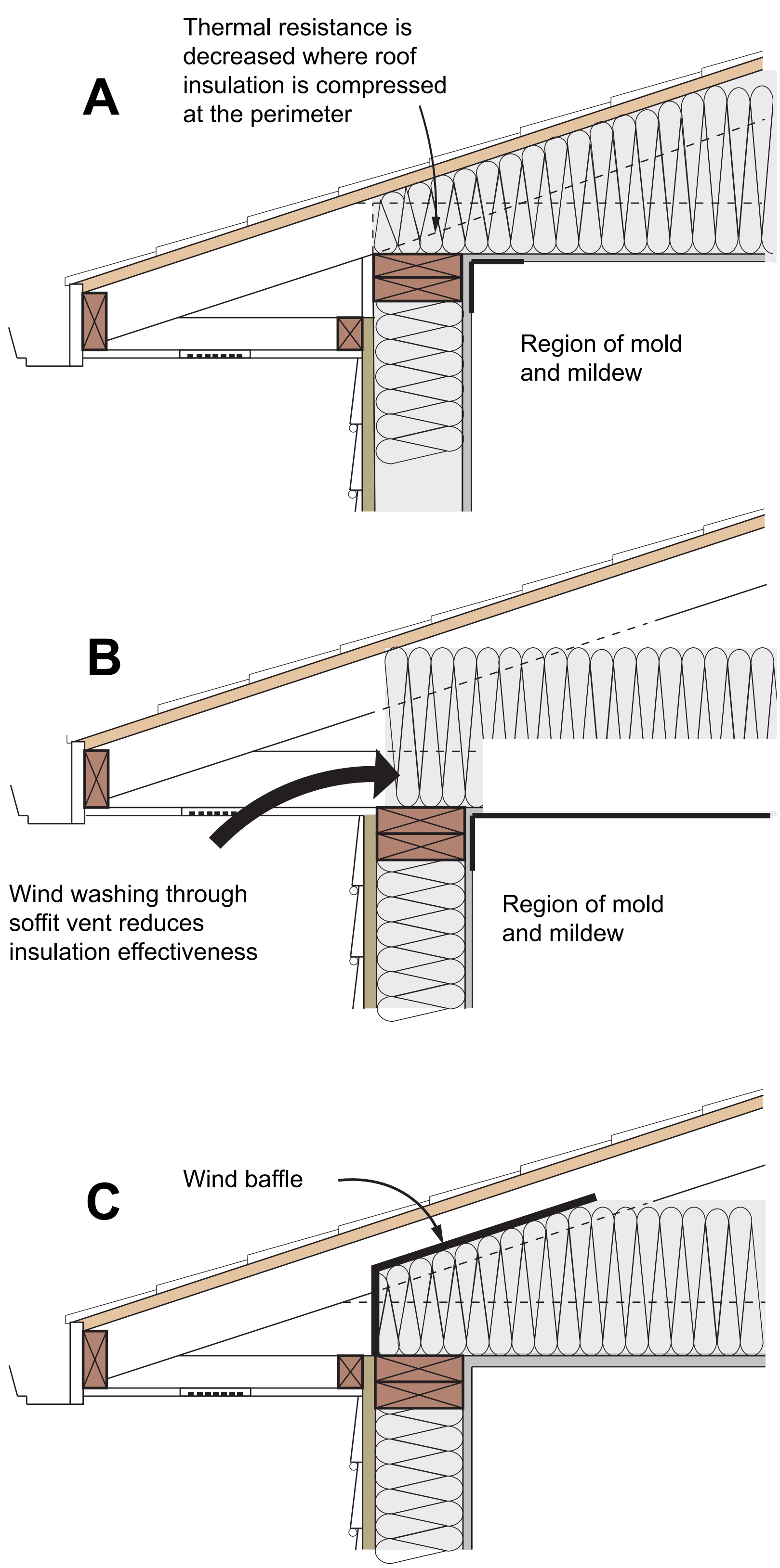

Figure 2.18: Heat Loss Effects Where Walls Intersect Roofs - Cool interior surfaces in heating climates also can occur where exterior walls intersect roofs.

heel" trusses and specialized roof framing details has allowed for greater thicknesses of ceiling insulation to be installed at building perimeters, thus reducing heat loss and minimizing the potential for condensation on interior surfaces at the roof/wall intersection. It is important to prevent the "wind-washing" of this perimeter insulation (**Figure 2.18b**) through the use of baffles (**Figure 2.18c**) or some other control mechanism.

Setback Thermostats

Setback thermostats can be effective in reducing heating energy consumption by dropping house temperature at night or when houses are unoccupied. However, when temperatures are reduced a corresponding increase in relative humidity occurs, which can result in mold growth at cool surfaces.

Closed Off Rooms

Where unused bedrooms or other rooms are closed off during heating periods the reduction in temperature in these spaces can result in high relative humidities and mold growth.

Thermal Bridges

Localized cooling of surfaces occurs as a result of thermal bridges. Thermal bridges are regions of relatively high heat flow conductance in a building enclosure. An example of a significant thermal bridge is the edge of a concrete floor slab in residential apartment construction (**Figure 2.19**). A more common example is the wood stud of a typical exterior frame wall (**Figure 2.20**). The wood stud allows more heat flow than the cavity insulation and therefor provides a path for heat to bridge the wall. The result is a cold spot at the interior face of the gypsum board where it is in contact with the stud. The best approach to address the thermal bridging of framing members is the use of continuous exterior insulation.

In conditioned spaces where dust particles, tobacco and cannabis smoke particulates, candle soot, gas fireplace pilot light soot, and aerosolized fragrances are airborne, accumulation can occur at these cold spots resulting in marks on the gypsum board that correspond to the location of the studs (a.k.a. "ghosting"). This is of particular concern with steel framing due to the high thermal conductivity of steel studs. The phenomenon involved is not mold but Brownian motion. Brownian motion is the vibration of particles due to temperature. The greater the temperature of the particles, the faster they vibrate. Particles vibrate less energetically at cold spots on surfaces, and therefore are more likely to adhere to these cold surfaces than nearby warmer surfaces, hence the discoloration at thermal bridges. Again, the use of continuous exterior insulation significantly reduces the impact of thermal bridges.

Condensation

When the relative humidity adjacent a surface reaches 100 percent, moisture can condense. The temperature at which the air/vapor mix reaches 100 percent relative humidity is called the dew point temperature. Condensation can occur on a surface if the temperature of that surface is below the dew point temperature of the air/vapor mix adjacent that surface. Such surfaces are called "condensing surfaces". Not all surfaces are condensing surfaces.

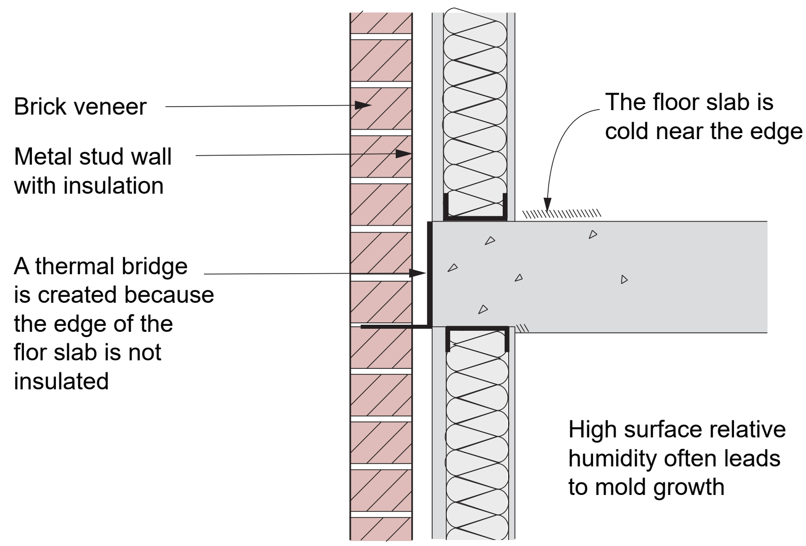

Figure 2.19: Thermal Bridge at Wall/Floor Intersection - Localized cooling of surfaces occurs as a result of thermal bridges. Thermal bridges are regions of relatively high heat flow conductance in a building enclosure. An example of a significant thermal bridge is the edge of a concrete floor slab in residential apartment construction.

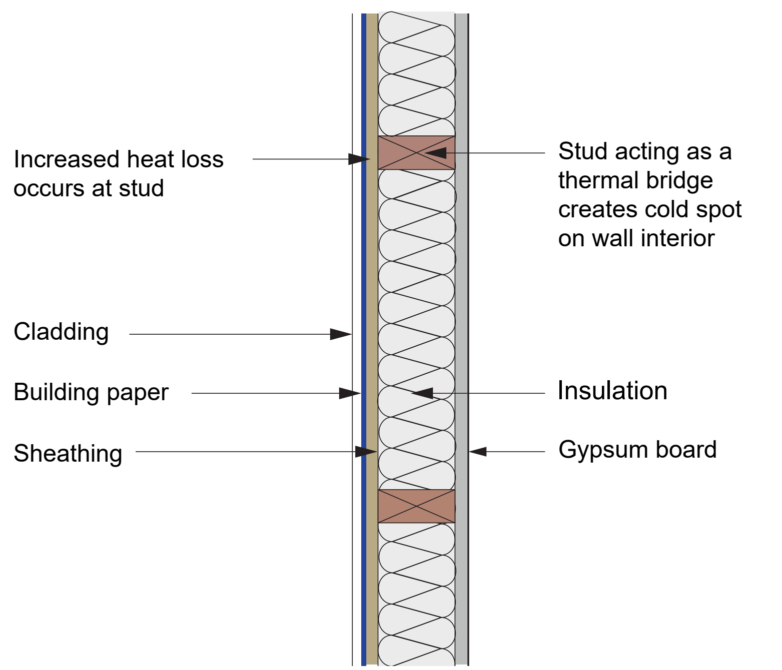

Figure 2.20: Thermal Bridge Through Framing Members - A more common example of thermal bridging is the wood stud of a typical exterior frame wall.

Condensing surfaces have to have sufficient thermal mass to dissipate the energy involved in the phase change between water vapor and liquid water. Gypsum board and sheathing materials typically have sufficient thermal mass to act as condensing surfaces. Fiberglass and cellulose cavity insulations typically do not and as such condensation occurs at either the gypsum board or the exterior sheathing rather than within the fiberglass or cellulose cavity insulation.

The colder the surface, the higher the relative humidity adjacent to that surface. The coldest surfaces in a room have the highest relative humidities adjacent to them. The coldest surface in a room will likely be the location where condensation happens first, should the relative humidity rise to 100 percent. The coldest surface in a room is typically referred to as the first condensing surface.

The same strategies that control mold growth also control condensation on surfaces – increasing surface temperatures and reducing vapor pressures (moisture levels) near surfaces.

Windows

Windows have historically been the coldest surfaces in a room and typically the location where moisture is most likely to condense. This is due to either interior airborne moisture levels rising, or due the exterior air temperature - which determines the temperature of the interior surface of the interior pane of glass. The interior surface of a window is often the first condensing surface in the room.

Historically, to control condensation on window surfaces, window surface temperatures were raised by the use of storm windows, providing perimeter heating directly below windows, the replacement of single glazed windows by double glazed windows, and the replacement of double glazed windows by triple glazed windows and spectrally selective gas-filled windows. The colder the climate, the greater the required thermal resistance of window surfaces and the greater the required sophistication of glazing systems.

When condensation occurs on the interior surface of a window, airborne moisture in the vapor phase is removed from the air and deposited on the interior surface of the window. The colder the window surfaces, the greater the amount of moisture removed from the air. The window acts as a dehumidifier for the room.

The temperature of the first condensing surface usually sets or limits the maximum vapor pressure that can exist in a room. The greater the amount of moisture generation or entry in a space, the greater the amount of moisture deposited on the condensing surface. Vapor pressures will rise only when the rate of moisture or generation or entry in a space exceeds the rate of moisture removal by the condensing surface. When moisture generation or entry stops or is reduced, equilibrium will occur at a vapor pressure limited by the temperature of the first condensing surface in the room. For all intents and purposes, the temperature of the first condensing surface controls the moisture behavior in that room.

To operate the room at a higher vapor pressure, the temperature of the first condensing surface must be raised. Historically, when homeowners and occupants in heating climates began to humidify building enclosures during the heating season for comfort reasons, window surface temperatures had to be raised to control condensation and hence the trend to higher-performance glazing systems.

In an ironic twist, the advent of higher performance glazing systems led to greater incidences of moisture problems in heating climate enclosures because the enclosures could be operated at higher interior vapor pressures without visible surface condensation on glazing systems. In older buildings, the thermally poor glazing systems limited interior moisture levels by condensing moisture. The visible condensation often alerted occupants to the need for ventilation to limit excessive levels of interior moisture.

Concealed Condensation

The use of thermal insulation in wall cavities increases interior surface temperatures in heating climates and therefore reducing the likelihood of interior surface mold and condensation. However, the use of thermal insulation also reduces the temperature of the outer portions of the wall assemblies by reducing heat loss from the conditioned space, therefore, increasing the potential for concealed condensation. The first condensing surface in a wall cavity is typically the interior surface (back side) of the exterior sheathing.

Concealed condensation can be controlled by reducing the entry of moisture into the wall cavities or by elevating the temperature of the first condensing surface. Elevating the temperature of the first condensing surface in a heating climate can be accomplished by installing insulation to the exterior of the first condensing surface. Continuous exterior insulation serves this function. When continuous exterior insulation is installed on the exterior of wall framing it warms everything to the interior of the continuous exterior insulation. Such insulation acts as "double glazing" or "triple glazing" for a wall assembly.

The first condensing surface in a framed wall assembly in a cooling climate is typically the back side of the interior gypsum finish. The most practical way of controlling this temperature is to not over cool the interior space.

Air Conditioned Spaces

In cooling climates, the problems of mold can be as extensive as problems in heating climates. The same principles apply: either surfaces are too cold, or the moisture levels are too high. Cold surfaces in cooling climates typically arise from the air conditioning of spaces. When exterior hot air is cooled, its relative humidity increases. If the exterior hot air is also humid, cooling this air will typically raise its relative humidity above the point at which mold growth can occur (80 percent).

A common example of mold growth can be found where air-conditioned air is supplied to a room and this air is blown against an exterior wall surface due to poor duct design, diffuser location, or diffuser performance. This creates a cold spot at the interior gypsum board. Although this cold air is typically dehumidified before it is supplied to the conditioned space, it can create a mold problem within a wall cavity due to exterior moisture rather than interior moisture. This occurs if exterior humid air comes in contact with the cavity side of the cooled interior gypsum board.

This is particularly a problem in rooms where impermeable wall coverings such as vinyl wallpaper are used, which can trap moisture between the interior finish and the gypsum board. When these interior finishes are coupled with cold spots and exterior moisture, mold growth can occur. Additional issues occur with closets that have limited or no heat gain. Several solutions are possible:

- preventing the hot, humid exterior air from contacting the cold gypsum board (controlling the vapor pressure at the surface and air pressure differentials across assemblies);
- eliminating the cold spots (elevating the temperature of the surface) by relocating ducts and diffusers;
- providing air change in interior closets to raise closet temperatures by using louvered doors or by installing a return air duct;
- providing supplemental dehumidification to reduce interior vapor pressure;
- avoiding over-ventilation of interior spaces with exterior air to reduce interior vapor pressure;
- increasing room temperatures (preventing the overcooling of rooms).

In all cases, it is a bad idea to install impermeable wall coverings.

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CHAPTER 3

Moisture Movement

In order to control moisture levels and moisture movement in buildings, the mechanisms governing such movement must be understood, along with their relative magnitude. Appreciating the magnitude of each transport mechanism is necessary in developing an effective design and construction strategy.

The four moisture transport mechanisms predominant in building science are:

- Liquid flow due to gravity, surface tension, momentum (kinetic energy) and air pressure
- Liquid flow due to capillary suction
- Vapor flow due to air transport
- Vapor flow due to diffusion

Almost all moisture-related problems are a result of one or a combination of these mechanisms.

Each of these mechanisms can act independently and must be dealt with during design and construction. The first mechanism, liquid flow due to gravity, surface tension, momentum, and air pressure, is primarily responsible for moving moisture into the building enclosure from the exterior.

The second mechanism, liquid flow due to capillary suction typically moves moisture into the building enclosure from the exterior and also redistributes condensed moisture within building enclosures.

The latter two mechanisms, vapor flow due to air transport and vapor flow due to diffusion, can move moisture both from the exterior as well as from within the conditioned space into the building enclosure, depending on exterior and interior conditions. For example, when a building in a cold climate is heated, air transport and vapor diffusion typically result in a net movement of moisture from within the conditioned space into the building enclosure – from the inside to the outside. When a building in a warm climate is cooled, air transport and vapor diffusion may result in a net movement of moisture from the exterior into the conditioned space – from the outside to the inside.

This duality of movement is dependent on both climatic and interior conditions.

Of the four transport mechanisms, the most significant is liquid flow where rainwater and groundwater are the moisture sources. Controlling rainwater entry above grade and groundwater entry below grade are the single most important factors in the design and construction of durable buildings.

Liquid flow due to gravity, surface tension, momentum and air pressure and liquid flow due to capillarity are also recognized as the primary factors in the wetting of materials. Vapor flow due to air transport and vapor flow due to vapor diffusion are less obvious contributions.

Liquid Flow with Rainwater and Groundwater as Moisture Sources

The first and most significant moisture transport mechanism a designer and builder must deal with is liquid flow. This involves rainwater and groundwater, which are moisture sources moving under the influence of a driving force, typically gravity, surface tension, capillarity, momentum, or air pressure. This mechanism is responsible for moving moisture from the exterior into the building enclosure.

Leakage will result if three conditions occur:

- Rainwater or groundwater is present
- An opening, hole, or pathway in the building enclosure exists.
- A driving force (gravity, surface tension, capillarity, momentum, and an air pressure difference) is present.

Understanding these conditions gives designers and builders flexibility in developing various strategies to control this moisture transport mechanism.

Designers or builders can seldom control whether rainwater or groundwater is present, and they certainly cannot control gravity or air pressure differences (wind). However, a designer or builder may be able to influence the magnitude (or source strength) of the rainwater and groundwater by proper site selection (minimizing wind exposure and building on elevated dry ground) and are also able to control the number of openings, holes, and pathways in a building enclosure. Furthermore, although the driving forces cannot be eliminated, they can be controlled by roof overhangs, cladding geometry, drainage, water control layers, and flashings.

Experience has shown that controlling the effects of the driving forces, rather than eliminating openings, is the most effective approach in controlling liquid flow, since it is impractical to build an enclosure without openings. When we are referring to eliminating openings we are not referring to windows, doors, and service penetrations – we are referring to small cracks and openings.

Of all the driving forces the most significant historically both above and below grade has been gravity. If rainwater and groundwater accumulate gravity acts on the accumulating water. Consider a column of water (**Figure 3.1**). The taller the column of water the more it weighs and the greater the force it exerts. This force is referred to as hydrostatic pressure or hydrostatic head. If rainwater penetrates a cladding system and drainage is not provided water can build up creating hydrostatic pressure (**Figure 3.2**). Similarly, if groundwater is not drained away from foundations water can build up creating hydrostatic pressure.

In the portions of the building enclosure above grade, gravity (hydrostatic pressure) and air pressure can be controlled by the use of ventilated and drained claddings. Momentum can be controlled by layering materials. Surface tension can be controlled by drip edges and flashings. Capillarity can be controlled by providing capillary breaks.

In the portions of the building enclosure below grade, gravity (hydrostatic pressure) can be controlled by providing drainage – the most common example is free-draining backfill material. Another option is a drainage board or "air gap membrane." Capillarity can be controlled by providing capillary breaks. Momentum and air pressure differences do not play a role with respect to liquid flow below grade. Surface tension rarely plays a role with respect to liquid flow below grade.

It is also possible to provide a barrier above grade to resist rain entry, and to provide a barrier below grade (waterproofing, or the elimination of below-grade openings) to resist hydrostatic pressure.

Finally, it is also possible to provide materials that can store, absorb, redistribute, and dry rainwater and groundwater without being damaged utilizing "mass/storage".

Historically, multi-wythe brick or stone wall construction was one of the dominant mass/storage approaches.

Above grade "perfect barriers" can be constructed from materials that are defined as waterproof such as glass, steel, dense concrete, or roof membranes. Below grade "perfect barriers" can be constructed from sheet waterproofing.

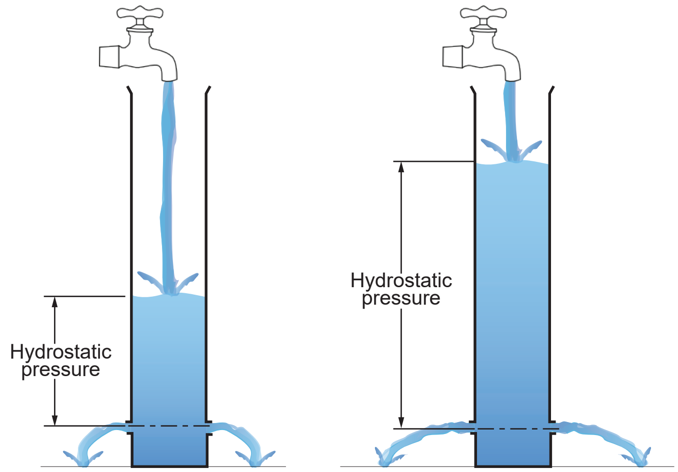


Figure 3.1: Hydrostatic Pressure - If rainwater and groundwater accumulate gravity acts on the accumulating water. The taller the column of water the more it weighs and the greater the force it exerts. This force is referred to as hydrostatic pressure or hydrostatic head.

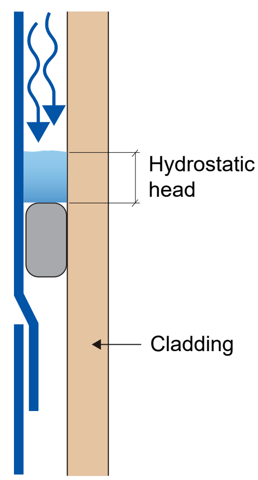


Figure 3.2: Hydrostatic Pressure Behind Cladding - If rainwater penetrates a cladding system and drainage is not provided water can build up creating hydrostatic pressure.

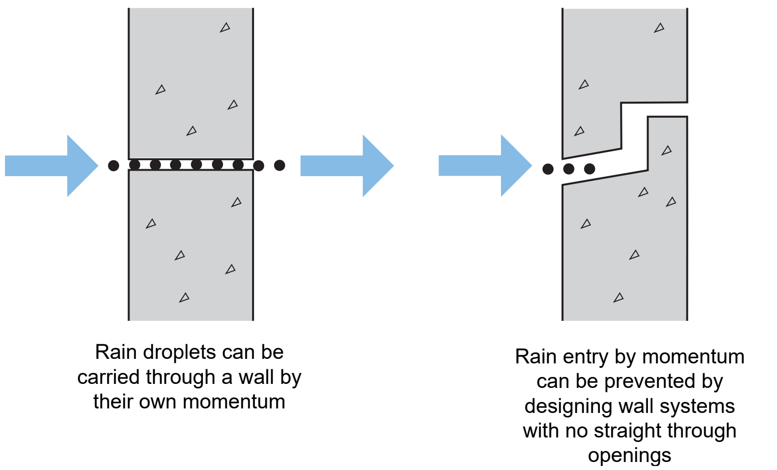


Figure 3.3: Momentum - A driving force for rain entry.

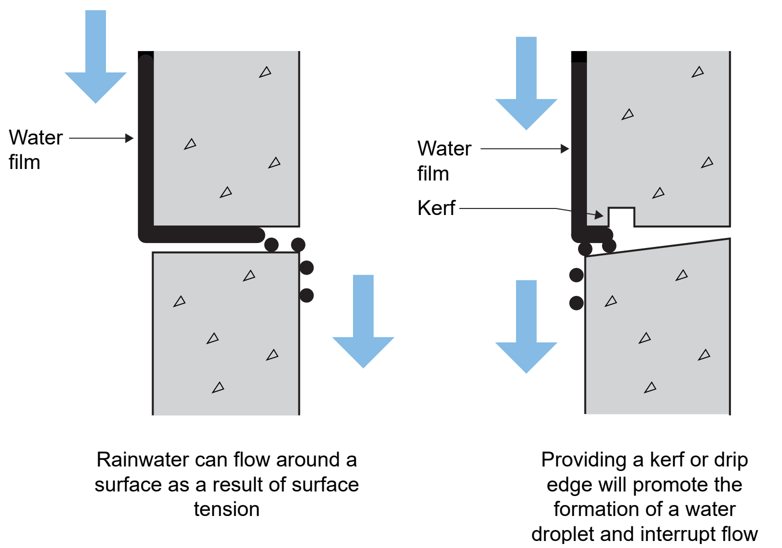


Figure 3.4: Surface Tension – A driving force for rain entry.

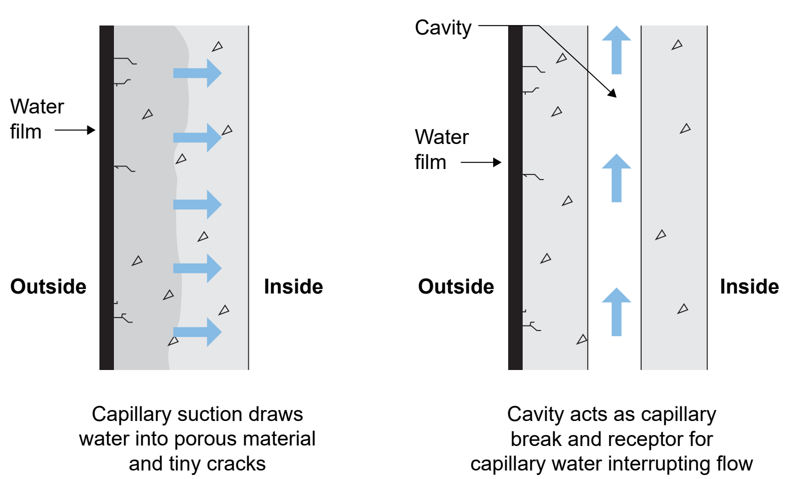


Figure 3.5: Capillarity – A driving force for rain entry.

Rainwater

Control of rainwater entry can be broken into two strategies:

- Reduce the amount of rainwater deposited on building surfaces and assemblies.
- Control rainwater deposited on building assemblies.

Both strategies should be implemented to control rainwater entry effectively. The first component deals with the amount of rainwater reaching a building surface or assembly and involves siting, exposures, and overhangs. The second component deals with the building assembly details themselves.

Reducing the amount of rainwater deposited on building surfaces and assemblies has traditionally been a function of siting and architectural design. The following measures have historically proven effective:

- Site buildings so that they are sheltered from prevailing winds, to reduce exposure to wind-driven rain.
- Provide roof overhangs to shelter exterior walls from rain deposition.
- Provide architectural detailing that sheds rainwater from building faces.
- Slope sites away from buildings.

Five typical driving forces are responsible for rain entry: gravity (hydrostatic pressure), surface tension, capillarity, momentum, and air pressure differences. Each can act independently or in combination. Each should be addressed by design and construction.

Controlling rainwater deposited on building surfaces or assemblies involves the following approaches:

- Layer building materials to control momentum.
- Employ kerfs, drip edges, and flashings to control surface tension.
- Provide an air gap or non-porous material to control capillarity.
- Drain any rainwater that enters building assemblies by employing a water control layer and drainage space to control gravity (hydrostatic pressure).
- Provide an air control layer to control air pressure.
- Where drainage of rainwater that enters building assemblies is not possible prevent rainwater from entering the assembly by providing a perfect barrier constructed from materials that are defined as waterproof such as glass, steel, dense concrete, or roof membranes.
- Where drainage of rainwater that enters building assemblies is not possible provide materials that can store, absorb, redistribute, and dry rainwater without being damaged such as multi-wythe brick assemblies.

Figure 3.3 illustrates how rainwater entry from momentum can be controlled by designing a wall with no straight-through openings or by layering building materials.

Figure 3.4 illustrates how rainwater entry from surface tension can be controlled by providing a kerf or drip edge.

Figure 3.5 illustrates how rainwater entry from capillarity can be controlled by providing a capillary break such as a cavity.

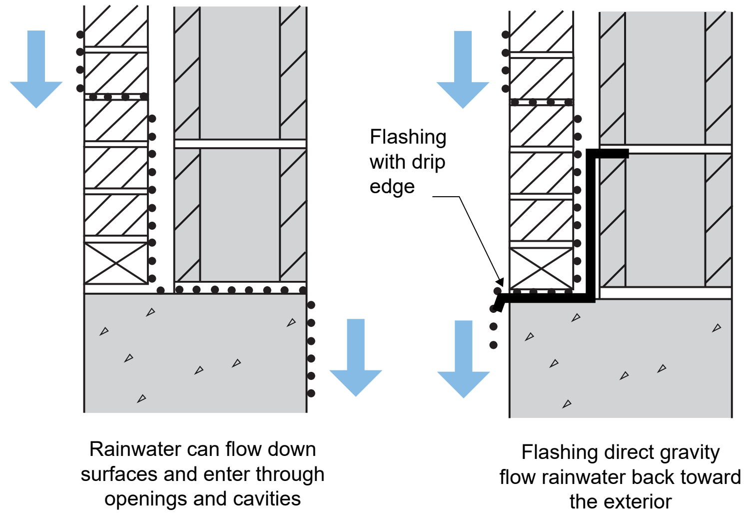


Figure 3.6: Gravity – A driving force for rain entry.

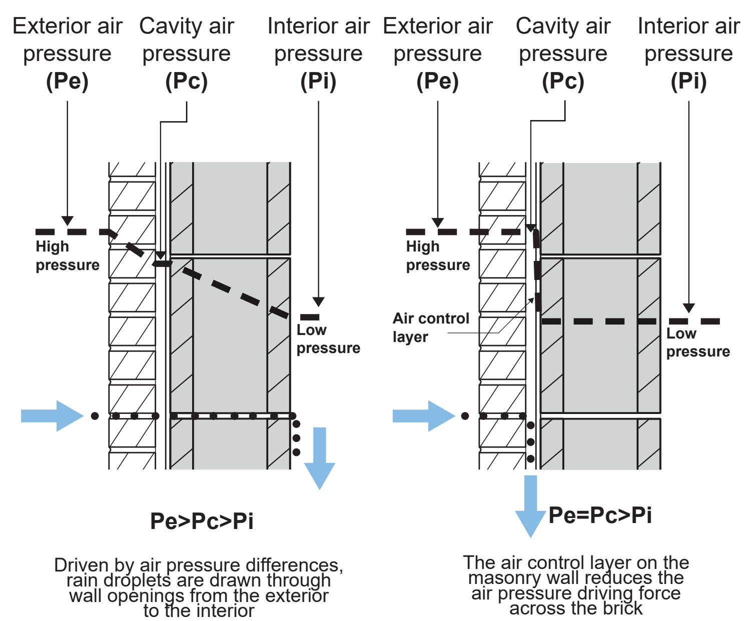


Figure 3.7: Air Pressure – A driving force for rain entry.

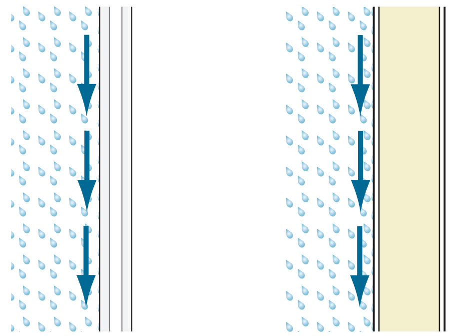


Figure 3.8: Perfect Barrier - Rainwater entry prevented by providing a barrier.

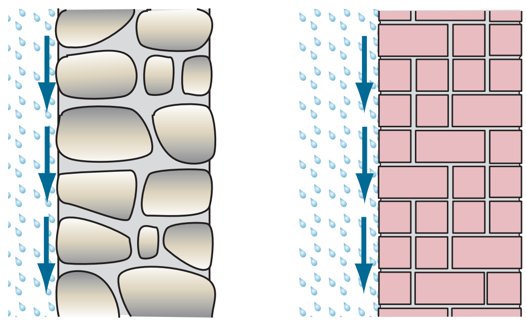


Figure 3.9: Mass/Storage - Rainwater entry controlled by providing materials that can store, absorb, redistribute and dry.

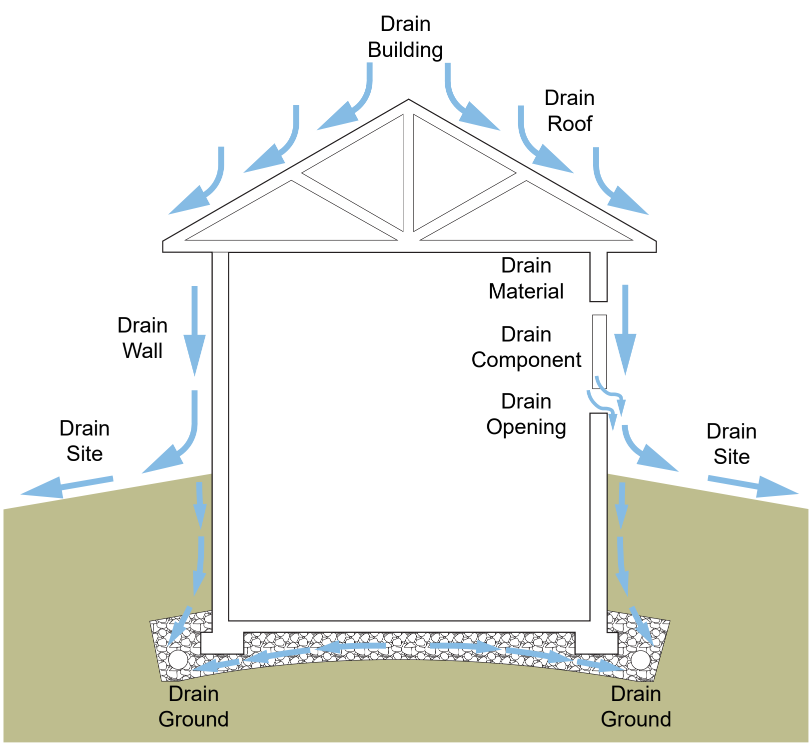


Figure 3.10: Drainage - Everything should be drained: the site, the ground, the building, the assemblies, the openings, the components and the materials.

Figure 3.6 illustrates how rainwater entry from gravity (hydrostatic pressure) can be controlled by providing drainage and flashings.

Figure 3.7 illustrates how rainwater entry from air pressure differences can be controlled by providing air tightness or an air control layer.

Figure 3.8 illustrates how rainwater entry can be prevented by providing a perfect barrier.

Figure 3.9 illustrates how rainwater entry can be controlled by providing materials that can store, absorb, redistribute and dry utilizing mass/storage.

Rainwater Management

The fundamental principle of rainwater management is to shed water by layering materials in such a way that water is directed downwards and outwards from the building or away from the building. It applies to assemblies such as walls and roofs and foundations, as well as to the components in walls, roofs, and foundations such as windows, doors and skylights. It also applies to assemblies that connect to walls, roofs, and foundations such as balconies, decks, railings, and dormers. The key to this fundamental principle is drainage. In essence everything should be drained: the site, the ground, the building, the assemblies, the openings, the components, and the materials (**Figure 3.10**).

Gravity is the driving force behind drainage. The "down" direction harnesses the force of gravity and the "out" direction gets the water away from the building enclosure assemblies, openings, components and materials. In addition to gravity, drainage requires a surface with an air gap for drainage to occur.

The most elegant expression of this concept is a flashing (**Figure 3.11**).

Flashings serve several important functions:

- Direct water out of joints
- Direct water out of building assemblies
- Direct water away from flowing along wall surfaces by providing a drip edge.

Flashings need to be integrated with water control layers such as building papers (**Figure 3.12**). For drainage to occur over the surface of the building paper and the projecting surface of the flashing an air gap must be present over the surface of the building paper and the projecting surface of the flashing to prevent the accumulation of water and resulting hydrostatic pressure.

The role of flashings should not be confused with the role of caulking or sealants. Caulking or sealants eliminate or close off an opening, whereas flashings promote drainage at the opening with respect to the opening itself or with respect to the entire assembly above the opening.

Flashings should always extend sufficiently outward from the exterior face of a cladding to provide a drip edge. Without this, water can subsequently be drawn back into an assembly under the flashing.

Drain the Building

Drain rainwater away from the building, and use the concept of "layering" the building and surrounding levels. Floor levels should always be above the surrounding grade

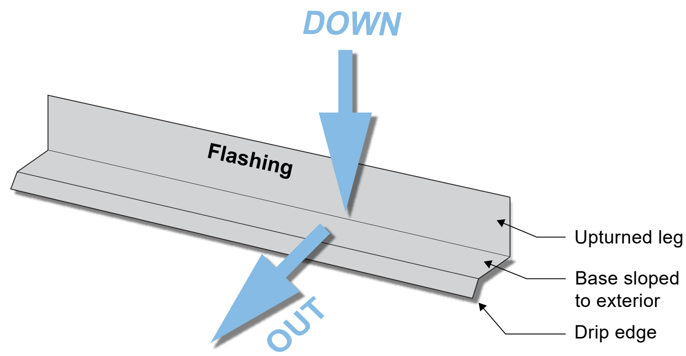


Figure 3.11: Flashings – Direct water downward and outward.

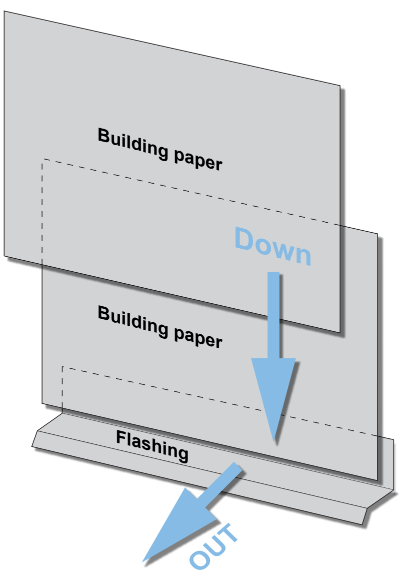


Figure 3.12: Flashing Integration - Flashings need to be integrated with water control layers such a building papers.

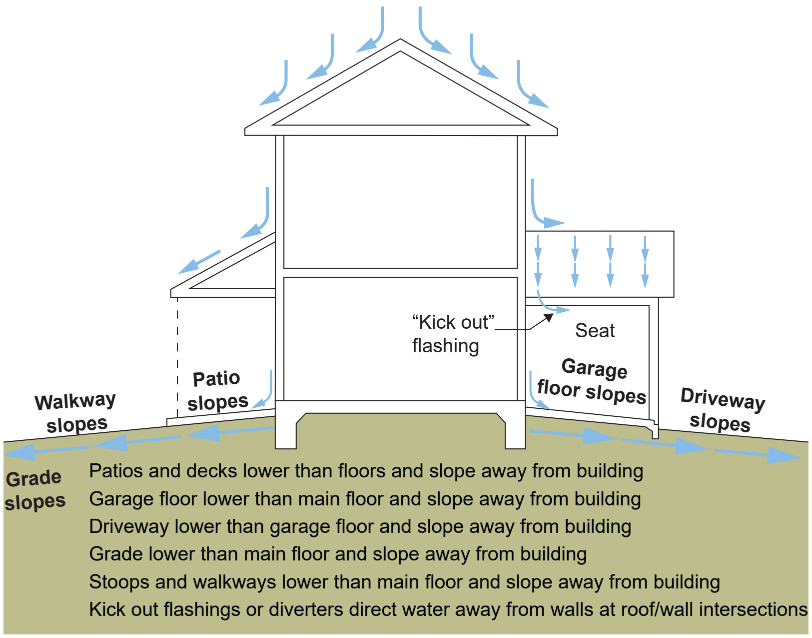


Figure 3.13: Drain the Building – Layer the levels and drain away from the building.

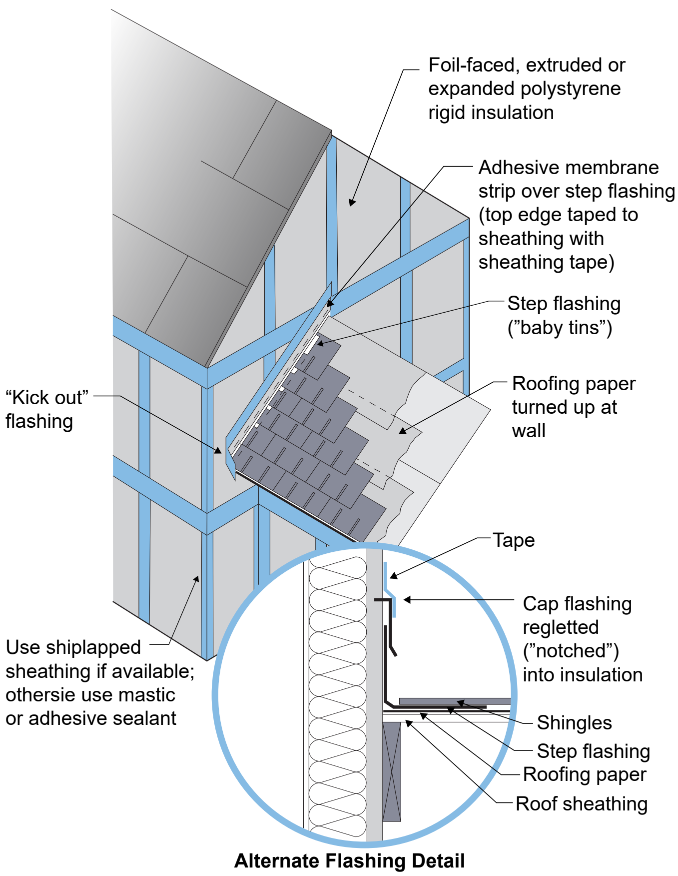


Figure 3.14: Roofs Intersecting Walls: Roofs can also concentrate rainwater where roofs intersect walls. Kickout flashings should be used at these locations

(except basement floors which should always be higher than the surrounding sub grade drainage system). Driveways and walkways should drain away from the building and be lower than floor levels. Patios and decks should also be lower than floor levels and should drain away from the building (**Figure 3.13**).

Sloping roofs should be used to drain water away from the top of buildings. Overhangs, canopies and porch roofs should be used to shed water away from the side of buildings – away from the walls. Flat roofs should never be flat; a more accurate term is a "low slope roof". All flat roofs should be tilted and sloped to drains – a minimum of ¼ inch per foot.

Roofs can concentrate rainwater at building perimeters. Collect the roof run-off with gutter systems and direct the water away from the building. Do not connect the gutter system to a perimeter foundation drain.

Roofs can also concentrate rainwater where roofs intersect walls (**Figure 3.14**). Kick-out flashings should be used at these locations (**Figure 3.15**). The name describes the function. Rainwater running down the slope of the roof is directed away from the wall at the bottom of the roof – it is "kicked out" of the wall at the roof wall intersection.

Drain the Assembly

Assemblies such as walls are constructed from materials that include claddings, sheathings, insulations and components such as windows, and doors. Some assemblies that have more than one layer dedicated to rainwater management and provide drainage are called "screens". Other assemblies do not provide drainage. Such assemblies are either perfect barriers or mass/storage assemblies.

Screen assemblies have multiple lines of defense for rainwater entry. In addition to the exterior cladding, screen assemblies layer building materials shingle fashion inboard of the exterior cladding to direct rainwater that penetrates the cladding back to the exterior. The inward layer is called the water control layer. A space or air gap between the water control layer and other materials promotes drainage, ventilation, and moisture redistribution.

Water control layers are typically water-repellent materials (building papers, house wraps, rigid insulations, fluid-applied coatings, fully adhered membranes, sheet goods) located behind the cladding and are designed and constructed to drain the rainwater that passes through the cladding. They are interconnected with flashings, window and door openings, and other penetrations of the building enclosure to provide drainage of rainwater to the exterior of the building. The materials that form the water control layer overlap each other shingle fashion or are sealed or are continuous so that rainwater flow is down and out of the wall.

Screen assemblies are typically used with water sensitive building materials such as wood framing, steel studs, wood-based sheathings, and gypsum-based sheathings. An example of a screen assembly is a wood frame wall with oriented strand board sheathing (OSB) covered with building paper and clad with wood siding on furring (**Figure 3.16**).

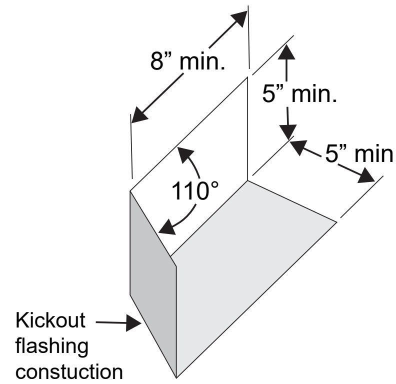


Figure 3.15: Kickout Flashing: The name describes the function. Rainwater running down the slope of the roof is directed away from the wall at the bottom of the roof – it is "kicked out" of the wall at the roof wall intersection.

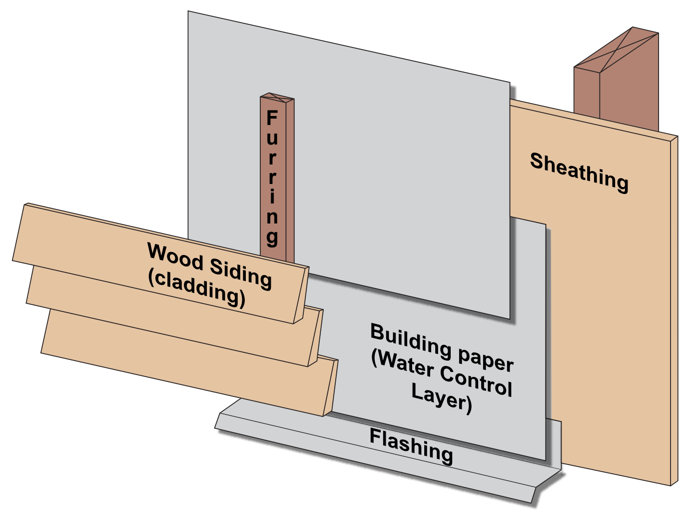


Figure 3.16: Screen Assemblies - Screen assemblies have multiple layers dedicated to water management.

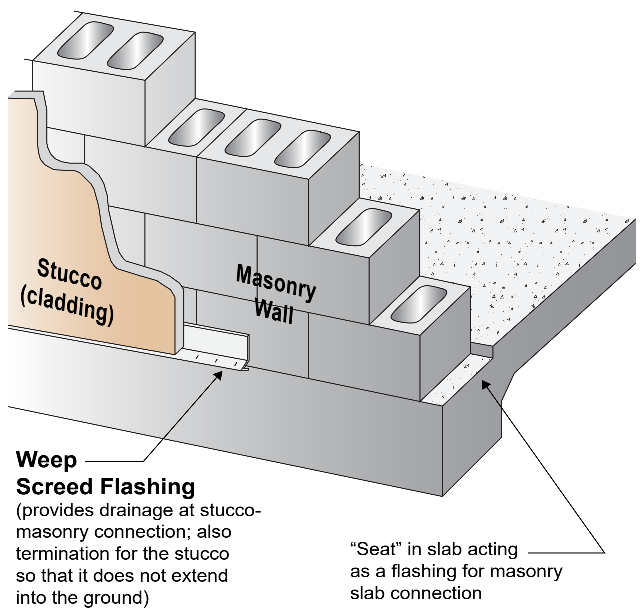


Figure 3.17: Mass/Storage Assemblies – Mass/storage assemblies store, absorb, redistribute and dry rainwater and groundwater without being damaged such as a masonry wall rendered with a Portland cement based stucco.

Perfect barrier assemblies typically rely on the exterior cladding to act as the water control layer and are not commonly used in residential construction. Examples of perfect barrier assemblies are precast panel walls, glass curtain walls and insulated metal panel systems.

Mass/storage assemblies are used with water resistant materials such as masonry, concrete, and multi-wythe brick and stone. An example of a mass/storage assembly that can store, absorb, redistribute, and dry rainwater and groundwater without being damaged is a masonry wall rendered with a Portland cement based stucco (**Figure 3.17**).

Screen assemblies, perfect barrier assemblies, and mass/storage assemblies rely on flashings to control rainwater entry and to direct rainwater to the exterior at areas such as connections between materials, at openings, and penetrations.

Screen assemblies and mass/storage assemblies anticipate water entry past the exterior cladding – perfect barrier assemblies do not. In screen assemblies the penetrating rainwater is drained back to the exterior in liquid form along the water control layer behind the cladding. Some water also penetrates the water control layer and is stored and redistributed and subsequently released in the vapor form. However, the tolerance for such stored and redistributed water is significantly less than for mass/storage assemblies due to the water-sensitive nature of the building materials commonly used with screen assemblies.

In mass/storage assemblies the penetrating rainwater is typically stored and redistributed in the water resistant building materials until it can be released to either the exterior or interior in the vapor form in a controlled manner that does not damage interior or exterior finishes.

Screen systems assume some rainwater will enter and provide a mechanism to remove it. Perfect barrier systems rely on the exterior cladding to shed water effectively for the life of the building. Mass/storage systems assume that rainwater that enters dries both outward and inward without damaging the materials that comprise the system.

Reservoir Claddings

Reservoir claddings are comprised of materials that can store rainwater. Once the reservoirs get wet, the stored rainwater can migrate inward and potentially cause problems. Absorbed rainwater can migrate inward in the liquid form by capillary transport or change to a vapor and migrate inward by air transport or vapor diffusion. In such cases rainwater is the wetting mechanism and capillarity, air transport, and vapor diffusion are the moisture redistribution mechanisms. Common reservoir claddings are brick veneers, stuccos, wood siding, wood trim, and fiber cement cladding.

Reservoir claddings should be uncoupled from the building. Uncoupling involves two approaches. The first reduces the moisture storage of the reservoir cladding. The second limits the inward moisture flow.

Back priming (painting all surfaces, back, front, edges, and ends of wood siding or fiber cement siding and all wood trim) are techniques that can limit the moisture storage of these materials.

Back venting brick veneers (**Figure 3.18**) and/or installing them over foam sheathings (**Figure 3.19**) disconnects or uncouples the brick veneer reservoir from the building.

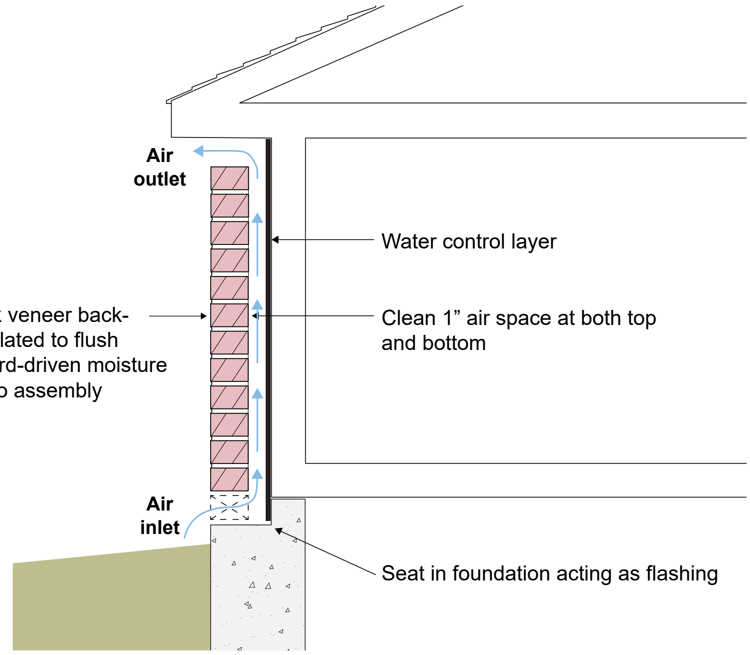


Figure 3.18: Ventilated Cavity – Brick veneer back ventilated to flush inward moving moisture out of the assembly.

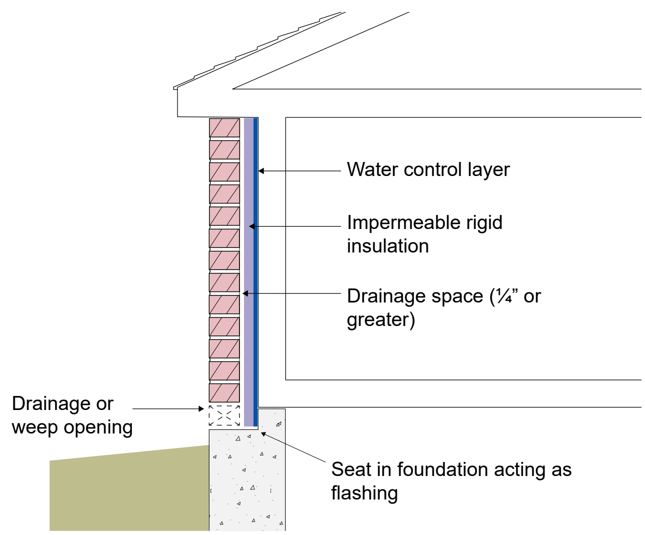


Figure 3.19: Drained Cavity With Condensing Surface – Brick veneer drained where inward moving moisture condenses on the exterior surface of the impermeable foam sheathing insulation.

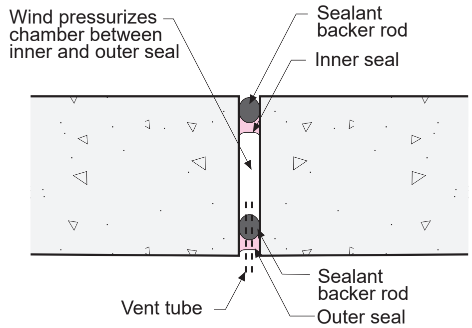


Figure 3.20: Two-Stage Joint – Continuous inner seal and a drained and vented cavity between the continuous inner seal and a weeped outer seal.

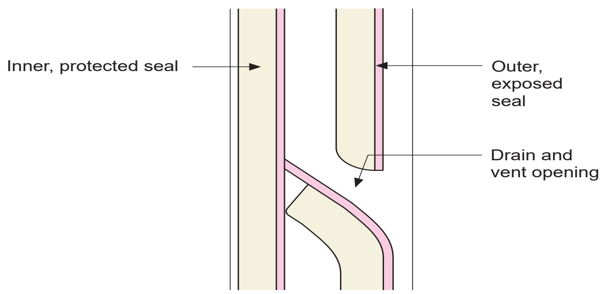


Figure 3.21: Two-Stage Joint Section - Section through a two-stage joint that uses sealant to direct water to the exterior.

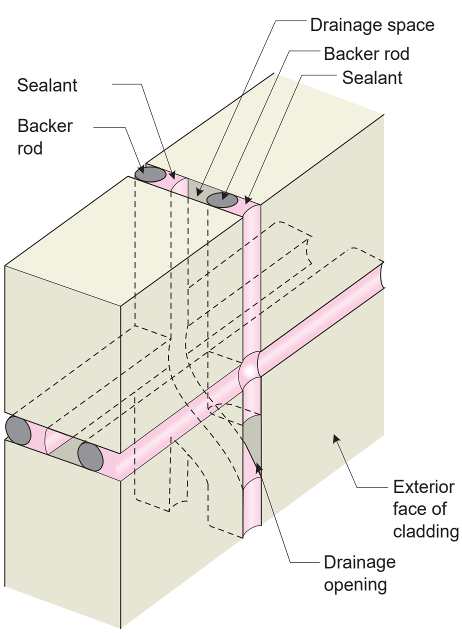


Figure 3.22: Three Dimensional Detail of Two-Stage Joint - Drainage paths are shown. The outer seal is exposed to the elements – ultra violet light, heat and water – but the assembly still works because of the interior protected seal.

Installing stucco over a drainage mat or over a capillary break such as foam sheathing also addresses stucco reservoirs.

Two-Stage Joints

A hybrid approach to controlling rainwater entry recognizes that most rainwater enters building assemblies at joints in cladding systems. Rather than applying a screen approach for the entire assembly a screen approach is applied only at the joints. An example of this is the two-stage joint common with precast panel claddings (**Figure 3.20**).

The approach involves (from the interior to the exterior) a continuous inner seal and a drained and vented cavity between the continuous inner seal and a weeped outer seal. The outer seal is exposed to the elements (principal damage functions of water, heat, and ultraviolet radiation) – but the assembly still works because of the interior protected seal. **Figure 3.21** shows a section through a two-stage joint that uses sealant to direct water to the exterior. **Figure 3.22** shows a three-dimensional detail of the drainage paths.

This approach of inner and outer seals is also common in window and door design and window and door installation (connection to the rough opening).

Drain the Opening

Rainwater should be directed out of building assembly openings – especially openings for windows and doors. The seal between a window or door component and the building assembly layer dedicated to rainwater management (the "water control layer") is rarely perfect – and even if it is perfect during installation it will pass rainwater as the building ages due to the principal damage functions of water, heat, and ultraviolet radiation.

Furthermore, window or door components also leak as they age. This rainwater leakage should be managed in the same manner any rainwater leakage is managed by drainage to the exterior.

Pan flashings, membrane linings, formable flashings, and fluid-applied flashings are typical elements in drainable systems. These approaches work best with end dams and back dams (**Figure 3.23**).

Windows and doors should be integrated into water managed walls using water management installation techniques – hybrid two-stage joints with inner and outer seals. All windows and doors should be air sealed around their entire perimeters on the interior with sealant. The air seal around the entire interior perimeter of the window or door provides for pressure equalization across the unsealed bottom flange of the window or door. The exterior seal around the exterior of windows and doors is weeped at the bottom or are unsealed at the bottom to permit drainage to the exterior (**Figure 3.24**).

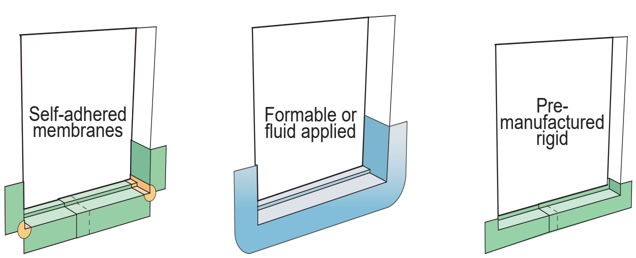
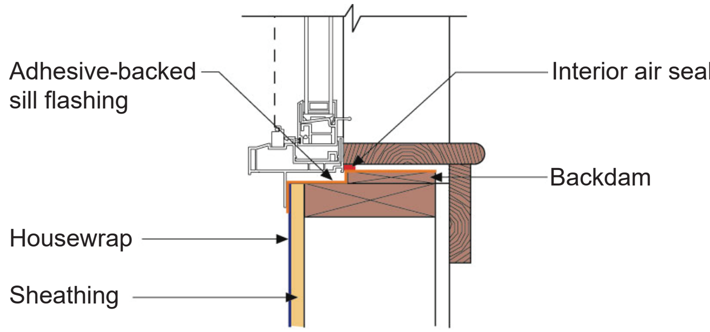
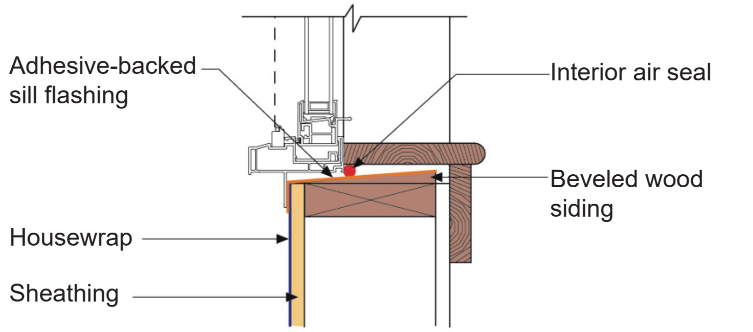


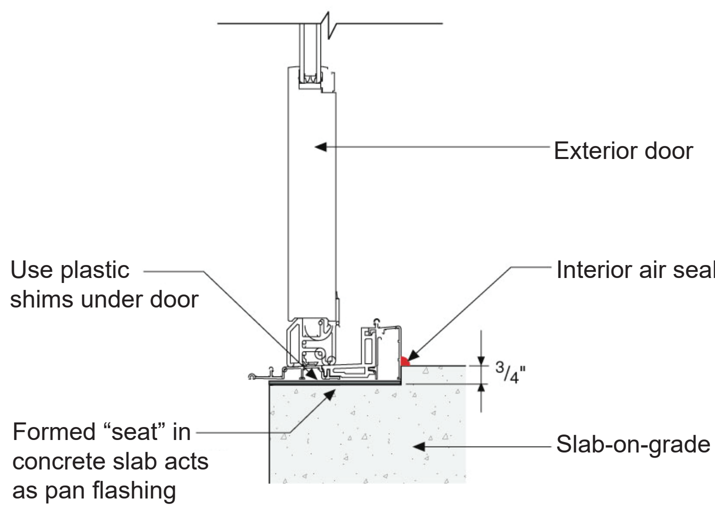
Figure 3.23: Pan Flashing Approaches – Note the back dams and end dams.



A strip of wood nailed at the back of the rough opening sill forms a dam to prevent water from draining into the interior



A piece of wood bevel siding nailed over the sill to create positive drainage towards the exterior is even better. Note that the rough opening needs to be enlarged to account for this and tapered shims in the opposite direction of the slope may be required



Forming a depression in a cast-in-place floor slab creates a built-in drainage pan for mulled entry doors and sliders, which are prone to leak at joints

Figure 3.24: Drained Window and Door Openings - The bottoms of the openings at their exterior are unsealed to permit drainage to the exterior.

Groundwater

The fundamental principles of groundwater control are to keep rainwater away from the foundation wall perimeter and to drain groundwater with subgrade perimeter drains before it gets to the foundation wall. This applies to slabs, crawlspaces, and basements.

Groundwater control can be broken into the following three strategies:

- Use surface drainage to reduce the rate at which surface water and rainwater enter the ground adjacent to a building enclosure, thereby becoming ground water.
- Use subsurface drainage to control hydrostatic pressure to prevent groundwater from entering the building enclosure below grade.
- Provide a membrane or barrier to resist hydrostatic pressure ("waterproofing").

The first two strategies have historically been proven to be more effective than waterproofing. Most foundation assemblies (as are most wall assemblies) are a combination of "screens" and "barriers". In foundations the screen typically involves a free-draining backfill or a drainage membrane or drainage board connected to a perimeter subgrade drain.

Reducing the rate at which surface water and rainwater enter the ground adjacent to a building enclosure is a rather straightforward exercise. Site grading is used to direct surface water away from building foundations and walls (**Figure 3.25**). Again, note that this applies to slabs, crawlspaces, and basements (**Figure 3.26**, **Figure 3.27** and **Figure 3.28**).

Rainwater and surface water absorption by backfill material can cause groundwater to concentrate at building perimeters. Locating heavily irrigated flower beds and gardens immediately adjacent to building perimeters has similar effects. The upper portions of foundation excavations should be backfilled with impermeable materials such as a clay cap (**Figure 3.28**).

Controlling Hydrostatic Pressure Below Grade

Hydrostatic pressure can be controlled by the placement of free-draining material immediately adjacent to foundation assemblies connected to a perimeter subgrade drain (**Figure 3.28**). This free-draining material, typically sand or gravel or a drainage membrane or a drainage board, allows for the free flow of water downwards towards a subgrade drainage system under the influence of gravity. This prevents the development of hydrostatic pressure. In the absence of hydrostatic pressure water running down the exterior of the basement wall will not be forced in through cracks.

Some provision for removing the water at the base of the free-draining material must be made, hence the subgrade drainage system. The subgrade drainage system, in essence, lowers the groundwater table immediately adjacent to the foundation.

The subgrade drainage system is usually a perforated drainage pipe located at the perimeter of the foundation below the basement floor level (if a basement space is present) to the exterior of the wall. The perforated drainage pipe is encased in crushed stone (free from fines) and surrounded by a filter medium. As

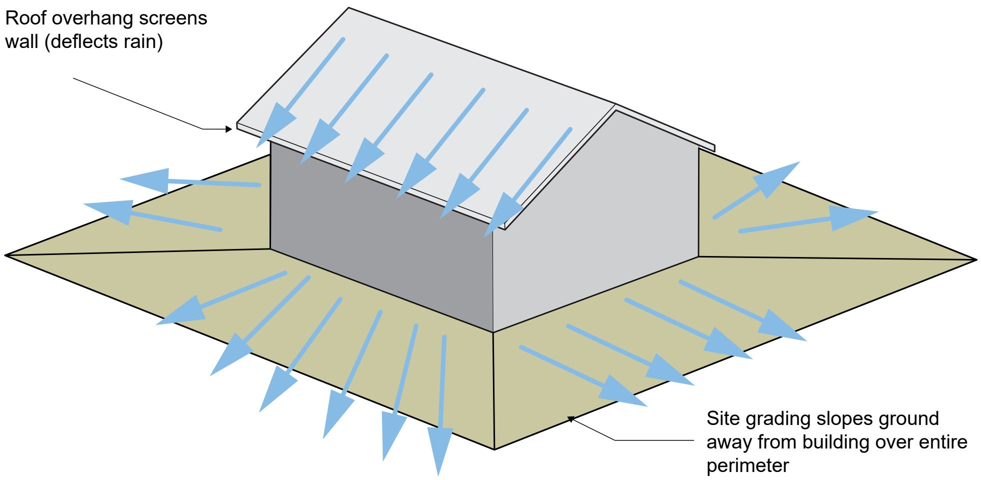


Figure 3.25: Site Grading - Site grading is used to direct surface water away from building foundations.

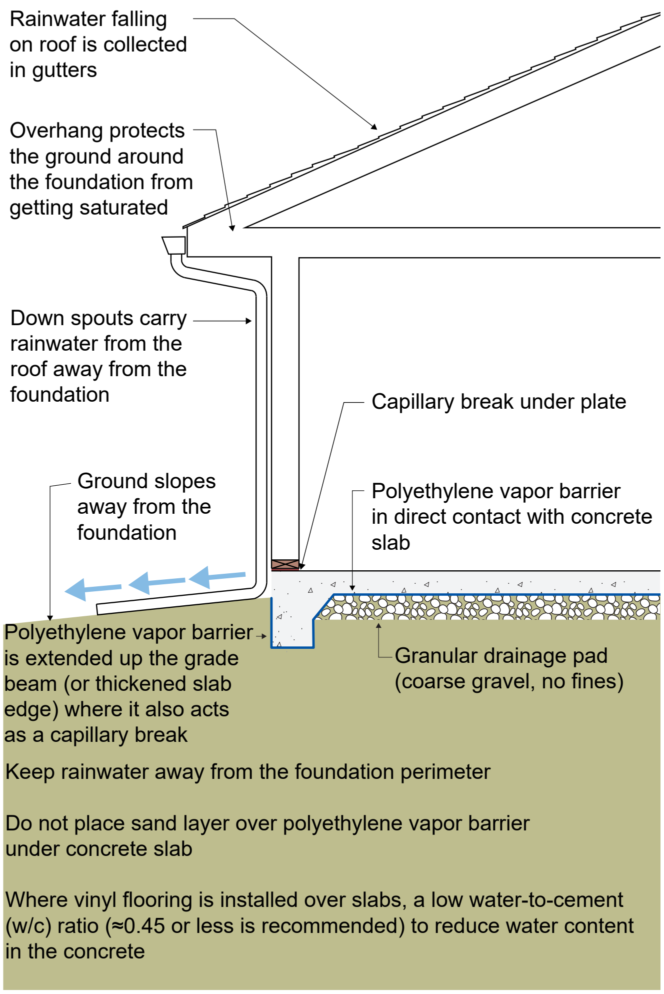


Figure 3.26: Slab-on-Grade – Water management for slab-on-grade construction.

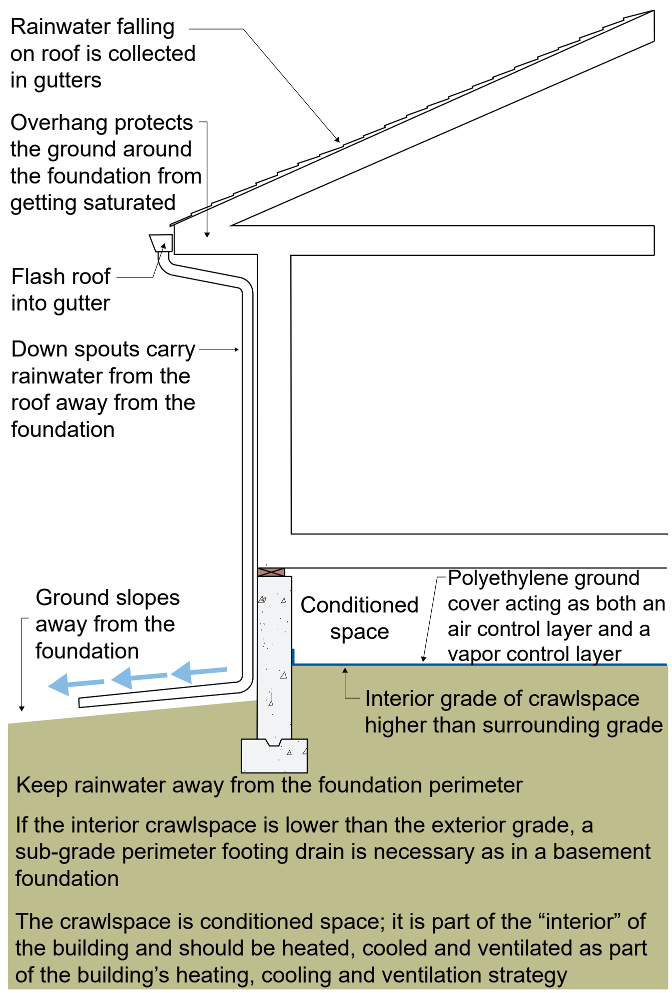


Figure 3.27: Crawl Space – Water management for crawl space construction.

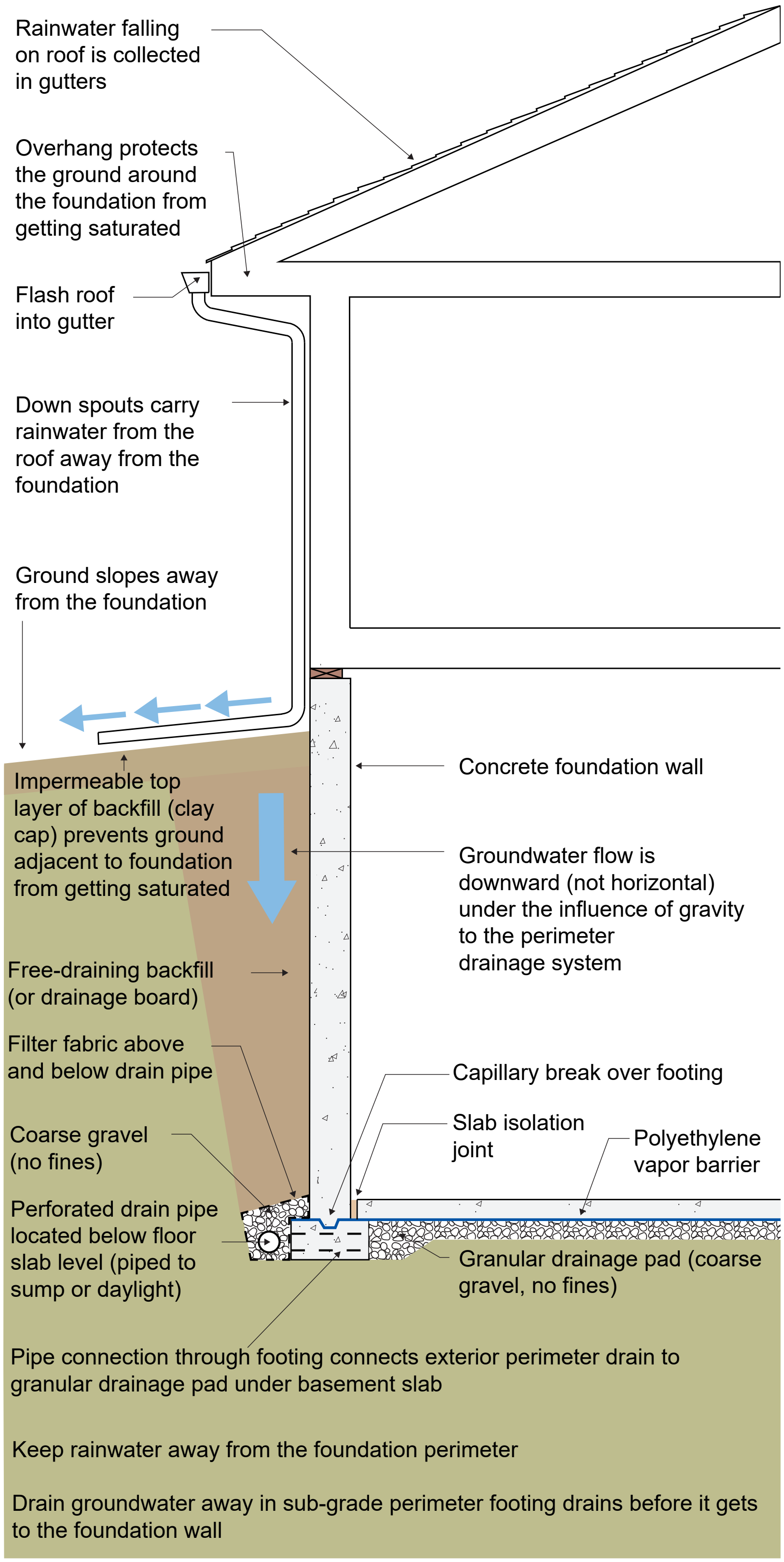


Figure 3.28: Basements – Water management for basement construction.

groundwater rises, it rises into the drainage pipe and is carried away. Drainpipes should be sloped to facilitate drainage and should be connected to a sump, or to daylight, or to a storm sewer. It should be noted that some storm sewer systems tend to back up during heavy rains and can pipe water to foundation assemblies rather than away from them. As a result, check valves at storm sewer connections should be installed only allowing groundwater flow away from foundations.

Granular drainage pads should be installed under basement floor slabs and should be connected through footings to the exterior perimeter subgrade drainage system. This provides redundancy and some capacity for groundwater storage during excessive rainfall events.

Free-draining materials have proven so effective that foundation assemblies remain dry even if numerous holes, openings, or cracks exist. Many modifications and innovations to classic free-draining sand or gravel layers have been developed. Many involve the use of drainage mats, drainage membranes, and drainage insulation layers rather than free-draining backfill material.

Free-draining materials rely on the provision of air spaces or openings of sufficient size allowing water to drain through them.

Free-draining materials can replace free-draining backfill. However, these free-draining materials must be connected to perimeter subgrade drainage systems (**Figure 3.29**) and be capped with a flashing to prevent surface water from entering via the top edges.

Drainage layers located on the interior instead of the exterior are generally not as effective. Groundwater should ideally be intercepted outboard of foundation structures. However, interior drainage may provide the only option available for groundwater control for certain types of renovation and rehabilitation work (**Figure 3.30**).

Control of groundwater entry by the elimination of all below-grade openings involves the installation of waterproofing barriers/membranes. These membranes are typically installed on the exterior of the perimeter foundation walls and under basement floor slabs. The assemblies must be able to resist the hydrostatic pressures that are likely to develop and must provide continuity between the exterior foundation wall waterproofing and the under basement floor slab waterproofing. These waterproofing systems are the exception in most residential construction, and are used where the design places the foundation at or below the water table. The foundation must be designed to also withstand the uplift/buoyancy forces created by the groundwater.

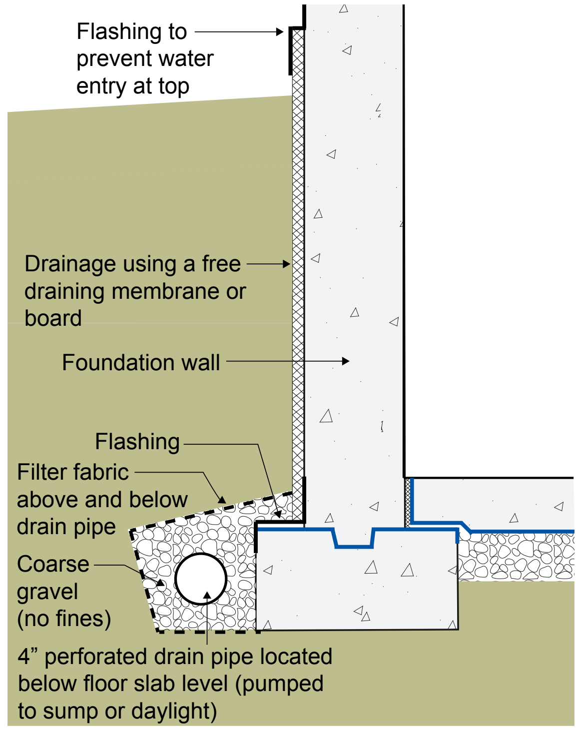


Figure 3.29: Free Draining Materials – Note the cap flashing and connection to perimeter drainage systems.

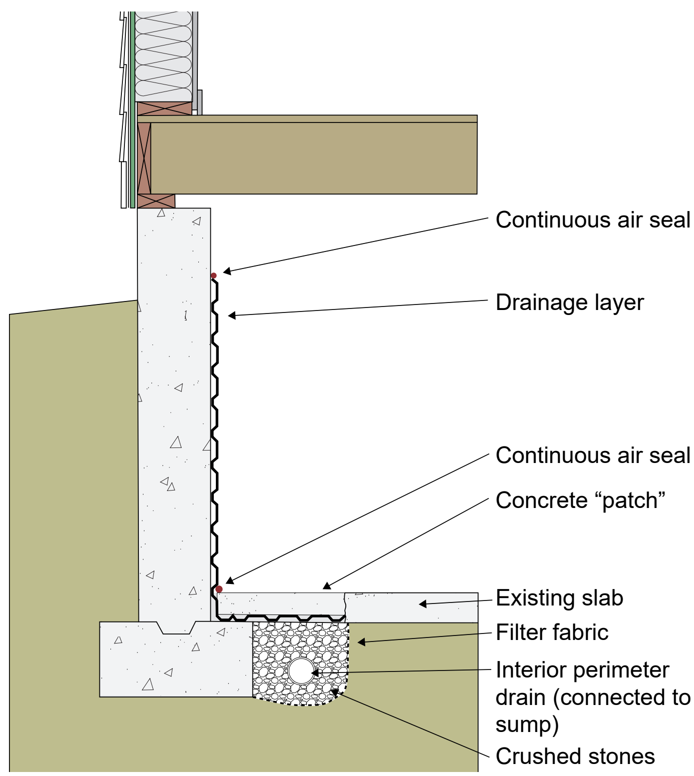


Figure 3.30: Interior Drainage – May be only option for remediation and rehabilitation work.

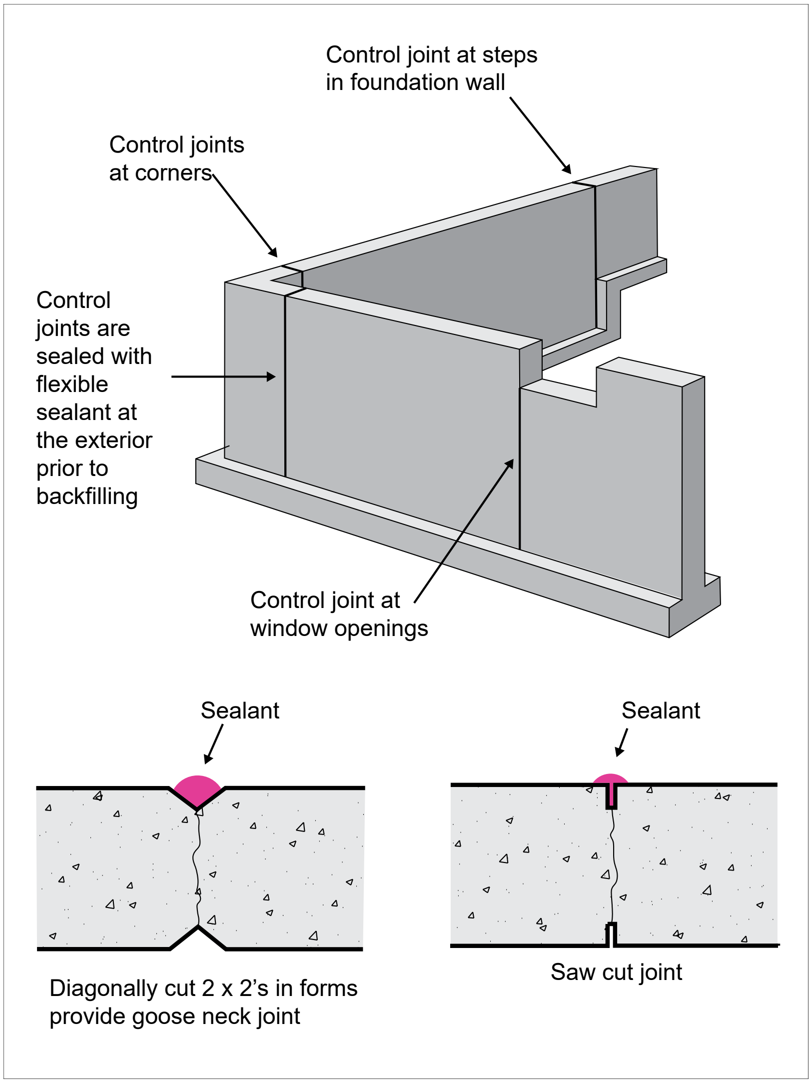


Figure 3.31: Foundation Control Joints - These cracks are repaired or sealed prior to backfilling.

Control Joints

An alternative to covering the entire wall with a waterproofing membrane is to use control joints in order to make the concrete foundation wall watertight. In most cast concrete foundation wall assemblies, shrinkage cracks appear after backfilling has occurred and subsequently lead to ground water entry. These cracks are usually repaired during the callback period. This is usually expensive and an aggravation to both the contractor and the occupant. It is very difficult to prevent concrete from cracking; however, it is quite straightforward to help the concrete crack predictably in straight lines at predetermined locations using control joints. Control joints involve weakening the wall at preselected locations by providing crack initiators. These cracks can be repaired or sealed prior to backfilling. Control joints can be provided by cutting the wall immediately after the forms are striped or cast into the wall initially (**Figure 3.31**).

Liquid Flow Due to Capillary Suction

The second moisture transport mechanism a designer or builder must deal with is capillary suction. Capillary suction acts primarily to move moisture into porous materials. For example, a paper towel, with one end in contact with liquid water, draws water into itself against the force of gravity as a result of capillary suction. Capillarity is a function of - among other things - pore size and available moisture. If pore size in a material is large, such as clear gravel and coarse sand, then capillarity will not exist. If pore size in a material is small, such as in concrete, silty clay, and paper, then capillarity is possible. Capillarity will not exist in materials that do not have pores such as glass, steel, and most plastics. However, if two materials that do not have any capillary pores are placed closely enough together, such as two panes of glass, the space between them can itself become a capillary pore. Another example of this phenomenon is the migration of solder by capillarity into the tight space between a plumbing pipe inserted in a plumbing fixture.
Capillarity can be significant in the portions

of building enclosures where they are below grade or where they come in contact with the ground. An example of this is a concrete footing cast on damp soil. Concrete is porous and susceptible to capillarity. Capillary water is drawn up into the footing and then into the perimeter concrete foundation wall. Once in the foundation wall the capillary water can evaporate into the interior of the basement at the bottom of the foundation wall. This often manifests itself as a ring of dampness visible around the perimeter of the basement foundation at the base of the wall (**Figure 3.32**). This mechanism is also referred to as rising damp.

Capillary suction can also be a factor in building enclosures above grade where a film of water is deposited on the exterior of the building enclosure as a result of rainfall or dew formation. This water film may be drawn into the building enclosure under the action of capillary suction. This is illustrated by the water trapped between the laps in horizontal wood siding. The water is held between the laps in spite of the influence of gravity (**Figure 3.33**). As such, joints between materials exposed to water, above and below grade, should be designed with capillarity in mind.

A designer or builder can control capillarity by controlling the availability of capillary moisture and the pore size of the building material or building assembly selected. Materials can be selected that do not support capillarity due to their large pore size such as gravel, or materials may be selected that do not have any pores, such as glass. Alternatively, capillary pores in susceptible materials can be filled to break the capillary draw such as is done where concrete basement foundation walls are dampproofed. Capillarity can be controlled by sealing connections between

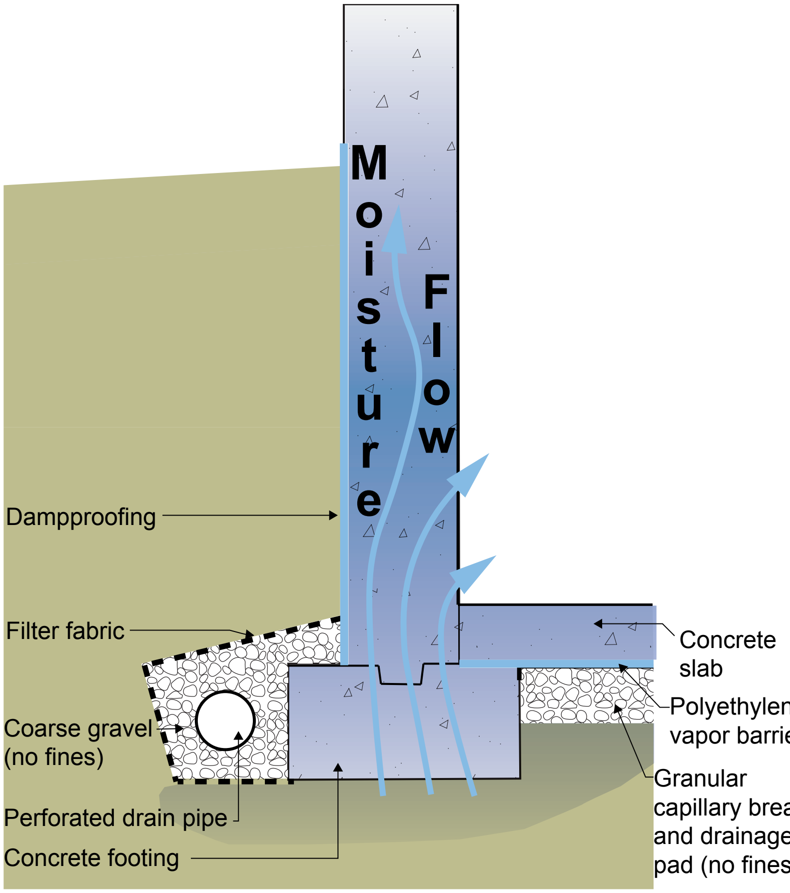


Figure 3:32: Capillarity – Footings typically do not have capillary breaks.

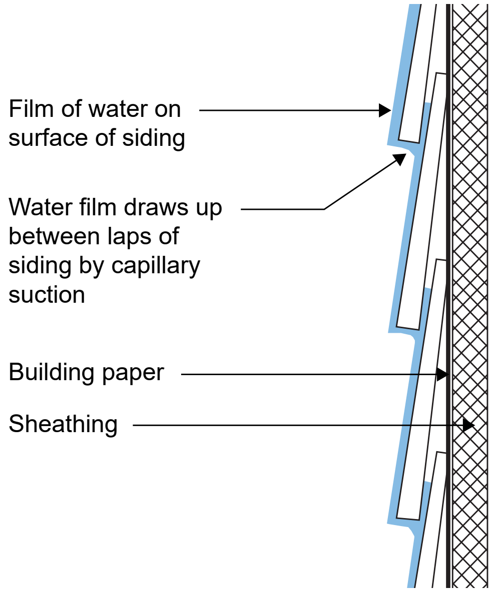


Figure 3:33: Capillarity Above Grade - Water trapped between the laps in horizontal wood siding.

materials (caulking joints) or by making the connections wide enough not to support capillarity. Furthermore, a receptor for capillary moisture can be provided such as an air space or a porous material. Capillarity can, therefore, be controlled as follows:

- Controlling the availability of capillary moisture
- Sealing capillary pores
- Making capillary pores larger
- Providing a receptor for capillary moisture

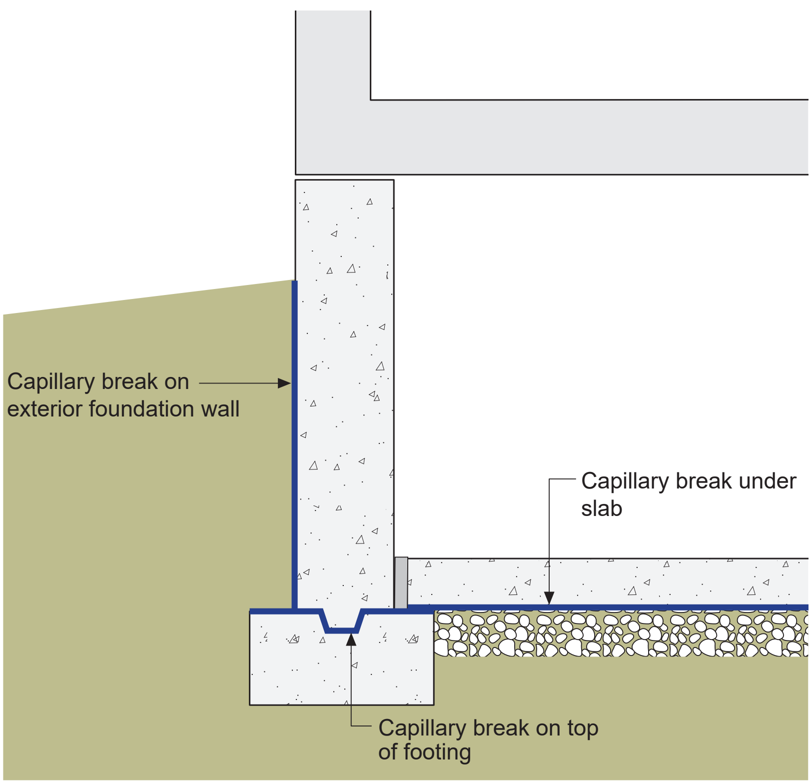


Figure 3.34: Capillary Breaks Below Grade - Capillary suction in concrete foundation walls is traditionally controlled by dampproofing the exterior surface of the wall where it is in contact with the surrounding damp soil.

Capillary Suction with Groundwater as the Moisture Source

Capillary suction in concrete foundation walls is traditionally controlled by dampproofing the exterior surface of the wall where it is in contact with the surrounding damp soil (**Figure 3.34**). This dampproofing film is typically not meant to span cracks or large openings, and as such it is not a waterproofing membrane. Whereas waterproofing membranes provide an excellent capillary break, dampproofing films are usually poor waterproofing membranes.

Capillary suction under concrete floor slabs is traditionally controlled by placing the floor slab over large-pore gravel (3/4 inch crushed stone with fines removed). Since the pore size in the granular pad is too large to support capillary suction, the granular pad acts as a capillary break (**Figure 3.34**). A sheet polyethylene layer installed directly under the concrete floor slab in direct contact with the concrete floor slab can also act as a capillary break.

Capillary suction in masonry block foundation walls is traditionally controlled by coating the exterior surface of the masonry blocks with thin layer of mortar (parge coat or rendering) and then applying a dampproof coating over it. Applying a dampproof coating directly on the masonry blocks has not always proven successful as the pore size of the mortar joints and the pore opening in the masonry block surfaces themselves can be too large for a fluid-applied dampproof coating to span.

Capillary breaks can also be located over the top of concrete footings prior to the construction of perimeter foundation walls (**Figure 3.34**) as well as between the top of the foundation walls and framing to prevent construction moisture in the foundation wall from migrating into the floor framing.

Capillary control also applies to slab-on-grade construction and crawlspaces. Monolithic slabs need polyethylene ground covers that extend under the perimeter grade beam and upwards to grade. Additionally, the exposed portion of slabs should be painted with latex paint to reduce water absorption and a capillary break should be installed under perimeter wall framing.

Capillary Suction with Rainwater as the Moisture Source

Capillary suction in porous cladding materials can be controlled by sealing or filling the pores. One of the most common examples of this is the application of a paint film on wood-based siding to reduce the absorption of deposited rainwater. The paint film seals the capillary pores on the surface of the wood. All six surfaces of the siding (the front, the back, the edges and the end cuts) should be sealed. Additionally, the siding should be installed over an air space behind the siding to act as a receptor for capillary moisture (**Figure 3.35**).

An additional example of an air space serving as a capillary break as well as serving as a receptor for capillary moisture is where a brick veneer is constructed over an air space (**Figure 3.36**). Significant amounts of deposited moisture can be absorbed by the bricks (brick is a "reservoir cladding"). When solar radiation warms the brick veneer, the moisture in the bricks is driven inward out of the bricks into the air space.

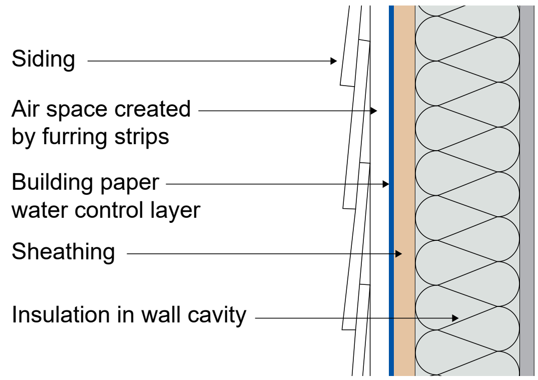


Figure 3.35: Capillary Control Above Grade - The paint film seals the capillary pores on the surface of the wood. Additionally, the siding should be installed over an air space behind the siding to act as a receptor for capillary moisture.

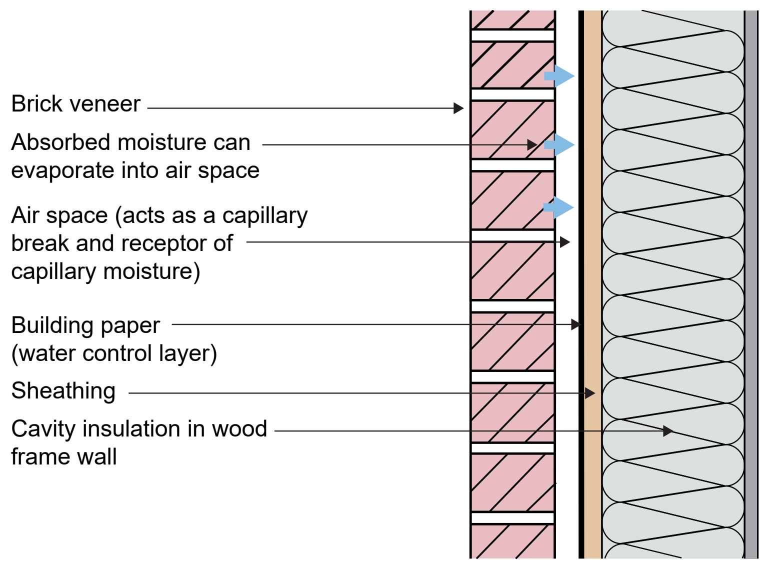


Figure 3.36: Brick Veneer - Air space serving as a capillary break as well as serving as a receptor for capillary moisture.

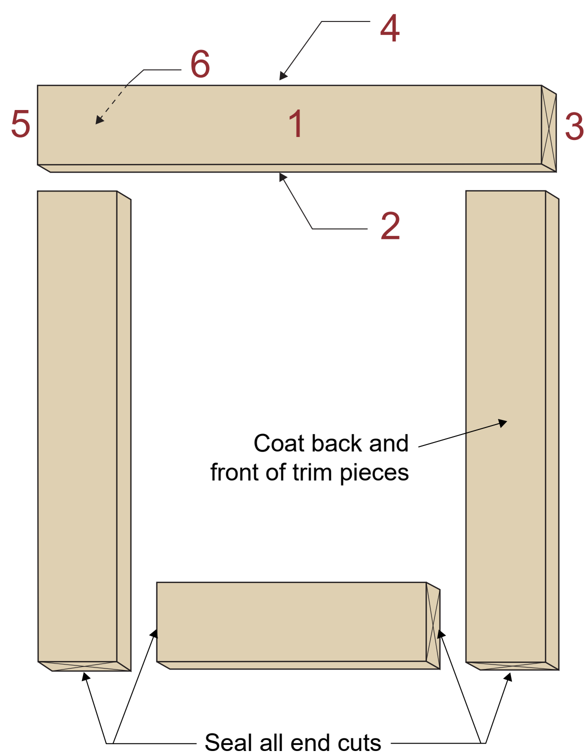


Figure 3.37: Wood Trim - All six surfaces of the trim (the front, the back, the edges and the end cuts) should be sealed

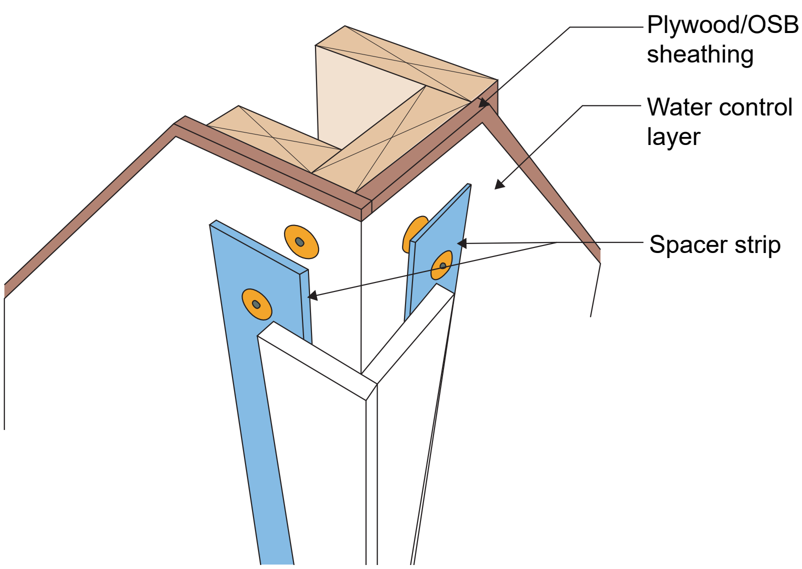


Figure 3.38: Wood Trim Over Air Space – Air space serves as a receptor for capillary moisture.

Wood or wood trim pieces should be sealed or coated or painted on all six surfaces to control capillary absorption of water (**Figure 3.37**). Additionally, these trim pieces should be installed over an air space (**Figure 3.38**).

Where wood shingles and shakes are installed over furring strips, or skip-sheathing on roof assemblies (**Figure 3.39**), the same phenomenon occurs. The wood shakes and shingles absorb deposited rainwater due to capillary suction. The wood shakes and shingles dry to both directions. The function of the building paper/roofing paper is to facilitate drainage and air pressure moderation across the roof assembly. The shakes/shingles are leaky, whereas the building/roofing paper is tight. Where sheet goods are used for roof sheathing (such as plywood or oriented strand board/OSB) with wood shakes and shingles an air gap must be added between the shakes and shingles to act as a receptor for the capillary moisture. The air gap is typically provided using a breathable drainage mesh (**Figure 3.40**).

Vapor Flow Due to Air Transport

The third moisture transport mechanism a designer or builder must deal with is vapor flow due to air transport. This mechanism can move moisture into building assemblies both from within the conditioned space and from the exterior.

As discussed previously, depending on temperature, air can contain varying amounts of moisture in the vapor state. When air moves as a result of an air pressure difference it will carry the moisture held within it. If air containing moisture comes in contact with a surface below the air's dew point temperature, the air may deposit some of its moisture on that surface in the form of condensation. Recall that for condensation to occur the surface needs to have sufficient thermal heat capacity to accept the energy released in the phase change from a vapor to a liquid. This is the condensing surface. Condensing surfaces in practice are typically window glazing, sheathing materials or framing materials. Not all insulations are condensing surfaces. Fiberglass and cellulose insulation surfaces are typically not condensing surfaces, whereas foam sheathings are.

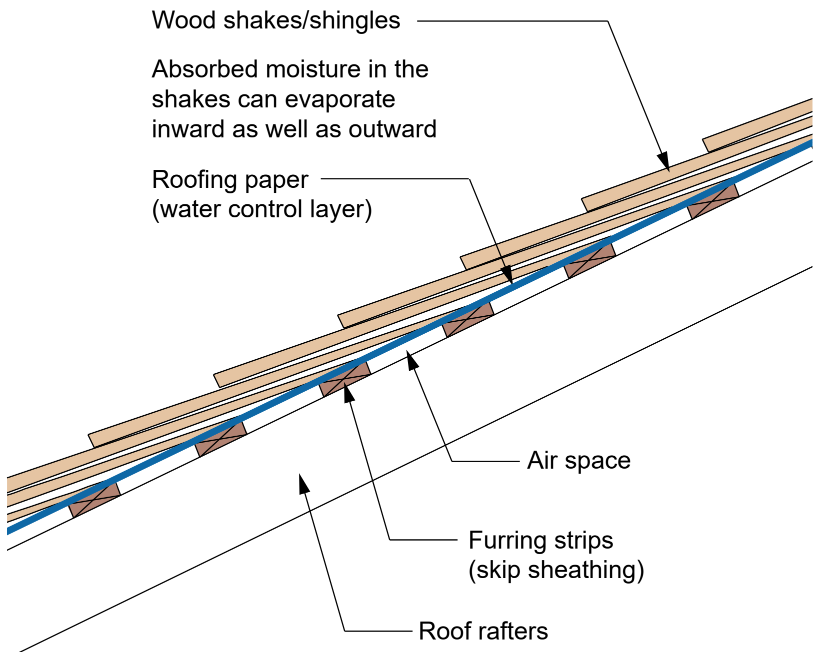


Figure 3.39: Wood Shingles and Shakes - The wood shakes and shingles absorb deposited rainwater due to capillary suction. The wood shakes and shingles dry to both directions.

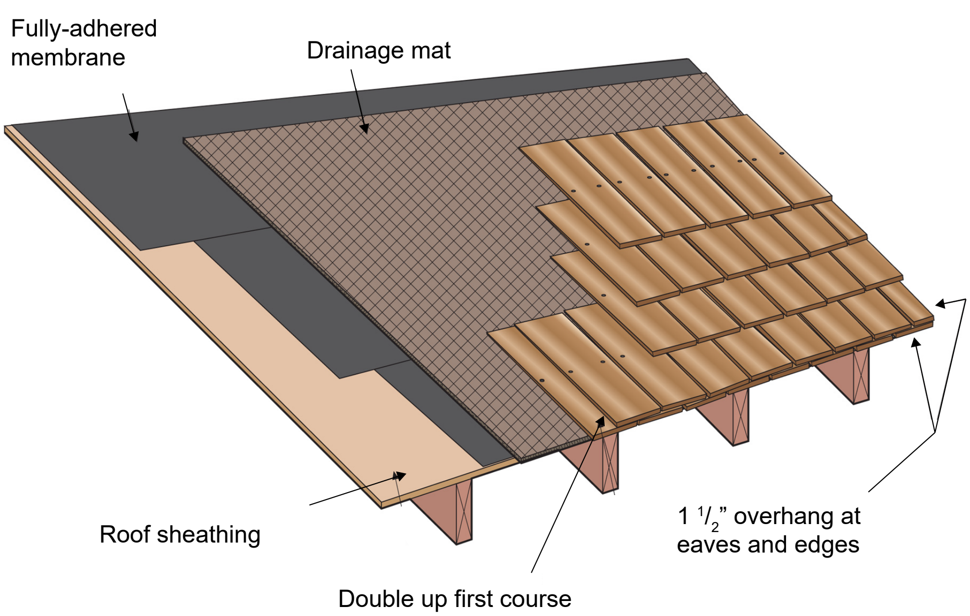


Figure 3.40: Sheet Goods and Wood Shingles and Shakes - Where sheet goods are used for roof sheathing such as plywood or oriented strand board (OSB) in conjunction with wood shakes and shingles an air gap must be added between the shakes and shingles to act as a receptor for the capillary moisture. The air gap is typically provided using a breathable drainage mesh.

For moisture to be moved into a building assembly as a result of air transport or air movement, three conditions must be satisfied:

- Air containing moisture must be present.
- An opening or hole or pathway must exist in the assembly.
- An air pressure difference acting across the opening or hole or pathway must exist.

Although moisture may enter a building assembly if these three conditions are met, moisture may not necessarily be deposited within the assemblies. Air flow speeds must be slow enough for the air to cool to the dew point temperature before it exits the air leakage path. Fast-flowing air can warm the surfaces of the flow path above the dew point temperature of the outflowing or inflowing air and condensation may not occur.

Controlling moisture movement due to air transport or air flow involves three approaches:

- Controlling the amount of moisture in the air.
- Controlling the number, location, size of openings, holes and pathways.
- Controlling the air pressure across the openings, holes and pathways.

Controlling the Amount of Moisture in Air

It is obvious that only interior airborne moisture levels can be controlled, since the local climate controls exterior airborne moisture levels. However, the local climate - and hence exterior moisture levels - typically influence the approach taken to control interior moisture levels.

Interior moisture levels can be controlled in three ways:

- Source control
- Dilution
- Dehumidification

Source Control

One of the most effective approaches to controlling interior airborne moisture levels is the control of moisture sources. If moisture is not generated within a space, or moisture is removed at the point of generation, or moisture is prevented from migrating into a space, it does not have to be removed or controlled after the fact. Source control is effective regardless of climate zone or season and is typically the most cost-effective and energy-efficient approach.

The largest sources of moisture affecting interior airborne moisture levels are typically climate-specific. In hot-humid and mixed-humid climates ventilation air and air change (exterior moisture sources) are the dominant moisture sources. In cold climates occupancy and occupant activities are the dominant moisture sources (interior moisture sources).

This has not always been the case historically, particularly in cold climates. In cold climates historically poor foundation construction practices resulted in the migration of moisture from the surrounding soil into foundations and subsequently into conditioned spaces. Historically, the trend of constructing dry basements, slabs and crawlspaces proved to be one of the most effective strategies in controlling interior airborne moisture. Leaky basements and exposed ground cover in crawlspaces were once the dominant moisture sources. However, modern construction practices have tended to address these sources.

Other historical sources of interior moisture in cold climates such as unvented clothes dryers, indoor firewood storage, and combustion products from unvented space heaters have also more or less become historic artifacts.

In hot-humid and mixed-humid climates, because the major moisture source is the exterior air, the greater the air change the greater the rate of inward moisture migration. In hot-humid and mixed-humid climates, source control of exterior moisture-laden air involves reducing ventilation rates (in a manner that does not compromise indoor air quality) and reducing infiltration. This is done by reducing leakage openings in building assemblies, sealing ductwork associated with forced air cooling systems that may be located outside of conditioned spaces, locating ductwork within conditioned spaces, controlling air pressure differences, and not over-ventilating conditioned spaces with exterior air.

In all climates, rooms where significant moisture generation can occur by occupant behavior, such as bathrooms and kitchens, should be vented directly to the exterior. These mechanical exhaust systems such as bathroom fans and kitchen range hoods, should be operated on an intermittent basis according to moisture load.

Some moisture sources that are not practical to control are respiration from occupants and the seasonal desorption of materials. Occupants generate moisture by merely breathing. Source control is therefore not possible for occupants.

Seasonal absorption/desorption of materials involves moisture pick-up by furnishings, carpets, and building materials within conditioned spaces during summer months in heating climates and the subsequent moisture release from these same materials during the heating season. Source control, in this case, is also not possible or practical.

A major moisture source in all climates is construction moisture. Newly constructed buildings give off significant quantities of moisture during their first year as a result of construction moisture stored in construction materials. Hundreds of gallons of water can be contained in fresh concrete, lumber and wet-applied insulations. To reduce this potential, the rate of evaporation of the moisture of construction (towards conditioned spaces from concrete and masonry) can be reduced by the use of coatings and sealants and certain types of insulation. Additionally, building assemblies can be designed and constructed to dry to the exterior.

Dilution

Dilution of interior airborne moisture involves air change, or the exchange of interior moisture-laden air with exterior dry air. The greater the air change, the greater the flushing action this air change has on interior moisture levels. Of course, this only holds if the exterior air is drier than the interior air.

In cooling climates or during cooling periods this is often not the case, and under such circumstances the greater the air change, the greater the inward migration of moisture. As such, dilution and air change are strategies typically utilized in heating climates during heating seasons. Dilution involving air change is most effective when implemented in a controlled manner through the use of controlled mechanical ventilation.

Historically, buildings with combustion heating systems linked to active chimneys had higher air change than buildings with sealed combustion systems or electric heating or heat pumps – buildings without active chimneys. Active chimneys were in essence exhaust fans or chimney fans, due the quantities of air extracted from a building enclosure for draft control and combustion. The high air change rates during heating periods resulted in low interior moisture levels – in many cases moisture levels were low enough to cause discomfort, often resulting in humidification during heating periods. This is no longer the case. Today, the typical use of sealed combustion systems, heat pumps, and electric heating has reduced air change and dilution leading to an increase in interior moisture.

Dehumidification

Warm air is capable of containing more moisture than cool air. Dehumidification usually involves the cooling of warm moisture-laden air to reduce its ability to hold moisture, thereby forcing the air to give up moisture in the form of condensation. As such dehumidification is most typically coupled with air conditioning systems and is common in most climates during cooling periods. In essence, air conditioners are dehumidifiers. In some cases dehumidification involves the use of desiccants, or materials that are initially dry, that draw moisture out of air and subsequently release this moisture under controlled conditions, usually when the desiccants are deliberately heated.

Historically, in cooling climates and in most climates during cooling periods, air conditioning loads were sufficiently large to result air conditioning system run times sufficiently long enough to provide dehumidification and control interior moisture levels. Due to significant energy efficiency improvements over the past several decades, air conditioning loads have been reduced to such an extent that typical air conditioning systems no longer run long enough to control interior moisture levels. Supplemental dehumidification, typically using dehumidifiers working in conjunction with air conditioning systems, is necessary in hot-humid and mixed-humid climates.

Dehumidification is most effective when coupled with source control. In hot-humid and mixed-humid climates the major source of airborne moisture is the infiltration of exterior moisture-laden air and the exterior air brought into building envelopes/ building enclosures by mechanical ventilation. Thus, source control in hot-humid and mixed-humid climates involves reducing air change by limiting ventilation, controlling leakage openings, and limiting air pressure differentials arising from forced-air duct systems.

Reducing Dilution and Indoor Air Quality

In today's buildings high levels of dilution ("air change") tend to lead to excessive dryness in cold climates during heating periods and excessively high levels of moisture in mixed-humid and hot-humid climates. In cold climates interior moisture sources have been dramatically reduced due to the construction of dry foundations. In mixed-humid and hot-humid climates the dehumidification provided by air conditioning systems is no longer capable of reducing indoor moisture levels due to the energy efficiency gains. The energy efficiency gains resulted in low thermal loads and reduced run times of air conditioning systems, thereby reducing incidental dehumidification.

The high levels of air change in today's modern buildings are not due to the leakage of air through poorly constructed building envelopes/ building enclosures but due to controlled mechanical ventilation. Building codes do not allow the construction of leaky building envelopes/ building enclosures. Either the controlled mechanical ventilation rates need to be reduced or humidification needs to be provided in cold climates during heating periods and supplemental dehumidification needs to be provided in mixed-humid and hot-humid climates.

The concern with reducing controlled mechanical ventilation rates is a potential increase in contaminants in indoor air. Dilution of indoor contaminants with exterior outdoor air is one of the most common approaches to controlling contaminants in indoor air. However, it has become clear that dilution of indoor contaminants with outdoor air is not as effective as source control of the contaminants in the first place. If contaminants are not generated in the indoor conditioned space or contaminants are not released from poorly selected building materials or indoor furnishings then dilution of these contaminants is not necessary. And in an unfortunate irony, the dilution air brought in from the exterior in mixed-humid and hot-humid climates is in fact a major contaminant. In a further irony, in cold climates the dilution air can result in serious discomfort due to excessive dryness and damage to interior materials and furnishings that are hygroscopic (wood floor and trim shrinkage and splitting). Dilution is not the best solution to indoor pollution. Source control is. If contaminants are not internally generated or released, then high levels of dilution with outdoor air are not necessary.

The effectiveness of ventilation rates to control indoor contaminants is also dependent on mixing and distribution of the outdoor supplied ventilation air. Balanced ventilation systems (equal rates of outdoor supply air to indoor exhaust air) that provide mixing and distribution are more effective at diluting and controlling indoor air contaminants than exhaust-only or supply-only systems without mixing and distribution. Hence, reducing ventilation rates without causing a rise in indoor contaminants is possible by using more effective ventilation systems such as balanced systems that provide mixing and distribution. The reduced rates lower indoor moisture levels in mixed-humid and hot-humid climates and reduce the need for humidification in cold climates. As an additional benefit, they reduce energy consumption and allow for the use of heat recovery and energy recovery mechanical ventilation systems.

It is likely that a combination of balanced ventilation, mixing and distribution of exterior ventilation air at a rate lower than is currently typical coupled with supplemental dehumidification in hot-humid and mixed-humid climates is necessary. In cold climates, the same strategy, but without the supplemental dehumidification is likely necessary. In all climates source control of indoor contaminant generation or release from building materials and furnishings will also be necessary. The alternatives are high exterior air ventilation rates coupled with significant dehumidification and humidification based on climate zone and time of year.

Controlling the Number, Location, Size of Openings, Holes and Pathways

If openings, holes and pathways in building assemblies are controlled, then air movement through assemblies can also be controlled. The less air movement through the assembly, the less moisture transported. When building assemblies are linked together, they form the conditioned space, or building enclosure. The components of the building enclosure that provide air leakage control or tightness are referred to as the air control layer.

Resistance to air flow can be provided at any location in a building assembly, at the exterior of the assembly, the interior of the assembly, or at any location between. Historically, air control layers started off being located on the interior and then due to ease of constructibility and effectiveness migrated to the exterior. In many assemblies both exterior and interior air control layers can be provided.

Air control layers are intended to resist the air pressure differences that act on them. Rigid materials such as gypsum board, exterior sheathing materials like plywood or OSB, and supported flexible barriers are typically effective air control layers if joints and seams are sealed. Spray foam systems can also act as effective air control layers either externally applied over structural elements or internally applied within building cavities.

Air control layers keep outside air out of the building enclosure or inside air out of the building enclosure depending on climate or configuration. Sometimes, air control layers do both.

In cold climates, interior air control layers control the exfiltration of interior, often moisture-laden air. In contrast, exterior air control layers control the infiltration of exterior air and prevent wind-washing through cavity insulation systems.

Air control layers should be:

- Impermeable to air flow
- Continuous over the entire building enclosure or continuous over the enclosure of any given unit (in multifamily construction)
- Able to withstand the forces that may act on them during and after construction
- Durable over the expected lifetime of the building

The significant advantage of exterior air control layers is the ease of installation and the lack of detailing issues related to intersecting partition walls and service penetrations.

An additional advantage of exterior air control layers is the control of wind-washing that an exterior air seal provides with insulted cavity frame assemblies.

The significant disadvantage of exterior air control layers is their inability to control the entry of air-transported moisture into insulated cavities from the interior. As a result most exterior air control layers are insulated on their exterior side with rigid or semi-rigid insulations that are not sensitive to wind-washing.

An advantage of interior air control layers over exterior systems is that they control the entry of interior moisture-laden air into insulated assembly cavities during heating periods. The significant disadvantage of interior air control layers is their inability to control wind-washing through cavity insulation and their inability to address the entry of exterior hot-humid air into insulated cavities in hot-humid climates.

Installing both interior and exterior air control layers can address the weakness of each.

Air control layers can also be provided with properties which also class them as vapor control layers. Examples include self-adhered modified bituminous membranes and sheet polyethylene: they can be used as both an air control layer and a vapor control layer.

Keep in mind however, sheet polyethylene on the inside of building assemblies in cold, mixed-humid, marine, hot-dry and hot-humid climates is not generally a good idea (IECC Climate Zones 1, 2, 3, 4 and 5); drying of building assemblies in these climates occurs to the inside as well as to the outside. Interior polyethylene eliminates inward drying.

Drying to the interior is typically necessary for enclosures in air conditioned buildings. In other words, interior vapor control layers such as polyethylene and vinyl wall coverings should never be installed in air conditioned buildings – even ones located in cold climates.

In practice, air control layers are increasingly combined with the properties of water control layers – both layers are combined. One layer serves both functions.

Performance Requirements

Air control layers typically are assembled from materials incorporated in assemblies that are interconnected to create enclosures. Each of these three elements has measurable resistance to airflow.

The recommended minimum resistances or air permanences for the three components are listed as follows:

Material	0.02 l/(s·m^2)@75 Pa
Assembly	0.20 l/(s·m^2)@75 Pa
Enclosure	2.00 l/(s·m^2)@75 Pa

Materials and assemblies that meet these performance requirements are said to be air control layer materials and air control layer assemblies. Air control layer materials incorporated in air control layer assemblies that in turn are interconnected to create enclosures are called air control layer systems.

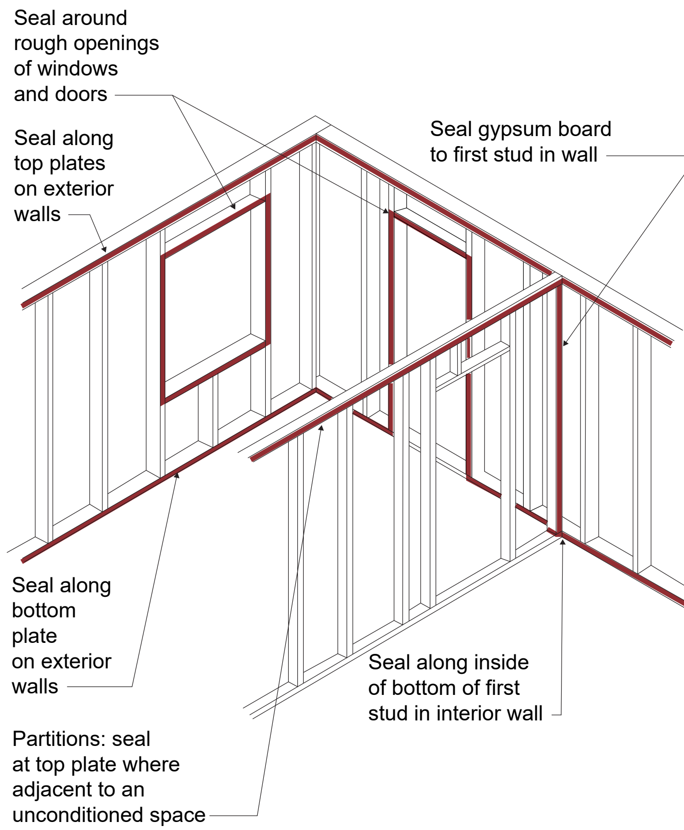


Figure 3.41: Interior Air Control Layer - Interior air control layers need to address air leakage concerns at multiple locations.

Interior Air Control Layer

Interior air control layers need to address air leakage concerns at the following locations (**Figure 3.41**):

- Exterior walls intersecting floor and roof assemblies
- Window openings
- Interior partition walls intersecting exterior walls
- Interior partition walls intersecting attic ceilings
- Electrical outlet boxes on exterior walls
- Bathtubs on exterior walls
- Dropped ceilings, coffer ceilings, and cabinet bulkheads
- Cantilevered floors
- Plumbing vent pipes

Resistance to air flow (airtightness) at the interior of building assemblies in cold climates is typically provided by installing a continuous, sealed polyethylene film between the interior cladding or gypsum board and the framing elements (**Figure 3.42**). Since the polyethylene film is also a vapor barrier this approach should not be used in climates where air conditioning systems are installed due to vapor flow from the exterior to the interior. Interior Class I vapor barriers, in general, should not be installed on the interior of wall assemblies in IECC Climate Zones 1, 2, 3, 4 and 5).

Resistance to air flow (airtightness) at the interior of building assemblies can also be provided by sealing the interior cladding (gypsum board) to framing elements (**Figure 3.43**). This approach is applicable in all climate zones.

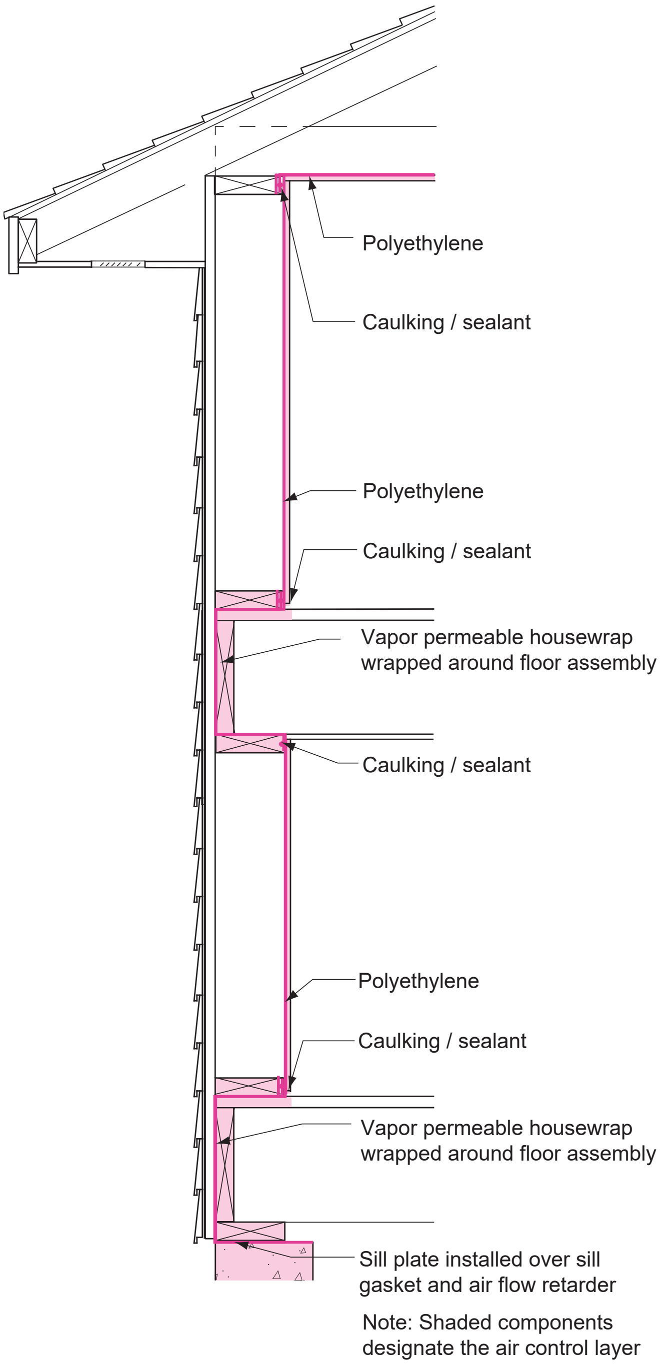


Figure 3.42: Interior Air Control Layer - Resistance to air flow (airtightness) at the interior of building assemblies in cold climates is typically provided by installing a continuous, sealed polyethylene film between the interior cladding or gypsum board and the framing elements.

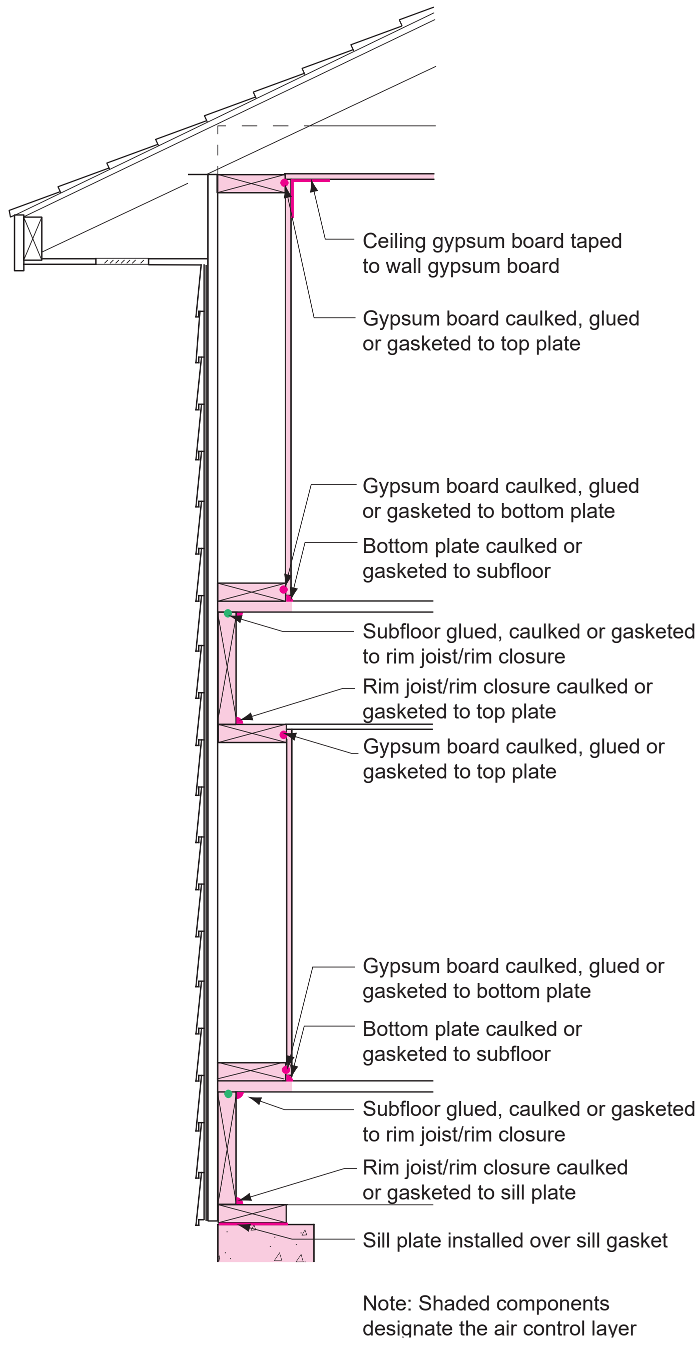


Figure 3.43: Interior Air Control Layer - Resistance to air flow (airtightness) at the interior of building assemblies can also be provided by sealing the interior cladding (gypsum board) to framing elements. This approach is applicable in all climate zones.

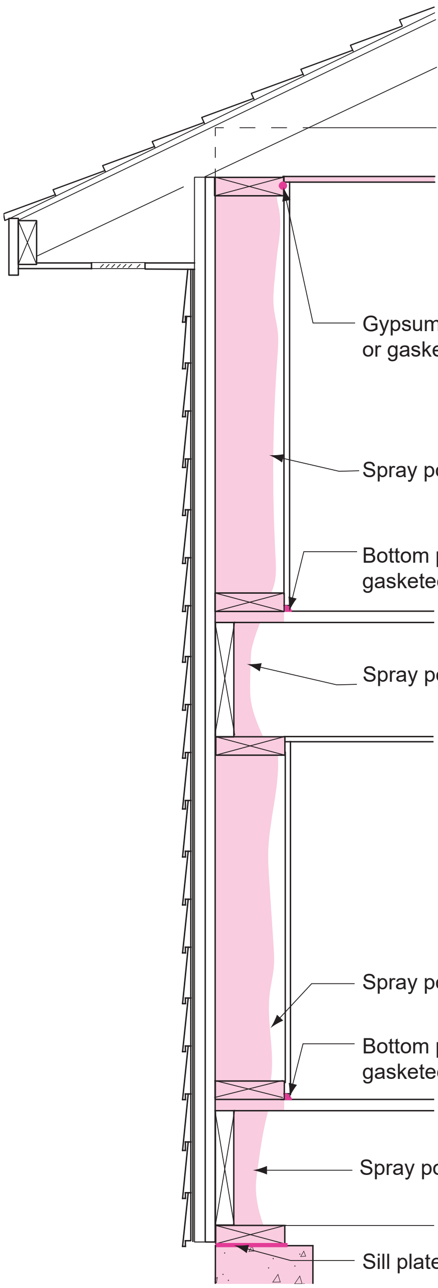


Figure 3.44: Interstitial Air Control Layer - Airtightness can also be provided within building framing elements. This is most commonly achieved using spray polyurethane foam (SPF).

Interstitial Air Control Layer

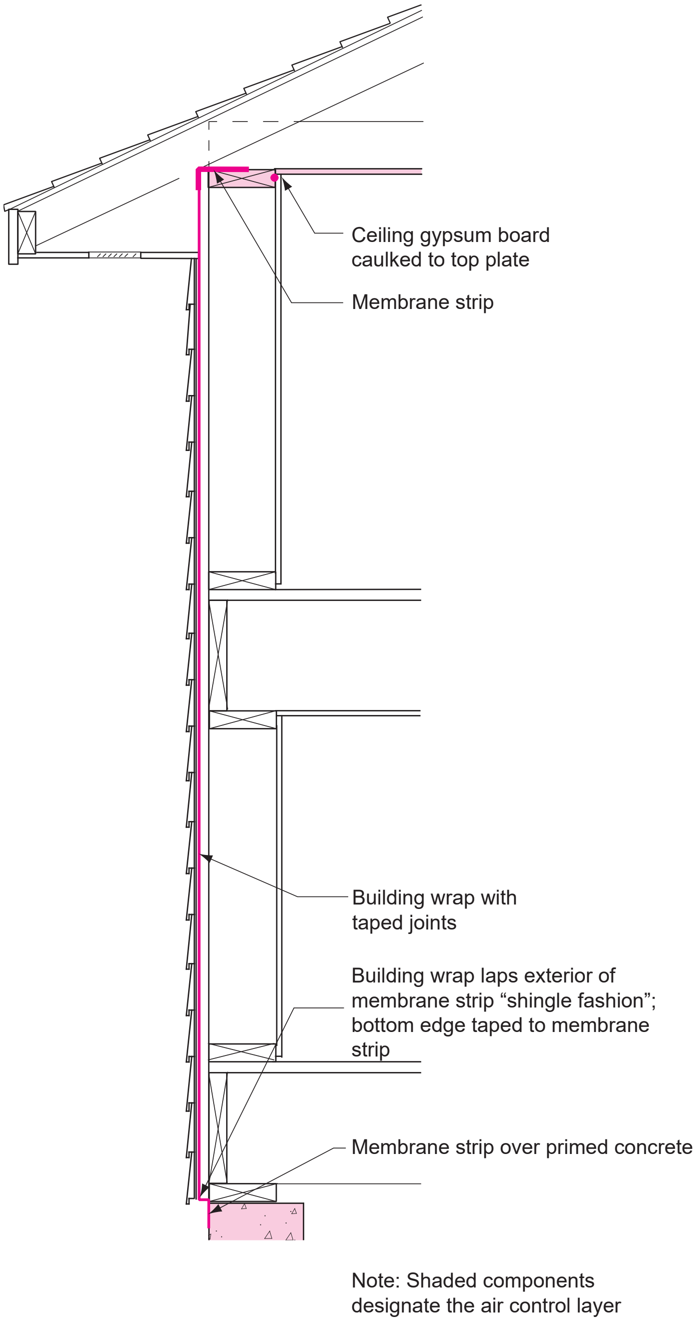
Airtightness can also be provided within building framing elements. This is most commonly achieved using spray polyurethane foam (SPF) (**Figure 3.44**). However, in frame construction, spray foam is not continuous at all wood-to-wood connections, such as built-up corners, window rough openings, and double top plates. These details must be addressed to ensure air control layer continuity.

Exterior Air Control Layer

Airtightness can be provided at the exterior surfaces of building assemblies. This can be accomplished by installing a continuous sealed building paper or building wrap over the exterior sheathing (**Figure 3.45**). It can also be accomplished by sealing the exterior sheathing to framing elements (**Figure 3.46**). Exterior continuous rigid insulation can also be sealed to the framing elements to act as an exterior air control layer (**Figure 3.47**).

Controlling the Air Pressure Across Openings, Holes and Pathways

The driving force for air movement is air pressure. Air moves from regions of higher air pressure to regions of lower air pressure. If moisture is present in air, it will be carried along the air leakage path way. Air transport of moisture due to a pressure difference along a flow path is the single greatest transport mechanism for moisture in the vapor form – significantly greater than vapor flow due to vapor diffusion – typically one to two orders of magnitude greater.



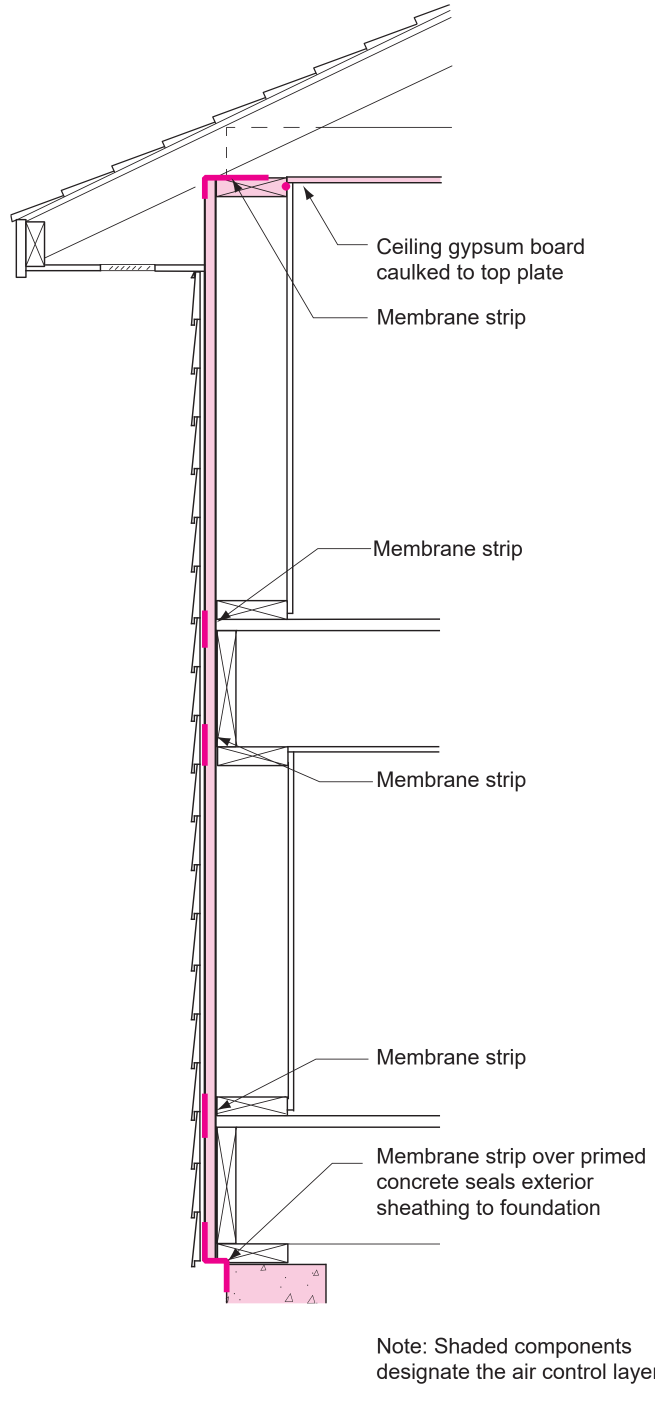


Figure 3.45: Exterior Air Control Layer - Airtightness can be provided at the exterior surfaces of building assemblies. This can be accomplished by installing a continuous sealed building paper or building wrap over the exterior sheathing.

Figure 3.46: Exterior Air Control Layer – Airtightness can also be accomplished by sealing the exterior sheathing to framing elements

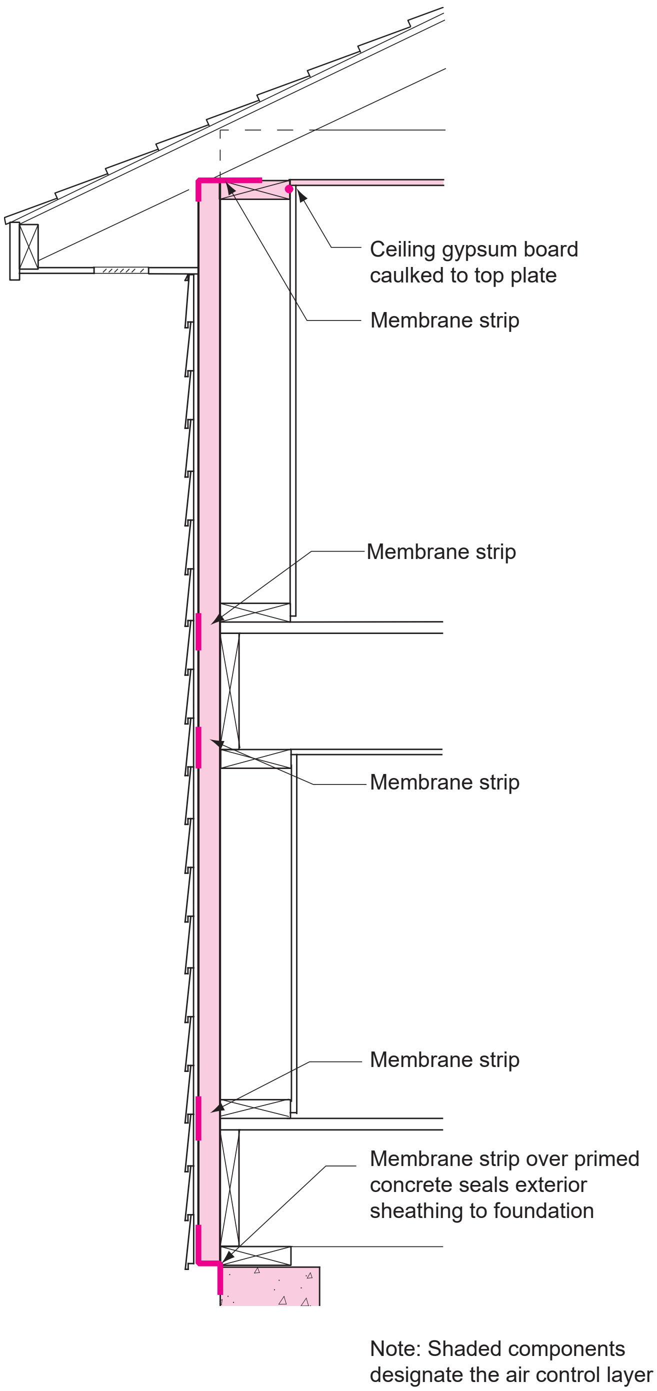


Figure 3.47: Exterior Air Control Layer - Exterior continuous rigid insulation can also be sealed to the framing elements to act as an exterior air control layer.

Air pressure differences across building assemblies can be influenced by the following:

- The stack effect
- Wind
- Mechanical systems

The Stack Effect

The stack effect is caused by the tendency of warm heated air to leak out of the upper portions of a building as a result of the buoyancy of heated air during cold weather. A heated building can be visualized as a hot air balloon that is too heavy to leave the ground: warm interior air exfiltrates the upper portions of the building, and cold exterior air infiltrates the lower portions. At the upper portion of the building, inside air pressure is greater than outside air pressure, leading to exfiltration. At the lower portion of the building, inside air pressure is lower than outside air pressure, leading to infiltration (**Figure 3.48**).

The force of exfiltration increases with height, and is therefore greater in taller buildings. At the upper portions of the building, the exfiltration becomes progressively greater with height. Conversely, the force of infiltration increases progressively in the lower portions of a building. The plane at which no pressure difference between the interior and the exterior exists is called the neutral pressure plane. Air exfiltrates through all openings located above the neutral pressure plane and infiltrates through all openings below the neutral pressure plane. Neither exfiltration nor infiltration occurs through an opening located at the neutral pressure plane.

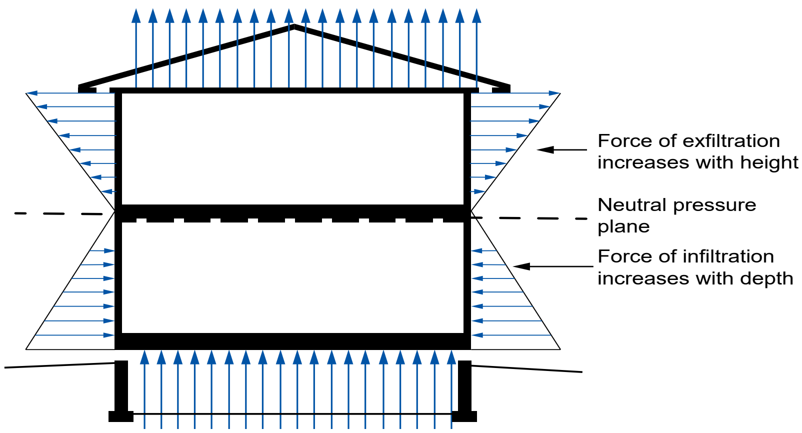


Figure 3.48: Stack Effect - The upper portion of the building, inside air pressure is greater than outside air pressure, leading to exfiltration. At the lower portion of the building, inside air pressure is lower than outside air pressure, leading to infiltration.

Approximately half the openings in a building are located above the neutral pressure plane and approximately half the openings are located below the neutral pressure plane, provided there are no mechanical exhaust or supply fans, or mechanical system-induced interior air pressure differences, or natural draft chimneys. Sealing openings in the upper portions of a heated building tends to lower the location of the neutral pressure plane, whereas sealing openings in the lower portions tends to raise it.

If an exhaust fan is installed in a building extracting air, it depressurizes the building, therefore raising the neutral pressure plane. Where sufficient exhaust flows exist and the neutral pressure plane rises above the building ceiling all openings are located below the neutral pressure plane and the building is said to be depressurized. Conversely, if a sufficiently large supply fan is installed in a building causing the neutral pressure plane to lower below the building basement or foundation slab all openings are located above the neutral pressure plane and the building is said to be pressurized.

In heating climates during heating periods, the stack effect is responsible for the exfiltration of warm interior heated air though building assemblies located in the upper portions of building enclosures. If the warm interior air also contains moisture, this moisture will be carried by the moving air and can be potentially deposited within the building assemblies as the exfiltrating air is cooled. The stack effect explains why moisture problems are likely to occur high up in buildings in heating climates, rather than down low.

In air conditioning climates during cooling periods, the stack effect can be reversed under certain conditions. Cold interior air can leak out the at the bottoms of buildings and exterior warm air can be drawn in at the top of buildings.`

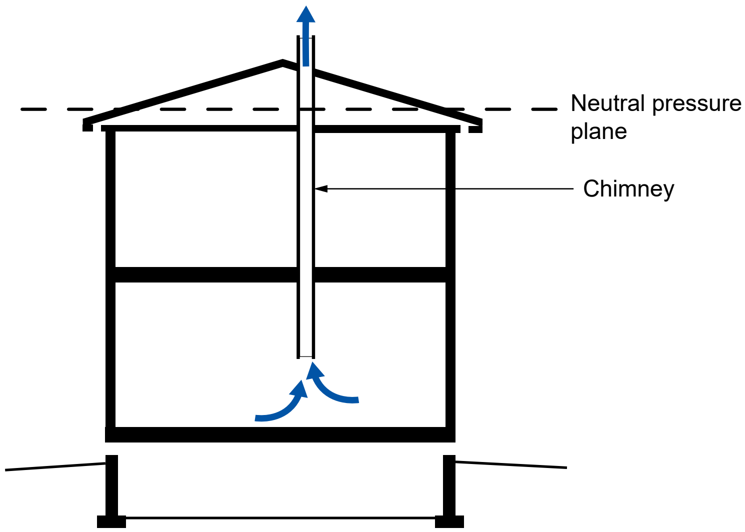


Figure 3.49: Natural Draft Chimneys - An active natural draft chimney acts similar to an exhaust fan tending to raise the neutral pressure plane, inducing infiltration over the majority of the surface area of the building enclosure.

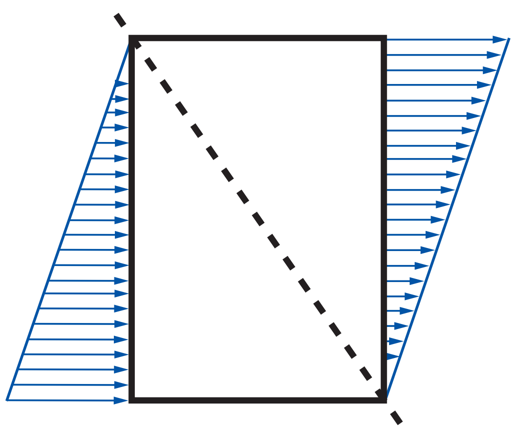


Figure 3.50: Wind And Stack Effect - The when wind effects are combined with the stack effect the wind tends to "tilt" the neutral pressure plane.

Natural Draft Chimneys

An active natural draft chimney acts similar to an exhaust fan tending to raise the neutral pressure plane, inducing infiltration over the majority of the surface area of the building enclosure (**Figure 3.49**). Buildings in heating climates with neutral pressure planes located above ceiling levels (i.e., fully depressurized buildings) tend to have fewer air-transported moisture problems than buildings with neutral pressure planes located below ceiling levels.

Wind

When wind blows over a building it tends to exert a positive air pressure on the windward side and a negative air pressure on the leeward side. The effect of wind to induce exfiltration on the leeward side and infiltration on the windward side leads to greater incidences of air transported moisture-related problems on the leeward side of buildings in heating climates – and the opposite effect in cooling climates. When combined with the stack effect the wind tends to "tilt" the neutral pressure plane (**Figure 3.50**).

Mechanical Systems

As noted previously, exhaust systems tend to depressurize conditioned spaces, inducing infiltration, while supply systems tend to pressurize conditioned spaces, inducing exfiltration. Ducted distribution systems in conditioned spaces, under typical design assumptions, have traditionally been thought not to alter interior air pressures. They have been viewed as interior circulation systems which move air from place to place within a conditioned space, with a neutral effect on the pressure differences between interior and exterior, and between interior rooms and spaces (**Figure 3.51** and **Figure 3.52**). However, ducted distribution systems (forced air heating and cooling systems) often have significant impacts on pressure differences across building assemblies—and subsequently on air change rates, interior airborne moisture levels, and moisture transport into and out of building assemblies.

A typical ducted, forced air heating and cooling system can be viewed as two systems: a supply duct system and a return duct system connected through a fan. In buildings in heating climates, most supply duct systems and air handlers (furnaces) are located in basement spaces. The supply system is relatively tight, with supply ducts usually running to every room in the building. In contrast, the return system is often rather limited in extent, with a single return, and is typically not particularly tight. This leads to rather unbalanced air flows, with most of the return air taken from the basement. The upper part of the building and bedrooms tend to be pressurized, and the common areas and basement tend to be depressurized (**Figure 3.53**). This is exacerbated in rooms with a supply register but no return register, such as bedrooms, when doors are closed (**Figure 3.54**).

When basements are depressurized, soil gas humidified by moist ground and containing other contaminants such a radon can infiltrate. Depressurization can also lead to the spillage of combustion products from combustion appliances.

The process of creating these pressure differences results in air change that can have significant impacts on energy consumption.

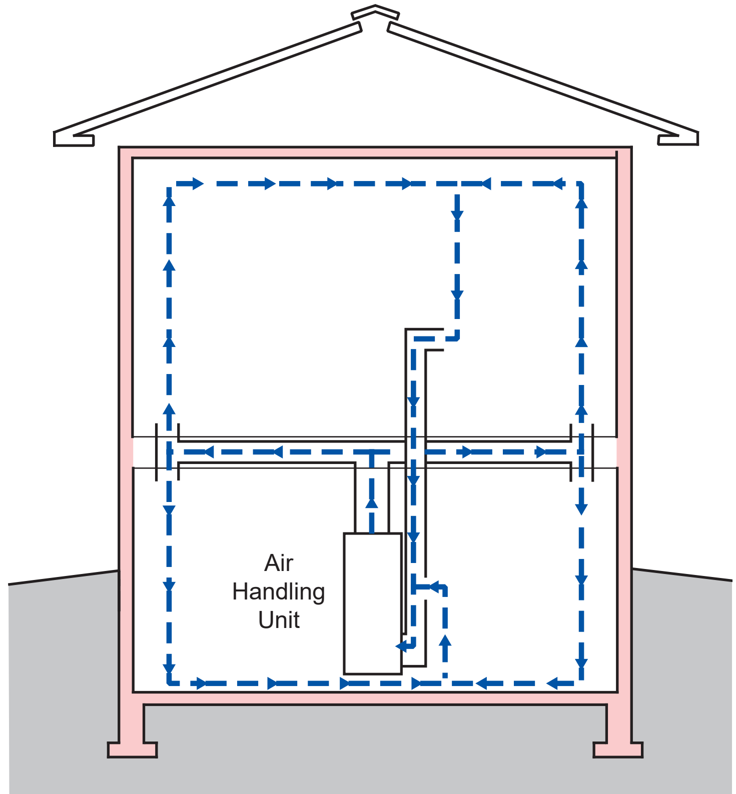


Figure 3.51: Mechanical System Pressure Effects – Interior air circulation system.

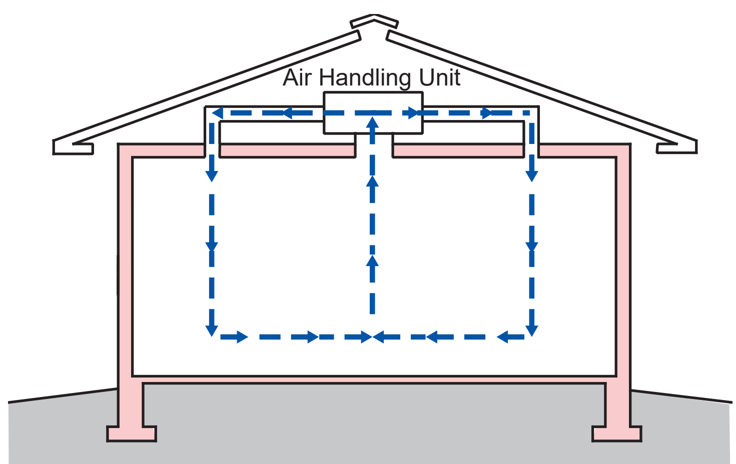
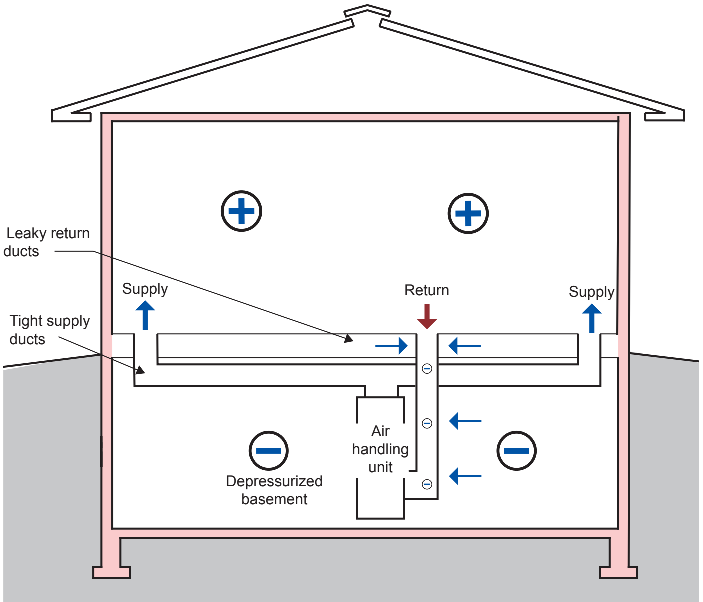


Figure 3.52: Mechanical System Pressure Effects – Interior air circulation system.



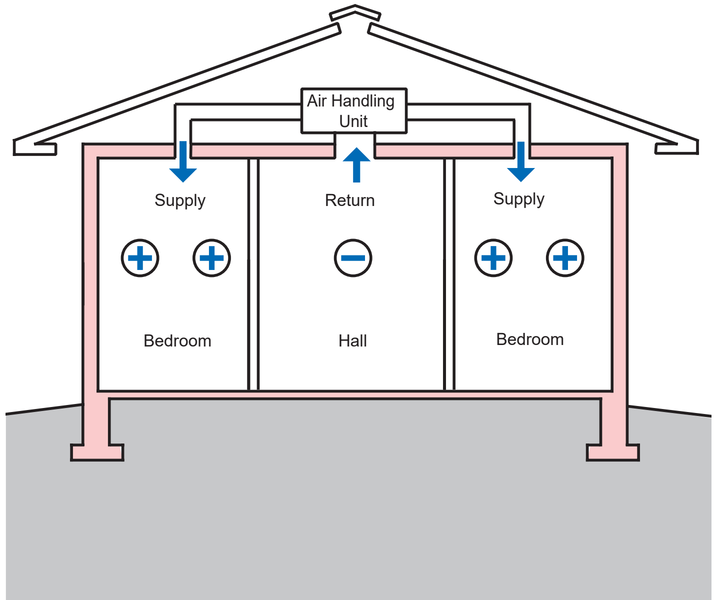
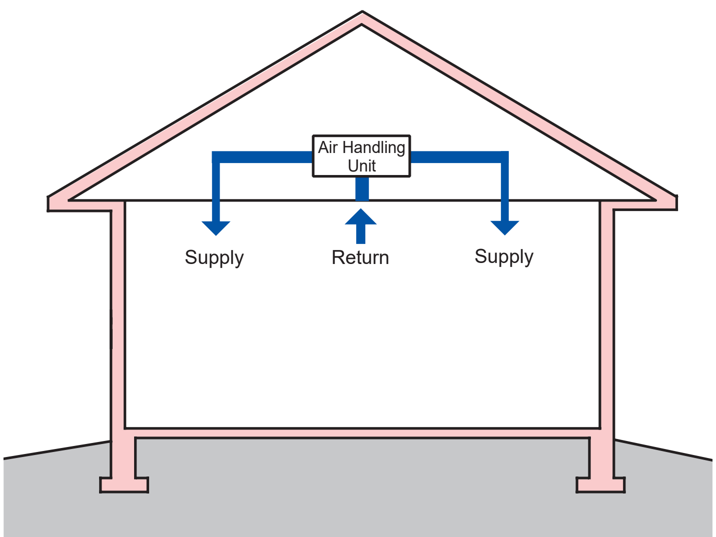


Figure 3.53: Basement Depressurization – Leaky ductwork and unbalanced air flows.

Figure 3.54: Pressurization of Bedrooms – Unbalanced airflows due to supply registers by no return registers.



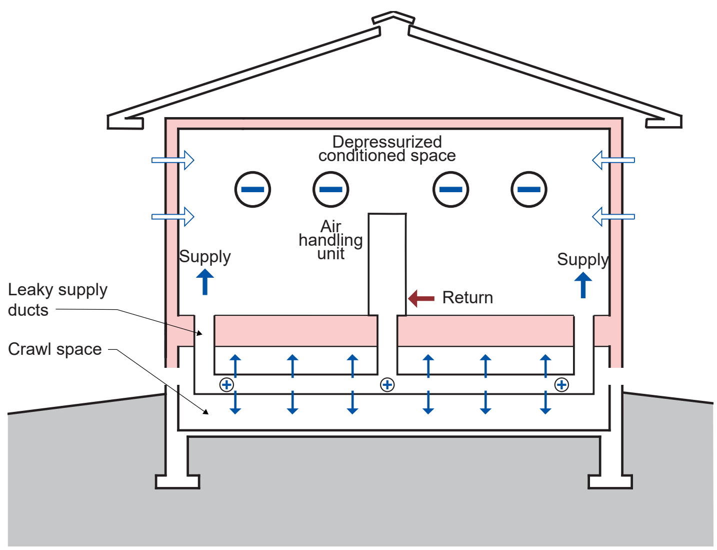


Figure 3.55: Depressurization of Slab Buildings – Leaky ductwork located in vented attics leads to depressurization.

Figure 3.56: Depressurization of Crawlspace Buildings – Leaky ductwork located in vented crawlspaces leads to depressurization.

It is recommended that supply and return ductwork be airtight and airflow be balanced to avoid air pressure differences.

In cooling climates supply ductwork is often located outside of conditioned spaces in vented unconditioned attics and vented unconditioned crawlspaces. These ducts tend to depressurize the space, inducing the infiltration of exterior hot and humid air (**Figure 3.55** and **Figure 3.56**) while dumping cold air-conditioned air into the attic or crawl space. Leaky return ducts also can draw radon and pesticides into the enclosure along with contaminants from attached garages. An obvious solution to ductwork located outside of conditioned spaces is to locate them inside of conditioned spaces. However, in most applications adequate space is not available. A more robust approach is to construct conditioned attics (**Figure 3.57**) and conditioned crawlspaces (**Figure 3.58**) thereby locating the ductwork within conditioned spaces.

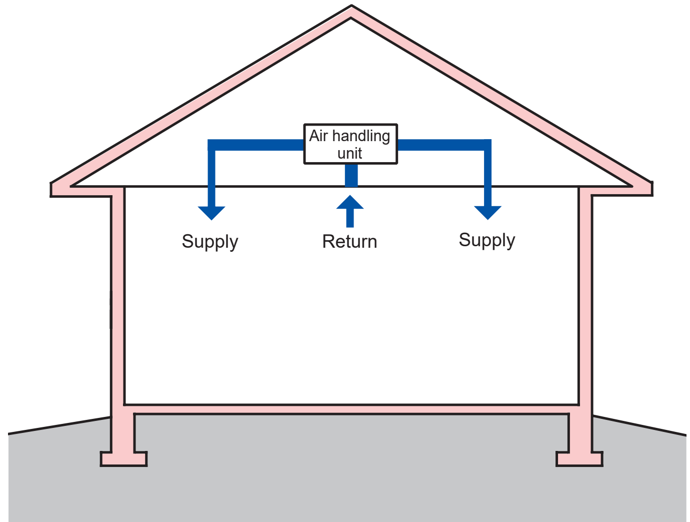


Figure 3.57: Conditioned Attic – Ductwork now located in conditioned space.

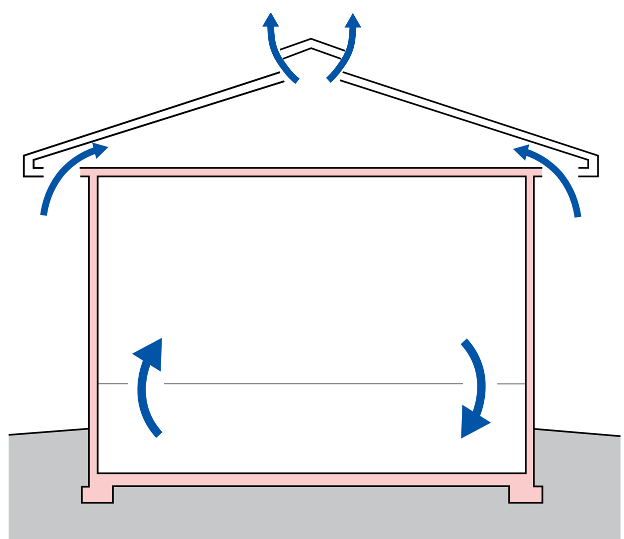


Figure 3.58: Conditioned Crawlspace – Ductwork now located in conditioned space.

Pressurizing Building Assemblies

Active control of air pressures in assemblies can be used to control the exfiltration of interior air or the infiltration of exterior air. In cold climates exterior air can be used to pressurize assemblies such as roofs to prevent the migration of air transported moisture from the conditioned space into the assembly (**Figure 3.59** and **Figure 3.60**). Conversely, in hot climates, interior air can be used to pressurize assemblies to prevent the migration of air transported moisture from the exterior into the assembly. Pressurization can be maintained with a fan, that needs only to operate when exterior temperatures drop below the dew point temperature of the conditioned space in cold climates, and vice versa in hot climates

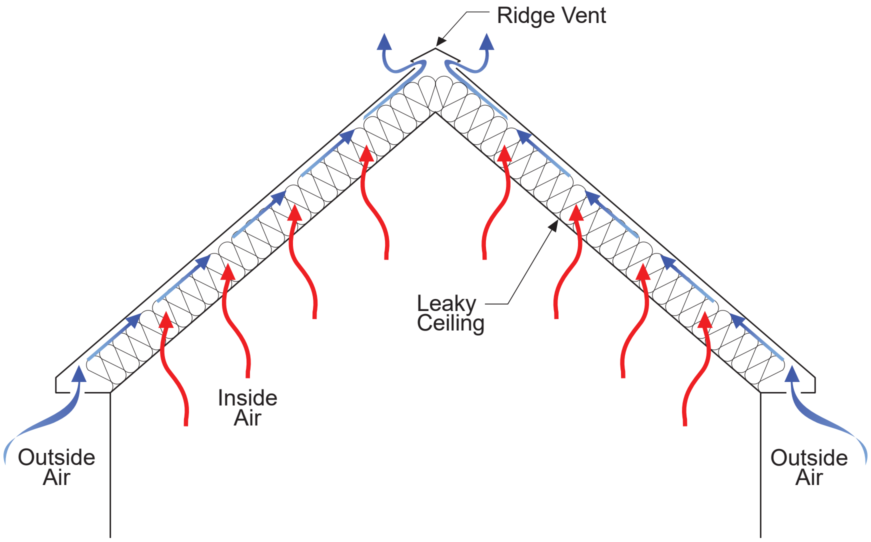


Figure 3.59: Air Leakage of Cathedral Ceiling – Cold climate condensation issue.

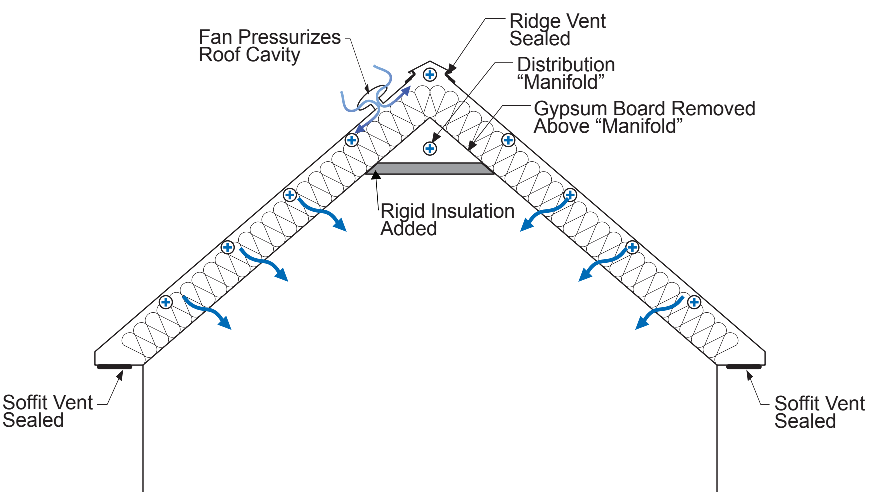


Figure 3.60: Pressurization of Building Assemblies - In cold climates exterior air can be used to pressurize assemblies such as roofs to prevent the migration of air transported moisture from the conditioned space into the assembly.

Vapor Flow Due to Diffusion

The fourth moisture transport mechanism is vapor diffusion. It can move moisture into building assemblies both from within the conditioned space as well as from the exterior. Vapor diffusion is the movement of moisture in the vapor state through a material.

Vapor diffusion is a function of the vapor permeability of a material and the driving force or vapor pressure differential acting across a material. The vapor pressure differential refers to the difference in amount of moisture or difference in moisture concentration across a material.

In a cold climate where buildings are being heated, vapor diffusion typically moves moisture from within the conditioned space into building assemblies during the colder months of the year. It is possible in heating climates to reduce the diffusion driving force by reducing interior moisture levels. It is also practical to select the vapor permeability of enclosure materials to control moisture movement by diffusion. Finally, it is practical to control the impact of vapor diffusion by controlling the temperature of assembly surfaces.

In warm climates with high exterior vapor pressures where cooling is occurring, the opposite occurs. Vapor diffusion typically moves moisture from the exterior into building assemblies and subsequently into the conditioned space.

However, exceptions to the above two generalizations are common. One such example is a solar heated wall in a heating climate with a brick veneer that has absorbed moisture from deposited rain (a “reservoir cladding”). This moisture can be driven out of the cladding during the day and into the wall assembly as a result of the temperature gradient due to high exterior surface temperatures from incident solar radiation. The vapor pressure gradient, under these circumstances, can move moisture by vapor diffusion from the exterior cladding into the wall assembly during sunny periods.

In foundations and below-grade assemblies, vapor diffusion can move moisture from the surrounding soil into the assembly as well as from the conditioned space into assemblies.

Vapor diffusion is also a function of surface area. If, for instance, 90 percent of a building enclosure surface area is covered with a specific vapor control layer, then, all other things being equal, that vapor control layer is 90 percent effective.

Principles

The fundamental principle of control of water in the vapor form is to keep it out and to let it out if it gets in. It gets complicated because sometimes the best strategies to keep water vapor out also trap water vapor in. This can be a real problem if the assemblies start out wet because of rain or the use of wet materials.

It gets even more complicated because of the climate. In general water vapor moves from the warm side of building assemblies to the cold side of building assemblies. Logically, this means we need different strategies for different climates. We must also account for differences between summer and winter.

A vapor control layer is defined as: "the element that is designed and installed in an assembly to control the movement of water by vapor diffusion."

The unit of measurement typically used in characterizing the water vapor permanence of materials is the "perm". Several classes of vapor control layers are further defined as follows:

Class I Vapor Control Layer:
0.1 perm or less

Class II Vapor Control Layer:
1.0 perm or less and greater than 0.1 perm

Class III Vapor Control Layer:
10.0 perm or less and greater than 1.0 perm

Test Procedure for vapor control layer: ASTM E-96 Test Method A (the desiccant method or dry cup method)

Finally, a vapor barrier is defined specifically as a Class I vapor control layer (0.1 perm or less).

Materials can be separated into four general classes based on their permanence:

Vapor impermeable:
0.1 perm or less

Vapor semi-impermeable:
1.0 perm or less and greater than 0.1 perm

Vapor semi-permeable:
10.0 perms or less and greater than 1.0 perm

Vapor permeable:
greater than 10.0 perms

Based on the definitions the following general principles should be followed in assembly design:

- Avoid using vapor impermeable layers where vapor semi-impermeable, vapor semi-permeable and vapor permeable layers will provide satisfactory performance thereby encouraging drying mechanisms over wetting prevention mechanisms
- Avoid installation of vapor impermeable layers such as polyethylene vapor barriers, foil-faced batt insulation, reflective radiant barrier foil insulation, and vinyl wall coverings on the interior of air-conditioned assemblies.

Control of Vapor Diffusion

There are three principal control approaches to dealing with water in the vapor form. The first is to let the water vapor pass through the assembly from the inside out and from the outside in. Where a wall assembly is concerned it is a wall that can dry to both sides. We call these types of assemblies "flow-through" assemblies.

The second is to locate a distinctive layer to control the flow of water vapor into the wall assembly from either the inside or from the outside. We call these types of assemblies "vapor control layer" assemblies.

The third is to control the temperature of the surfaces where condensation is likely to occur by raising the surface temperature with insulation. The most common method of doing this is to use rigid insulation on the exterior of assemblies, to control wintertime condensation. We call these types of assemblies "control of condensing surface temperature" assemblies.

Flow-Through Assemblies

A wall assembly that is vapor open on both the interior and exterior, whose cavity is insulated with a vapor open insulation such as a fiberglass or mineral fiber batt, or fiberglass or cellulose (blown or netted), is called a flow-through assembly (**Figure 3.61**). Plywood and OSB sheathing installed on the exterior are semi vapor permeable – they "breathe".

The water control layers (building paper, housewrap, and building wrap) typically installed over plywood and OSB are typically semi vapor permeable or vapor permeable. Gypsum board installed on the interior painted with latex paint is also semi vapor permeable.

The key to a flow-through assembly is the exterior cladding layer and its attachment. Many exterior claddings can retard the flow of vapor. For example vinyl siding (as a material) is a vapor barrier. But since vinyl siding is leaky to air at each joint and its profile yields an airspace between it and the water control layer it is said to be "back ventilated." This air circulation behind the vinyl siding prevents the vinyl siding from trapping water vapor, thus allowing the assembly to dry to the exterior.

A brick veneer that is free from mortar droppings with weep openings at the bottom and top is also back ventilated thereby allowing the assembly to dry to the exterior.

Wood siding and fiber cement siding should be installed on furring strips or spacer strips to provide back ventilation creating a flow-through assembly. These furring strips or spacer strips can be as thin as 3/8 inch to provide effective back ventilation.

With stucco renderings, a continuous air gap should be provided behind the stucco to facilitate back ventilation. This is typically done by providing a drainage mat over the water control layer and then installing a paper backed lath over the drainage mat. Ventilation openings also are provided at the top and bottom of the stucco clad walls.

An attic assembly that is vented and constructed with latex painted ceiling gypsum board and insulated with fiberglass, cellulose, or mineral fiber is also called a flow-through assembly (**Figure 3.62**).

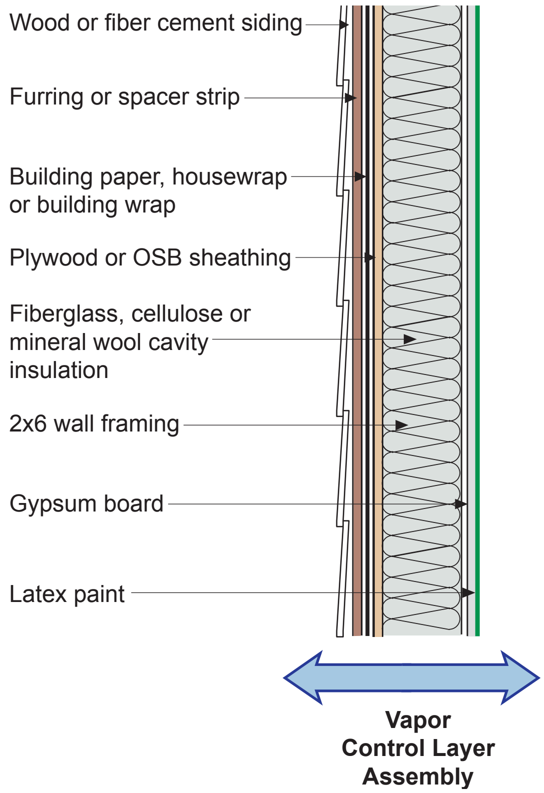


Figure 3.61: Flow-Through Assembly – Wall assembly that is vapor open on both the interior and exterior whose cavity is insulated with a vapor open insulation.

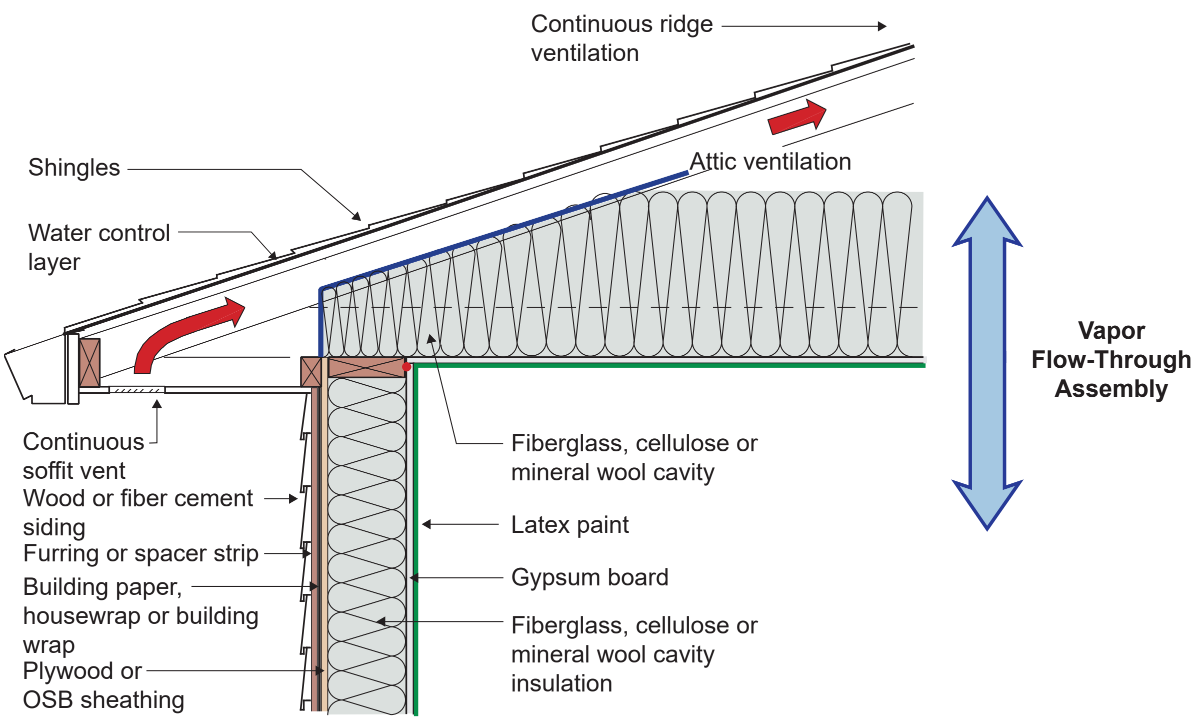


Figure 3.62: Flow-Through Assembly - An attic assembly that is vented and constructed with latex painted ceiling gypsum board and insulated with fiberglass batts or cellulose is also called a flow-through assembly.

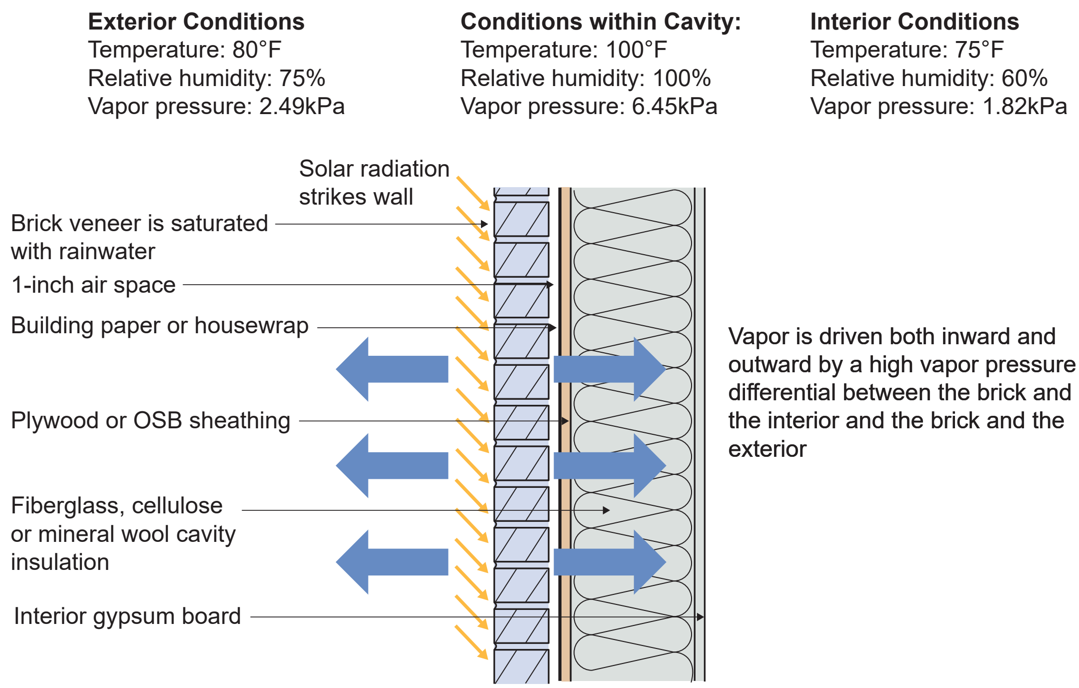


Figure 3.63: Reservoir Claddings - Brick veneer becomes saturated after a rainstorm. The brick acts as a reservoir storing water. When the sun shines on the rain wetter brick veneer it raises the temperature of the water stored in the brick. This water is now driven out of the brick in both directions.

Limitations of Flow-Through Assemblies

Flow-through assemblies perform well in most climates. However, they can be overwhelmed in certain conditions. For example in climates with cold winters where interior moisture levels can get high during the winter months more moisture can enter these assemblies from the interior than can leave these assemblies to the exterior. In such situations it is common to throttle down the vapor flow into the assemblies from the interior by installing a vapor control layer on the interior. The model building codes recognize this and limit flow-through assemblies to specific regions. The 2021 IRC limits flow-through assemblies with vented claddings and wood based sheathings to IECC Climate Zones 1 through 5.

Another example where a flow-through assembly can be overwhelmed is where a "reservoir" cladding is located on the exterior of vapor semi-permeable water control layers and exterior sheathing such as building paper installed over plywood and OSB sheathing. Consider the case where a brick veneer becomes saturated after a rainstorm. The brick acts as a reservoir storing water. When the sun shines on the rain wetted brick veneer it raises the temperature of the water stored in the brick. This water is now driven out of the brick in both directions (**Figure 3.63**). The outward drive does not hurt the assembly, but the inward drive can. The water vapor driven inward can pass through the air gap, vapor permeable housewrap, and vapor semi-permeable sheathing into the wall cavity.

It is possible to drive sufficient moisture into the assembly to create problems. One effective way of addressing this issue is to have a cavity behind the brick veneer free of mortar droppings that is vented at the top and bottom. The moisture driven inward out of the brick can then be intercepted by a moving stream of ventilation air that dries the assembly to the exterior. Another effective way of addressing this issue is to install a vapor impermeable or semi vapor impermeable rigid insulation layer behind the brick veneer that throttles this inward vapor drive. Note that a drainage gap and a water control layer are still necessary to handle rainwater entry.

Vapor Control Layer Assemblies

In more extreme climates such a cold climates where vapor drive from the interior towards the exterior occurs for extended periods of time during the winter months this outward vapor drive can be controlled by installing a vapor control layer on the interior of the insulation (**Figure 3.64** and **Figure 3.65**).

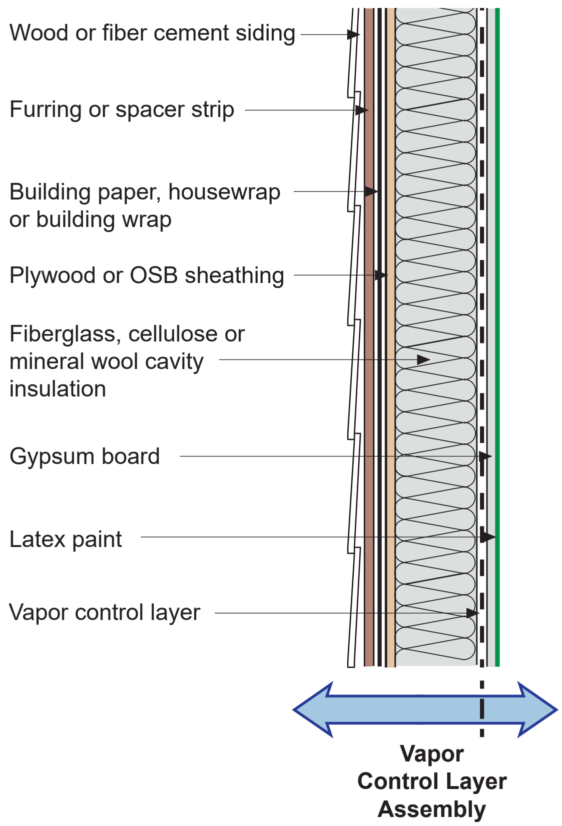


Figure 3.64: Interior Vapor Control Layer Assembly – Wall with vapor control layer on the interior of wall cavity insulation.

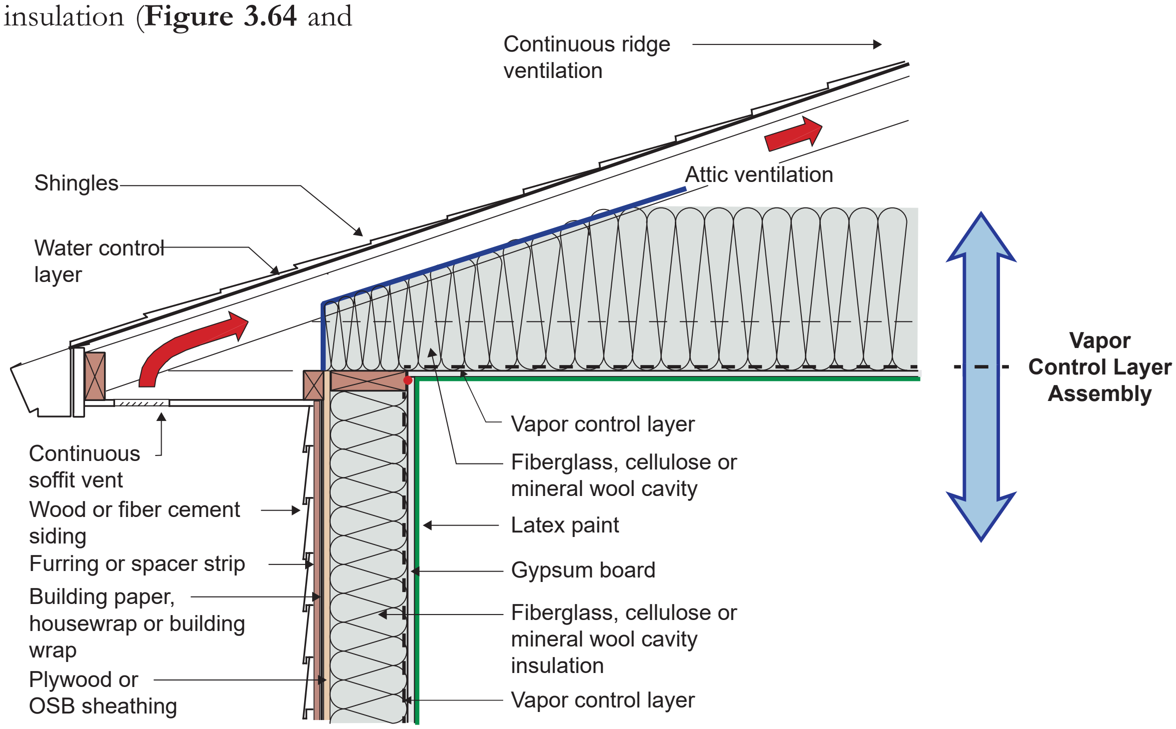


Figure 3.65: Interior Vapor Control Layer Assembly – Attic with vapor control layer at the underside of attic insulation.

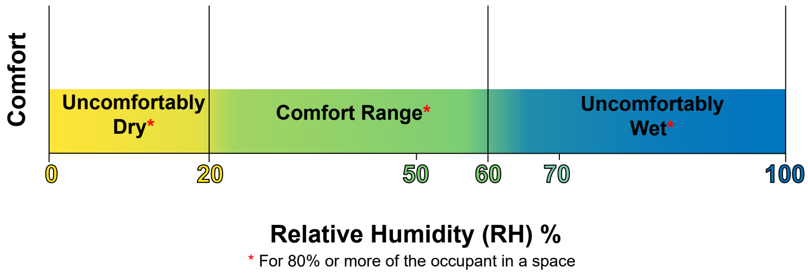


Figure 3.66: Interior Relative Humidity - Winter interior humidity's are typically between 20 percent and 30 percent relative humidity (RH). Summer interior humidity's are typically between 50 and 60 percent RH. Note that the comfort range for most people is between 20 percent and 60 percent.

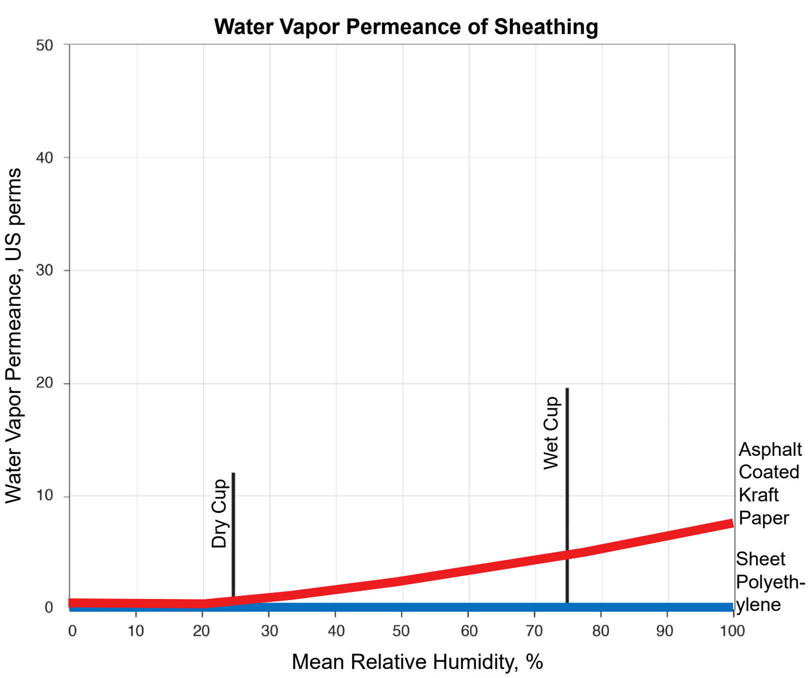


Figure 3.67: Kraft Paper Vapor Transfer - Asphalt coated kraft paper installed on the interior fiberglass batt cavity insulation changes its water vapor permeance as a function of relative humidity.

The concern with inwardly located vapor control layers is if they are too impermeable such as sheet polyethylene they can trap moisture in the assembly by preventing inward drying. An effective way to address this issue is to use a material that changes its permanence seasonally, using the typical differences in interior relative humidity between the winter and summer months.

In newly-constructed code-compliant North American houses winter interior humidities are typically between 20 percent and 30 percent relative humidity (RH). Summer interior humidity's are typically between 50 and 60 percent RH. Note that the comfort range for most people is between 20 percent and 60 percent (**Figure 3.66**).

Asphalt-coated kraft paper installed on the interior fiberglass batt cavity insulation changes its water vapor permanence as a function of relative humidity (**Figure 3.67**). At 25 percent RH it has a permanence of approximately 1 perm. At 60 percent RH it has a permanence of approximately 10 perms. So under typical interior winter conditions the facing is a vapor control layer limiting or throttling the outward vapor drive protecting the assembly. Under typical interior summer conditions the facing is vapor permeable allowing drying to the interior.

Control of Condensing Surface Temperature Assemblies

Vapor drive from the interior to the exterior can also be controlled by installing rigid insulation (e.g., extruded polystyrene/ XPS, polyisocyanurate, semi-rigid mineral fiber, and other materials) on the exterior of the structural framing. This rigid insulation raises the temperature of the wall cavity surfaces where condensation is likely to occur. We call these types of assemblies "control of condensing surface temperature" assemblies (**Figure 3.68**).

Figure 3.69 shows the potential for condensation for a wall assembly located in Chicago, IL with various levels of interior RH. When wintertime condensation occurs, it collects on the interior surface of the exterior sheathing. When this exterior sheathing has little or no thermal resistance, the interior surface ("condensing surface of interest") its temperature is approximated by the exterior temperature. Note that as interior RH goes up, so does the potential for condensation.

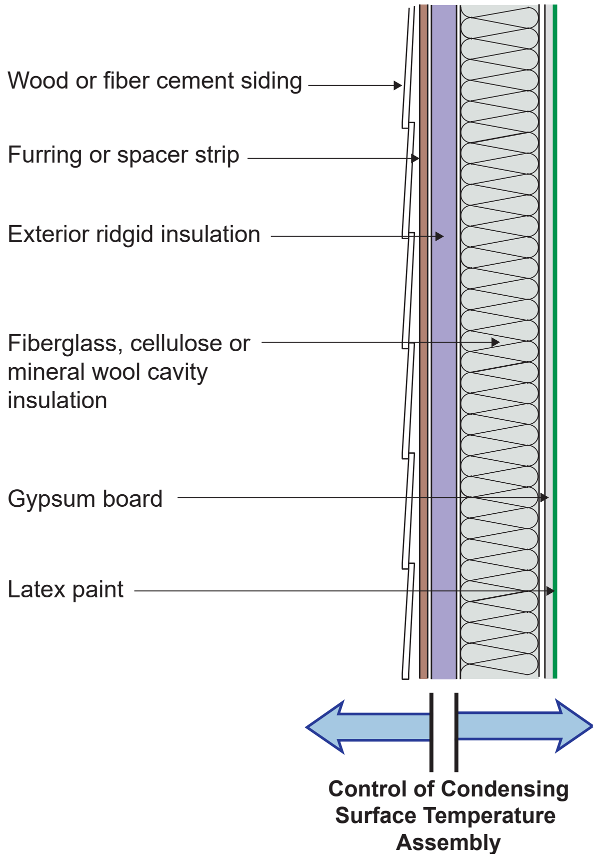


Figure 3.68: Control of Condensing Surface Assembly - Rigid insulation raises the temperature of the wall cavity surfaces where condensation is likely to occur.

Insulation for Condensation Control*

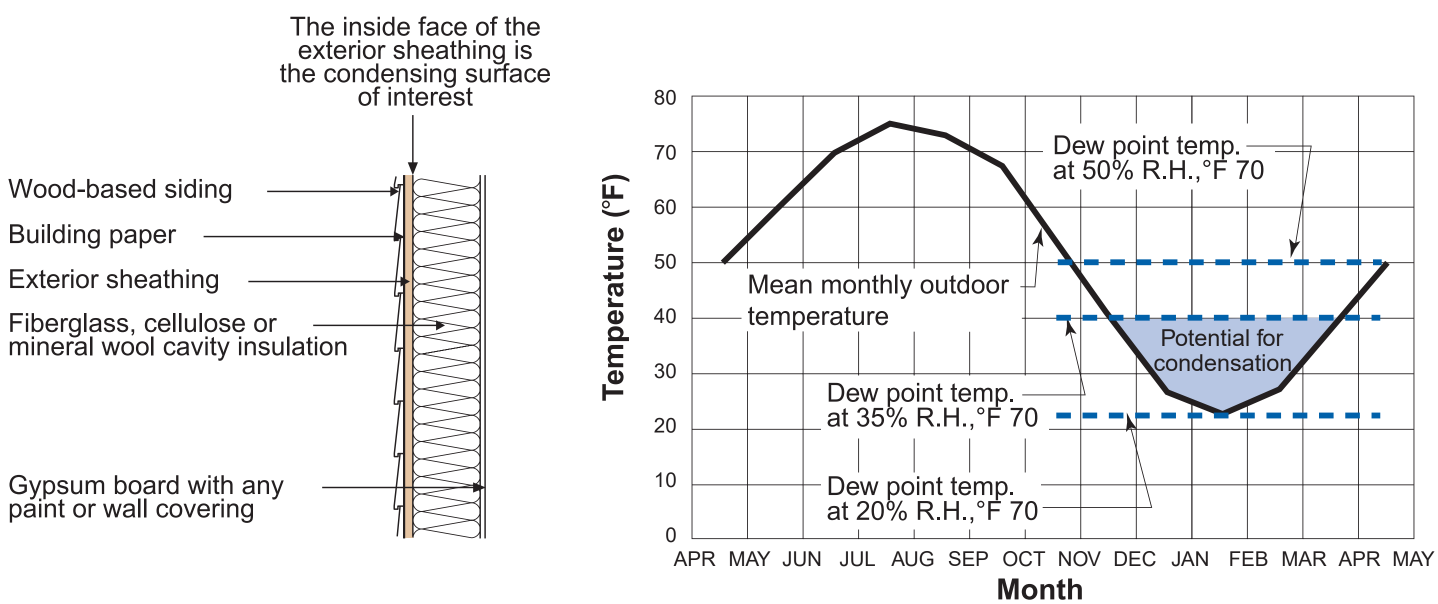
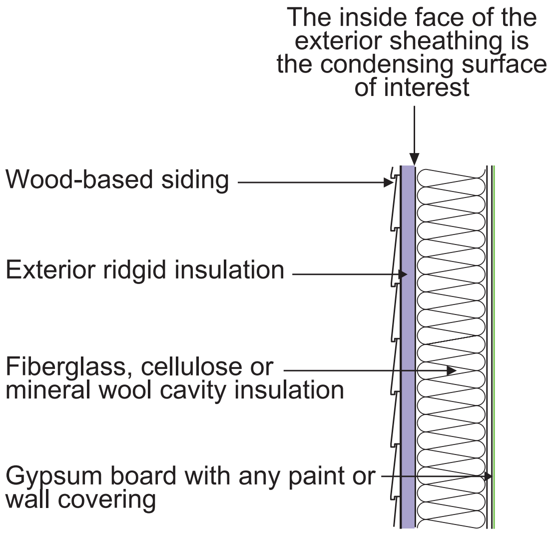


Figure 3.69: Potential for Condensation - Potential for condensation for a wall assembly located in Chicago, IL with various levels of interior RH.



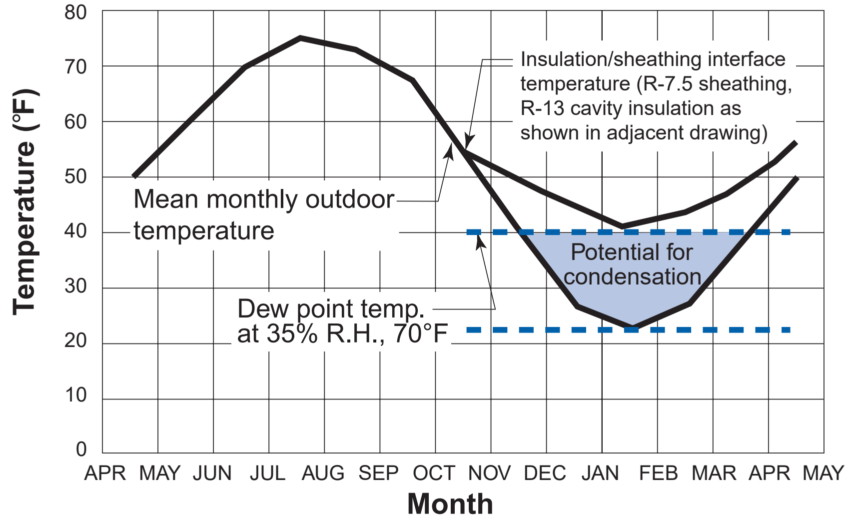


Figure 3.70: Rigid Insulation Reducing Potential for Condensation - Rigid insulation installed on the exterior of the structural framing raises the temperature of the condensing surface of interest controlling condensation from interior water vapor migrating into the wall assembly. This allows assemblies to be constructed in cold climates without interior vapor control layers.

Climate Zone	Rigid Board or Air Impermeable Insulation	Total Cavity Insulation	Total Wall Assembly Insulation	Ratio of Rigid Board Insulation or Air Impermeable R-Value to Total Insulation R-Value
4C	R-2.5	R-13	R-15.5	15%
	R-3.75	R-20	R-23.75	15%
5	R-5	R-13	R-18	30%
	R-7.5	R-20	R-27.5	30%
6	R-7.5	R-13	R-20.5	35%
	R-11.25	R-20	R-31.25	35%
7	R-10	R-13	R-28	45%
	R-15	R-20	R-35	45%
8	R-15	R-13	R-28	50%
	R-20	R-20	R-40	50%

Table 3.1: Adapted from Table R702.1 2015 International Residential Code

Figure 3.70 shows how the potential for condensation is reduced for the same wall assembly when rigid insulation is installed on the exterior of the structural framing. By raising the temperature of the condensing surface of interest sufficiently, condensation from interior water vapor migrating into the wall assembly does not occur. This allows assemblies to be constructed in cold climates without interior Class I or II vapor control layers. The model building codes recognize this and provide guidance on the minimum thermal resistance values of rigid insulation required to control condensation in specific Climate Zones.

Table 3.1 is information taken from the 2012 IRC and provides guidance for thermal resistance values to control condensation for Climate Zones 5, 6, 7, 8, and Marine 4.

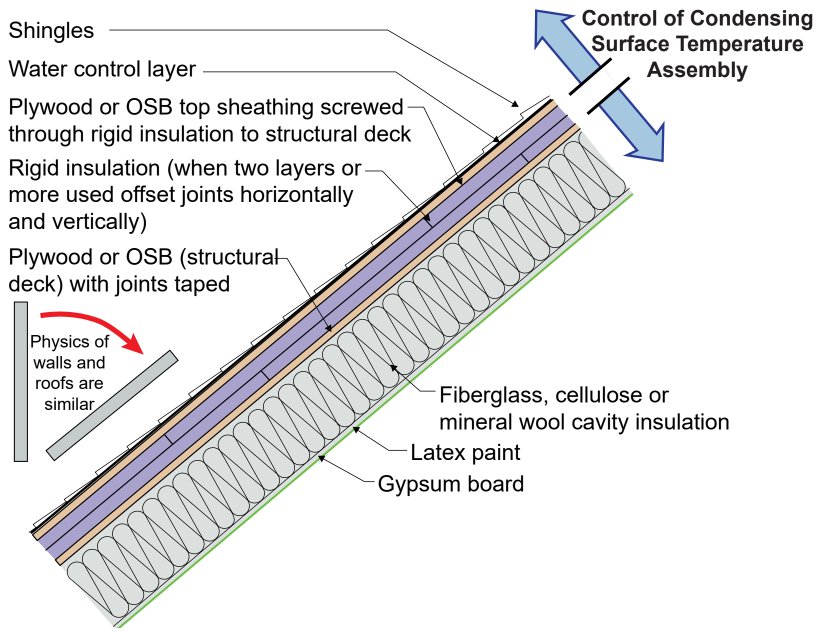


Figure 3.71: Roof Assembly - Rigid insulation is installed over the top of the structural roof deck elevating the temperature of the underside of the roof deck to control condensation.

Figure 3.71 illustrates the same principle applied to roofing assemblies. Rigid insulation is installed over the top of the structural roof deck elevating the temperature of the underside of the roof deck to control condensation.

Table 3.2 is information taken from the 2012 IRC and provides guidance for thermal resistance values to control condensation in roof/attic assemblies for all Climate Zones.

Climate Zone	Rigid Board or Air Impermeable Insulation	Code Required R-Value	Ratio of Rigid Board Insulation or Air Impermeable R-Value to Total Insulation R-Value
1,2,3	R-5	R-38	10%
4C	R-10	R-49	20%
4A, 4B	R-15	R-49	30%
5	R-20	R-49	40%
6	R-25	R-49	50%
7	R-30	R-49	60%
8	R-35	R-49	70%

Table 3.2: Adapted from Table R806.5 2015 International Residential Code

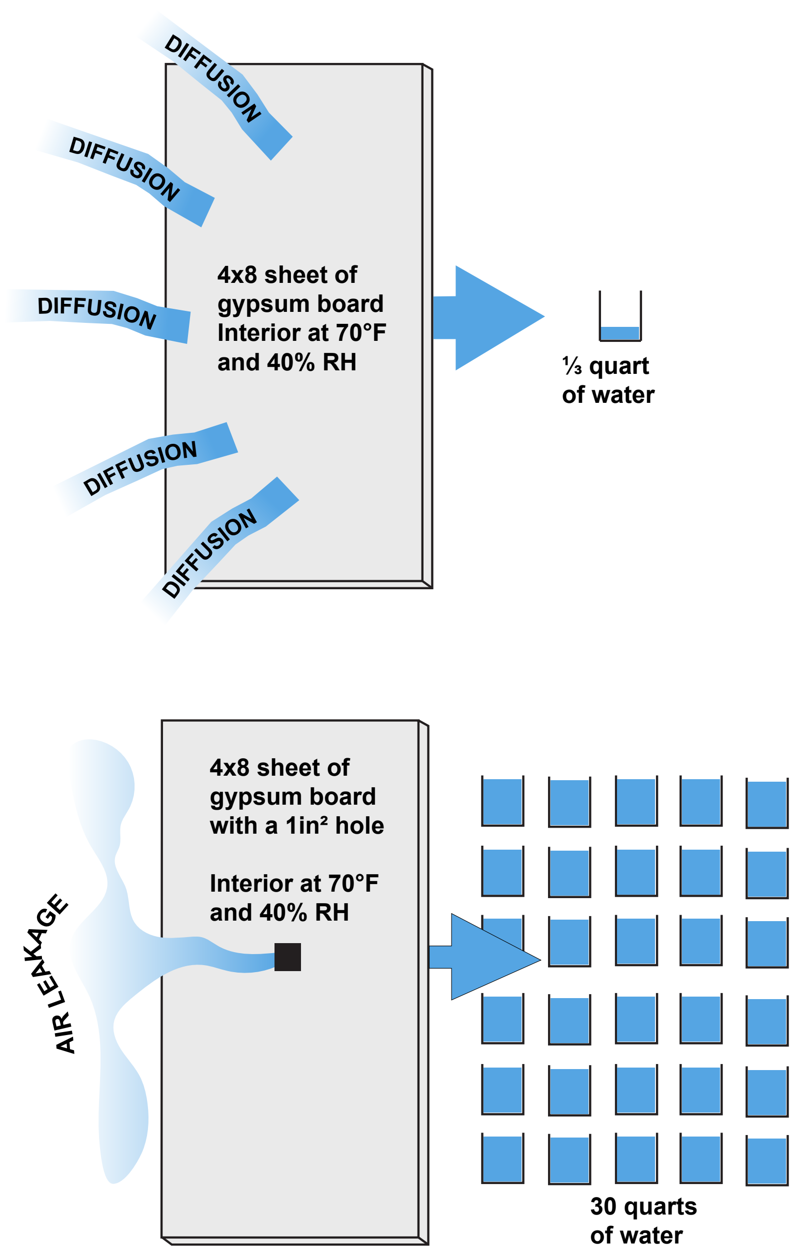


Figure 3.72: Air Transport vs Vapor Diffusion - In a cold climate (Chicago) the movement of water vapor over a winter from the interior to the exterior through a 1-inch square hole as a result of a 5 Pascal air pressure differential is 100 times greater than the movement of water vapor as a result of vapor diffusion through a 32-square-foot sheet of gypsum board under normal heating conditions and interior moisture levels.

Magnitude of Vapor Flow Due to Air Transport and Vapor Flow Due to Diffusion

The differences in the significance and magnitude of vapor diffusion versus air transported moisture are typically misunderstood. Air movement as a moisture transport mechanism is typically far more important than vapor diffusion in many (but not all) conditions.

In a cold climate (Chicago) the movement of water vapor over a winter from the interior to the exterior through a 1-inch square hole as a result of a 5 Pascal air pressure differential is 100 times greater than the movement of water vapor as a result of vapor diffusion through a 32-square-foot sheet of painted gypsum board under normal heating conditions and interior moisture levels (**Figure 3.72**).

In a hot-humid climate (Atlanta) the movement of water vapor over the spring, summer and fall from the exterior to the interior through a 1-inch square hole as a result of a 5 Pascal air pressure differential is 10 times greater than the movement of water vapor as a result of vapor diffusion through a 32-square foot sheet of painted gypsum board under normal cooling conditions and exterior moisture levels (**Figure 3.73**).

In most climates, if the movement of moisture-laden air into a wall or building assembly is eliminated, movement of moisture by vapor diffusion is likely insignificant. The notable exceptions are hot-humid climates, rain wetted walls experiencing solar heating, and extremely cold climates.

Furthermore, the amount of vapor that diffuses through a building component is a direct function of area. That is, if 90 percent of the building enclosure surface area is covered with a vapor retarder, then that vapor retarder is 90 percent effective. In other words, continuity of the vapor retarder is not as significant as the continuity of the air barrier. For instance, polyethylene film which may have tears and numerous punctures present will act as an effective vapor barrier, whereas at the same time it is a poor . Similarly, the kraft-facing on fiberglass batts installed in exterior walls acts as an effective vapor retarder, in spite of the numerous gaps and joints in the kraft-facing.

It is possible and often practical to use one material as the air control layer and a different material as the vapor control layer. However, the air control layer must be continuous and free from holes, whereas the vapor control layer need not be.

In practice, it is not possible to eliminate all holes and install a "perfect" air control layer. Most strategies to control air transported moisture depend on the combination of an air control layer, interior/exterior moisture condition control and the prevention of excessive air pressure differentials to be effective. Air control layers are often utilized to eliminate the major openings in building enclosures to allow the practical control of air pressure differentials. It is easier to control the air pressures within and across building enclosures made tight through the installation of air control layers than it is to control these pressures when the building enclosure is leaky. The interior moisture levels in a tight building enclosure are also much easier to control by ventilation and dehumidification than those in a leaky building enclosure.

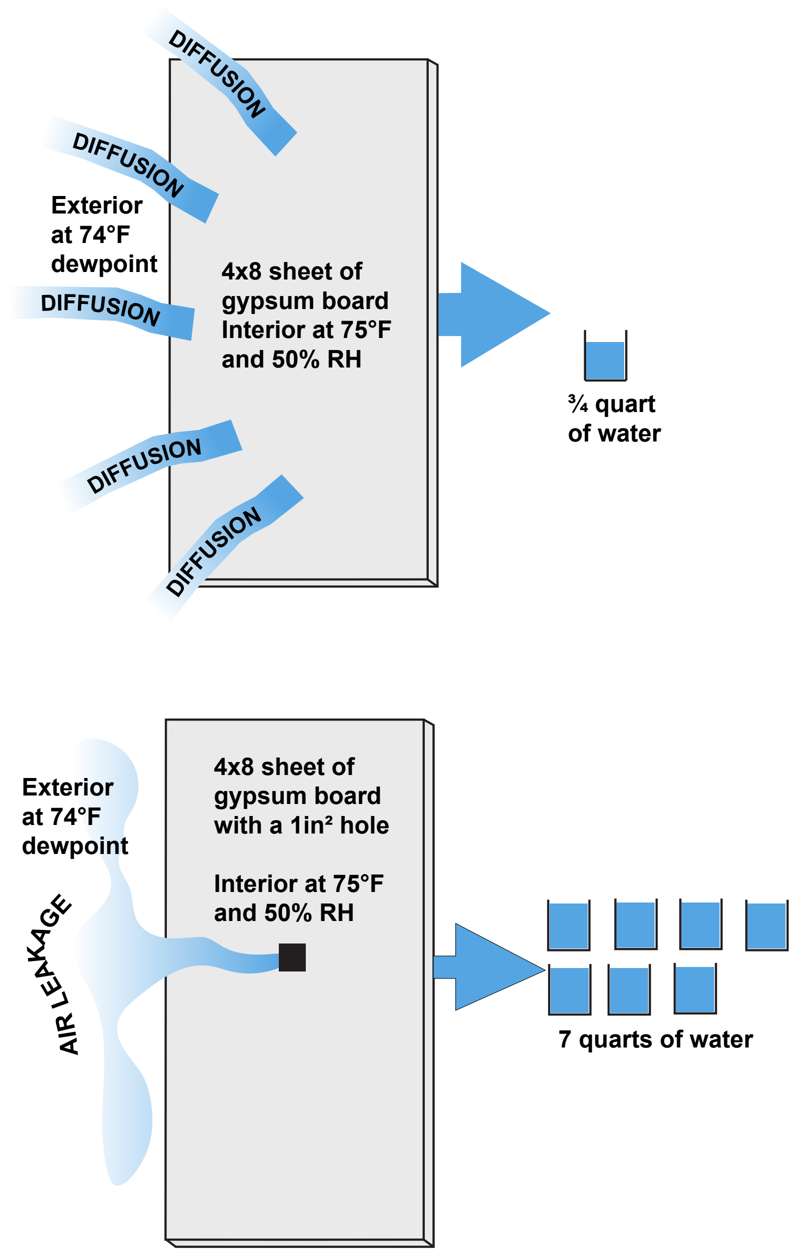


Figure 3.73: Air Transport vs Vapor Diffusion - In a hot-humid climate (Atlanta) the movement of water vapor over the spring, summer and fall from the exterior to the interior through a 1-inch square hole as a result of a 5 Pascal air pressure differential is 10 times greater than the movement of water vapor as a result of vapor diffusion through a 32-square foot sheet of painted gypsum board under normal cooling conditions and exterior moisture levels

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CHAPTER 4

Wall Assemblies

Wall assembly design and construction needs to consider rain, temperature, humidity as defined by the hygro-thermal regions, annual rainfall and the interior climate classes as environmental loads that affect mold, decay, and corrosion as well as other degradation mechanisms. Design and construction needs to consider the exterior and interior environmental loads, the nature of the materials that comprise the environmental separation, and the energy flow across the environmental separation.

Wall assemblies should be designed and constructed for specific hygro-thermal regions, rain exposure zones, and interior climate classes. To this end the wall assembly should have four principal control layers or control approaches as overlays to the structure. They are presented in order of importance:

- a water control layer or water control approach for rainwater
- an air control layer or air control approach for air transported moisture
- a vapor control layer or vapor control approach for vapor transported moisture
- a thermal control layer or thermal control approach for thermal transfer

If a control layer approach is selected the best place for the control layers is to locate them on the outside of the structure in order to protect the structure. The optimum configuration is presented in **Figure 4.1**. However, many configurations are possible. In many assemblies a combination of control layers and control approaches are typical.

The most common examples of configurations of control layers and control approaches follow for residential wood frame and residential concrete masonry unit (CMU) assemblies.

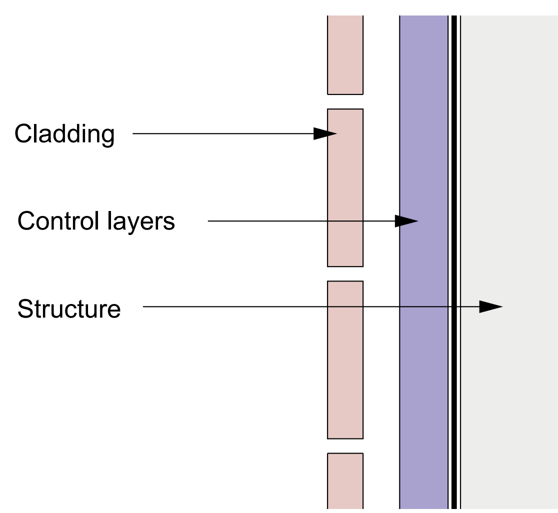


Figure 4.1: Control Layers – Optimum configuration is to place the control layers on the outside of the structure.

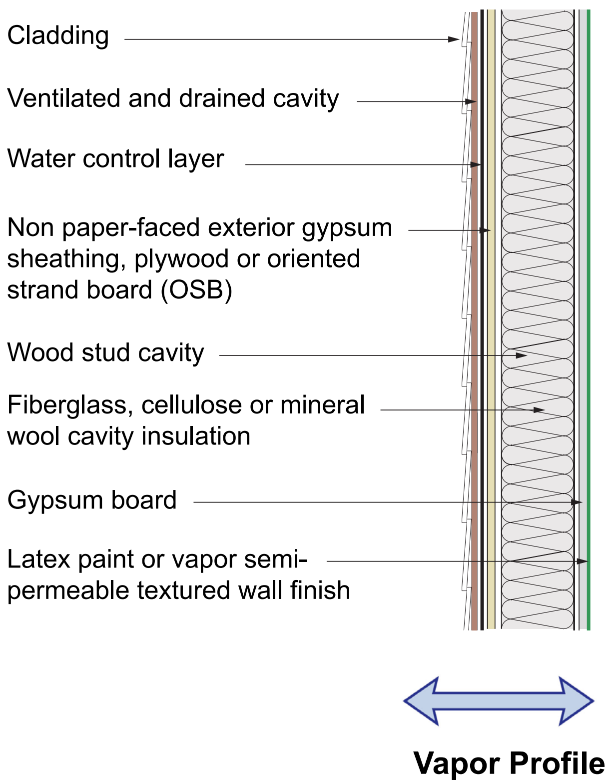


Figure 4.2: Wood Frame Assembly With Interior Cavity Insulation and Siding

Figure 4.2: Wood Frame Assembly With Interior Cavity Insulation and Siding

Applicability
OK: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Very cold and subarctic/arctic regions.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall is a flow through assembly: it can dry to both the exterior and the interior.

Drainage cavity
The exterior siding should be uncoupled from the wall assembly with a ventilated and drained cavity. The air gap behind the cladding can be provided by using a textured housewrap, a drainage mat, or furring strips at least 3/16 inch thick.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints.

Air control layer
Interior gypsum board, exterior gypsum board/structural sheathing, or exterior building wrap (water control layer).

Vapor control layer
No specific vapor control layer. Controls vapor flow by allowing vapor transfer in both directions. Interior vapor control Class III latex paint on interior gypsum board.

Thermal control layer
Stud bay cavity insulation.

Figure 4.3: Wood Frame Assembly With Interior Cavity Insulation and Brick or Stone Veneer

Applicability
OK: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Very cold and subarctic/arctic regions
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall is a variation of Figure 4.2. As in Figure 4.2, this wall is a flow through assembly: it can dry to both the exterior and the interior.

Drainage cavity
Exterior brick veneer (a "reservoir" cladding) must be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints.

Air control layer
Interior gypsum board, exterior gypsum board/structural sheathing, or exterior building wrap (water control layer).

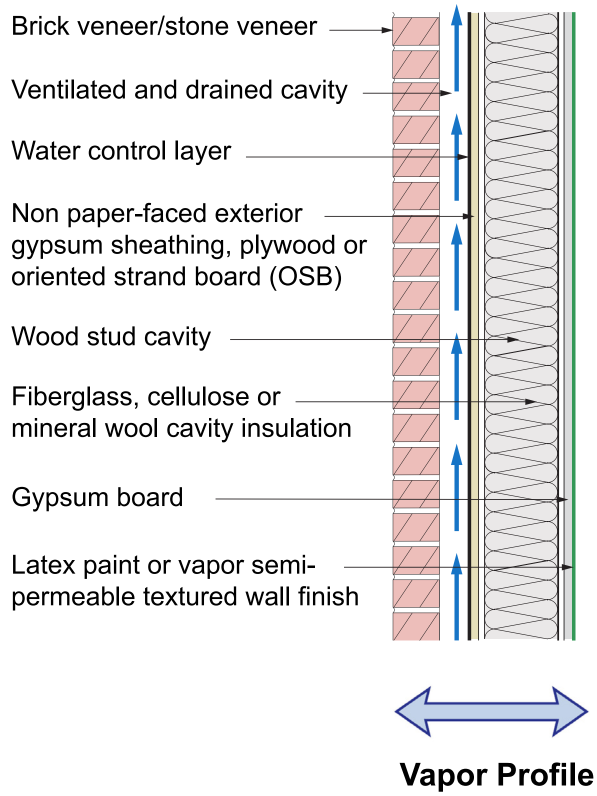


Figure 4.3: Wood Frame Assembly With Interior Cavity Insulation and Brick or Stone Veneer

Vapor control layer
No specific vapor control layer. Controls vapor flow by allowing vapor transfer in both directions. Interior vapor control Class III latex paint on interior gypsum board.

Thermal control layer
Stud bay cavity insulation.

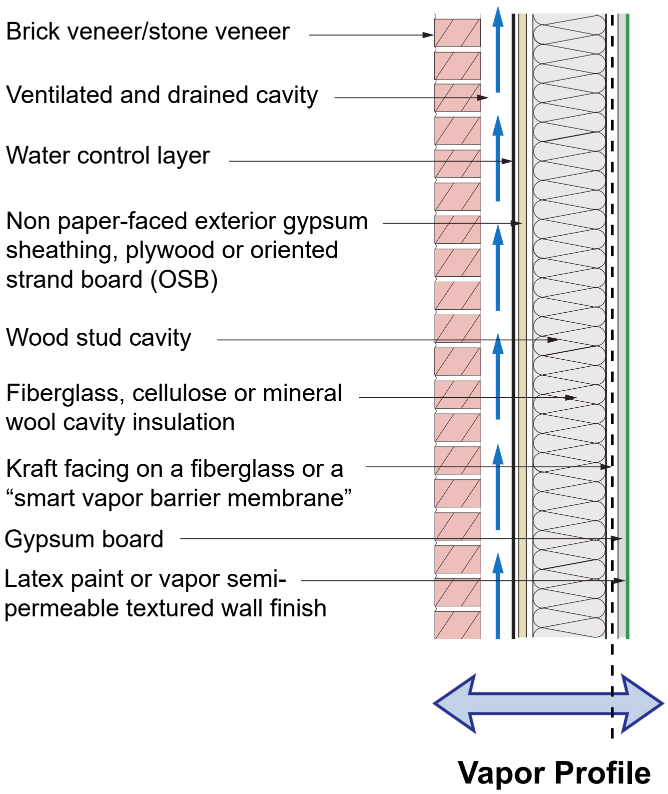


Figure 4.4: Wood Frame Assembly With Interior Cavity Insulation and Brick or Stone Veneer With an Interior Vapor Control Layer

Figure 4.4: Wood Frame Assembly With Interior Cavity Insulation and Brick or Stone Veneer With an Interior Vapor Control Layer

Applicability

OK: cold and very cold regions
NO: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and subarctic/arctic regions
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description

This wall is a variation of Figure 4.2 and Figure 4.3 except it has an interior vapor control layer – a Class II vapor control layer on the interior limiting its inward drying – but not eliminating it. It still considered a flow through assembly – it can dry to both the exterior and the interior.

Drainage cavity

Exterior brick veneer (a “reservoir” cladding) must be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets (“weep holes”) at its base and air outlets (“weep holes”) at its top in order to provide back ventilation of the brick veneer.

Water control layer

Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints.

Air control layer

Interior gypsum board, exterior gypsum board/structural sheathing, or exterior building wrap (water control layer).

Vapor control layer

Class II vapor control layer (not Class I/ polyethylene or foil). Examples include Kraft facer on the cavity batt insulation or a Class II membrane on the interior side of the framing.

Thermal control layer

Stud bay cavity insulation.

Figure 4.5: Wood Frame Assembly With Interior Cavity Insulation and Brick or Stone Veneer With an Interior Vapor Control Layer.

Applicability
OK: very cold, subarctic and arctic regions.
NO: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall is a further variation of Figure 4.4, but now it has a Class I vapor control layer on the interior (a "vapor barrier") completely eliminating any inward drying. This assembly is considered the "classic" cold climate wall assembly.

Drainage cavity
Exterior brick veneer (a "reservoir" cladding) must be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints.

Air control layer
Interior polyethylene, interior gypsum board, exterior gypsum board/structural sheathing, or exterior building wrap (water control layer).

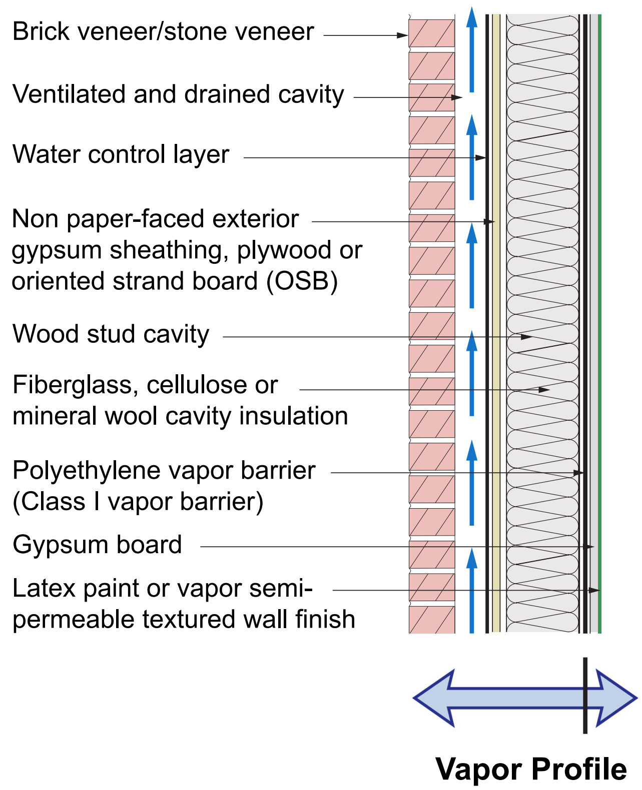
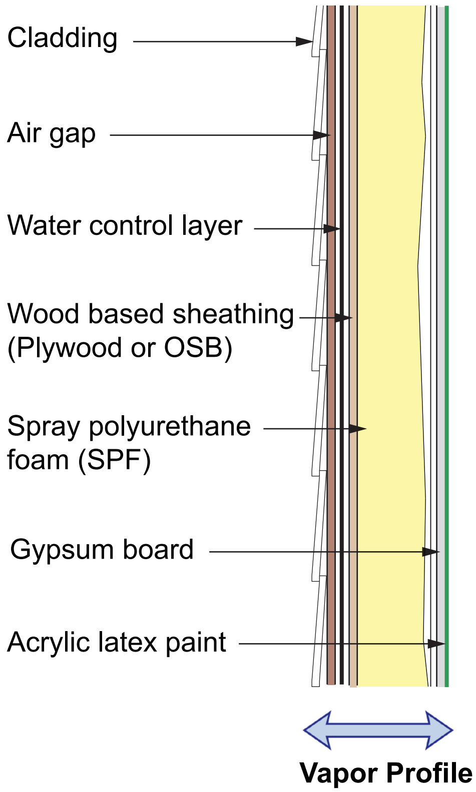


Figure 4.5: Wood Frame Assembly With Interior Cavity Insulation and Brick or Stone Veneer With an Interior Vapor Control Layer**.**

Vapor control layer
Class I interior polyethylene on framing.

Thermal control layer
Stud bay cavity insulation.



Notes: High density closed cell foam can be used in al IECC Climate Zones. Low density open cell foam can be used in IECC Clmate Zones 1 through 4 without an interior vapor retarder

Figure 4.6: Wood Frame Assembly with Interior Spray Foam Cavity Insulation

Figure 4.6: Wood Frame Assembly With Interior Spray Foam Cavity Insulation and Siding

Applicability
OK: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Very cold and subarctic/arctic regions.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
The spray foam insulation can be low density open cell or high density closed cell spray foam. Both foam types work in most climates.

Drainage cavity
The exterior siding should be uncoupled from the wall assembly with a ventilated and drained cavity. The air gap behind the cladding can be provided by using a textured housewrap, a drainage mat, or furring strips at least 3/16 inch thick.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints. The water control layer in this type of wall should not be a vapor barrier – it should be semi vapor permeable.

Air control layer
Stud bay cavity polyurethane spray foam insulation.

Vapor control layer
If high density closed cell spray foam, vapor control layer is spray polyurethane foam.
If low density open cell spray foam, flow through assembly (controls vapor flow by allowing vapor transfer in both directions).

Interior vapor control Class III latex paint on interior gypsum board. Interior vapor barrier coatings on the gypsum board such as vinyl wallcoverings, oil or alkyd paints should be avoided.

Thermal control layer
Stud bay cavity polyurethane spray foam insulation.

Figure 4.7: Wood Frame Assembly With Interior Spray Foam Cavity Insulation and Siding

Applicability
OK: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Very cold and subarctic/arctic regions.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
Figure 4.7 is a variation of Figure 4.6, where high density closed cell spray polyurethane foam (air-impermeable insulation) is installed on the interior surface of the exterior sheathing. Then, the remainder of the cavity is filled with fiberglass/cellulose/mineral fiber insulation (air-permeable insulation). The thickness or thermal resistance of the spray foam is based on climate zone and thickness of the wall framing (Table 3.1).

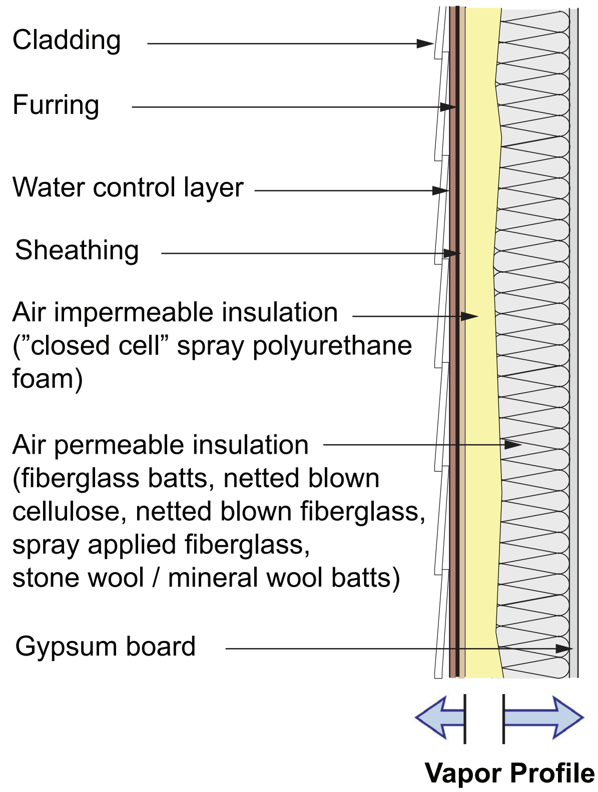


Figure 4.7: Wood Frame Assembly With Interior Spray Foam Cavity Insulation and Siding

Drainage cavity
The exterior siding should be uncoupled from the wall assembly with a ventilated and drained cavity. The air gap behind the cladding can be provided by using a textured housewrap, a drainage mat, or furring strips at least 3/16 inch thick.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints. The water control layer in this type of wall should not be a vapor barrier – it should be semi vapor permeable.

Air control layer
Stud bay cavity polyurethane spray foam insulation.
Vapor control layer
Spray polyurethane foam in stud bay cavities.

Thermal control layer
Stud bay cavity polyurethane spray foam insulation and fiberglass/cellulose/mineral fiber.

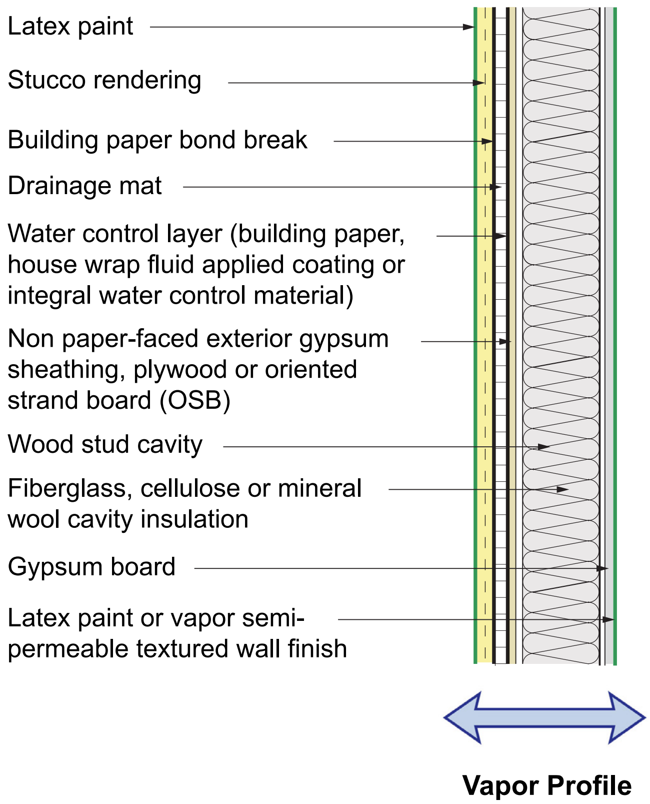


Figure 4.8: Wood Frame Assembly With Interior Cavity Insulation and Stucco

Figure 4.8: Wood Frame Assembly With Interior Cavity Insulation and Stucco

Applicability
OK: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Very cold and subarctic/arctic regions.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall is also a flow through assembly similar to Figure 4.3, but without the brick veneer – it has a stucco cladding. It can dry to both the exterior and the interior.

Drainage cavity
This wall assembly must have a drainage space between the stucco rendering and the water control layer. This can be accomplished by installing a drainage mat. Alternately, a textured or profiled water control layer (building wrap) can be used.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints

Air control layer
Interior gypsum board, exterior stucco rendering, exterior gypsum board/ structural sheathing, or exterior building wrap (water control layer).

Vapor control layer
No specific vapor control layer. Controls vapor flow by allowing vapor transfer in both directions. Interior vapor control Class III latex paint on interior gypsum board.

Thermal control layer
Stud bay cavity insulation.

Figure 4.9: Wood Frame Assembly With Interior Cavity Insulation and Stucco With an Interior Vapor Control Layer

Applicability
OK: cold and very cold regions
NO: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and subarctic/arctic regions
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall is a variation of Figure 4.8 except it has an interior vapor control layer - a Class II vapor control layer limiting inward drying – but not eliminating it. It still considered a flow through assembly – it can dry to both the exterior and the interior.

Drainage cavity
This wall assembly must have a drainage space between the stucco rendering and the water control layer. This can be accomplished by installing a drainage mat. Alternatively, a textured or profiled water control layer (building wrap) can be used.

Water control layer
Mechanically fastened membrane (building paper or building wrap), vapor-permeable self-adhered membrane, fluid-applied membrane, or integral surface of the sheathing with taped joints.

Air control layer
Interior gypsum board, exterior gypsum board/structural sheathing, or exterior building wrap (water control layer).

Vapor control layer
Class II vapor control layer (not Class I/ polyethylene or foil). Examples include Kraft facer on the cavity batt insulation or a Class II membrane on the interior side of the framing.

Thermal control layer
Stud bay cavity insulation.

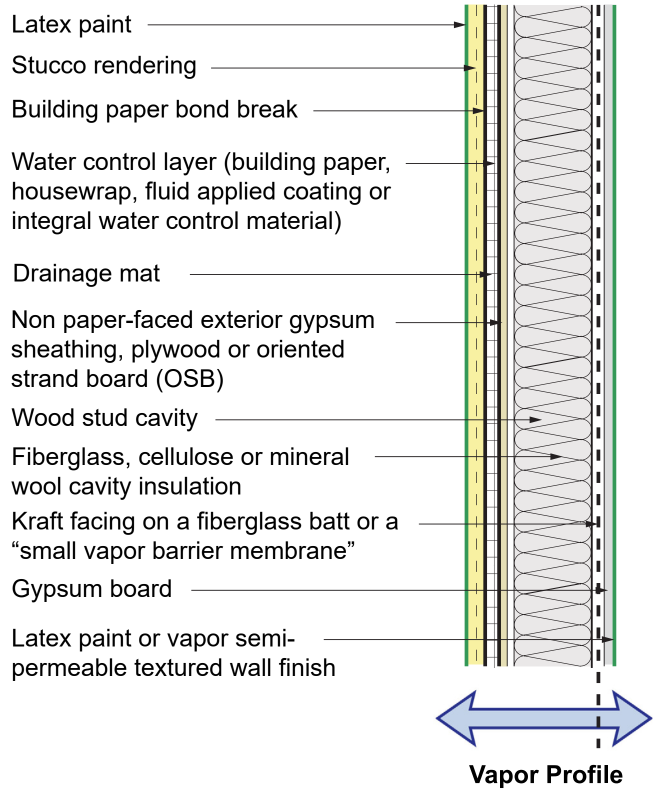


Figure 4.9: Wood Frame Assembly With Interior Cavity Insulation and Stucco With an Interior Vapor Control Layer

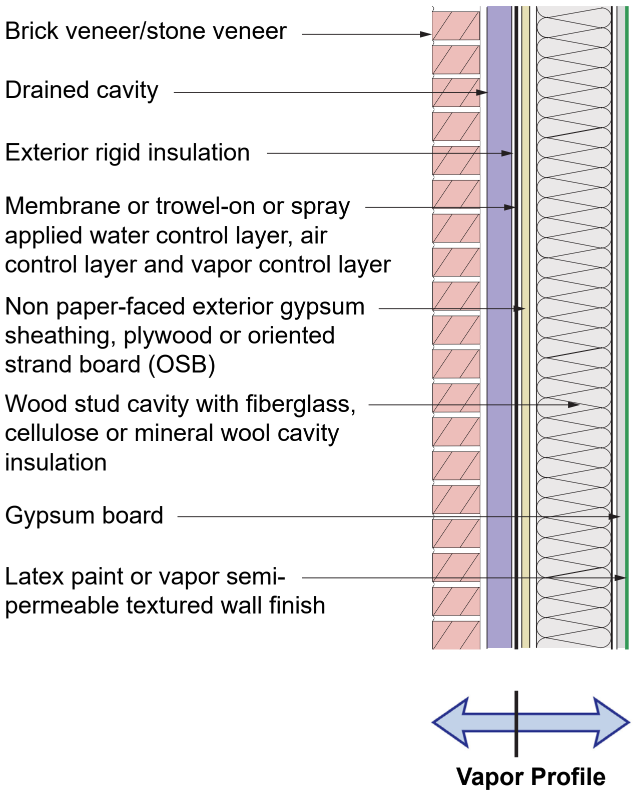


Figure 4.10: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and No Interior Vapor Control Layer

Figure 4.10: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and No Interior Vapor Control Layer

Applicability

OK: All hygro-thermal regions, all rain exposure zones and interior climate classes I and II.

NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description

This wall has a combined air/vapor/water control layer at the exterior sheathing, inboard of continuous exterior insulation. The sheathing can be non-paper-faced exterior gypsum, plywood, fiberboard, or oriented strand board. This wall assembly will dry from the vapor control layer inwards and will dry from the vapor control layer outwards.

Drainage cavity

Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer. Alternately, in milder or lower-rainfall climates, a ¼ inch drainage mat or drainable insulation can be substituted for the 1 inch air cavity. This option should not be used in IECC Climate Zone 5 and higher, with rainfall over 20 inches per year (due to freeze-thaw risks).

Exterior Insulation
Vapor impermeable (foil faced polyisocyanurate) or vapor semi-impermeable (extruded polystyrene) acceptable.

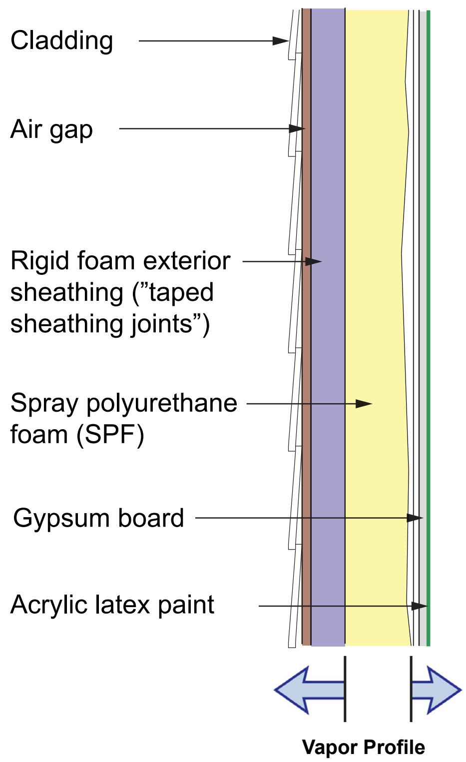
Water control layer
Combined air/vapor/water control layer at the exterior sheathing. Can be fully adhered sheet membrane, trowel-on or spray applied coating, mechanically attached sheet, or integral water control layer within the sheathing.

Air control layer
Combined air/vapor/water control layer at the exterior sheathing (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior sheathing (see above); vapor impermeable layer at exterior of wall.

Vapor Control Layer (Interior) and Condensation Control
In cold climates, condensation is limited on the interior side of the water/air control layer and vapor control layer by installing sufficient exterior thermal insulation on the exterior side of these control layers, and limiting the interior climate class to I and II. In hot-humid climates any moisture that condenses on the exterior side of the water control layer will be drained to the exterior. This assembly must allow inward drying; therefore, vapor impermeable and vapor semi impermeable interior finishes such as vinyl wall coverings, epoxy paints, and alkyd paints should be avoided. Interior finish is Class III latex paint on interior gypsum board. The thermal resistance of the exterior insulation to avoid condensation is specified in Table 3.1. This wall assembly is also limited to interior climate class I and II buildings.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.



Notes: High density closed cell foam can be used in all IECC Climate Zones. Where Low density open cell foam can be used the thckness or thermal resistance of the rigid foam exterior sheathing is specified by the international Residential Code (IRC) base on Climate Zone and the thickness of the wall framing.

Figure 4.11: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation and Siding

Figure 4.11: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation and Siding

Applicability
OK: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and cold regions
NO: Very cold and subarctic/arctic regions.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
The cavity insulation in this wall assembly is spray polyurethane foam, and is a variation of Figure 4.6. The spray foam insulation can be low density open cell or high density closed cell spray foam. Both foam types work in most climates.

Drainage cavity
The exterior siding should be uncoupled from the wall assembly with a ventilated and drained cavity. The air gap behind the cladding can be provided by using a textured housewrap, a drainage mat, or furring strips at least 3/16 inch thick. If a housewrap is used to create this air gap, it should be semi vapor permeable (i.e., not be a vapor barrier).

Exterior Insulation
Vapor impermeable (foil-faced poly-isocyanurate) or vapor semi-impermeable (extruded polystyrene) acceptable.

Water control layer
Taped joints of the exterior rigid insulation (typical).

Air control layer
Spray polyurethane foam in stud bay cavities.

Vapor control layer
If high density closed cell spray foam, vapor control layer is spray polyurethane foam.

If low density open cell spray foam, vapor control is provided by controlling the temperature of the condensing surface, as a result of installing exterior thermal insulation of sufficient thermal resistance as well as by limiting the interior climate class to I and II. With low density open cell spray foam, the thickness (thermal resistance) of the rigid foam exterior sheathing is based on climate zone and thickness of the wall framing (Table 3.1).

Interior vapor barrier coatings on the gypsum board such as vinyl wallcoverings, oil or alkyd paints should be avoided.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

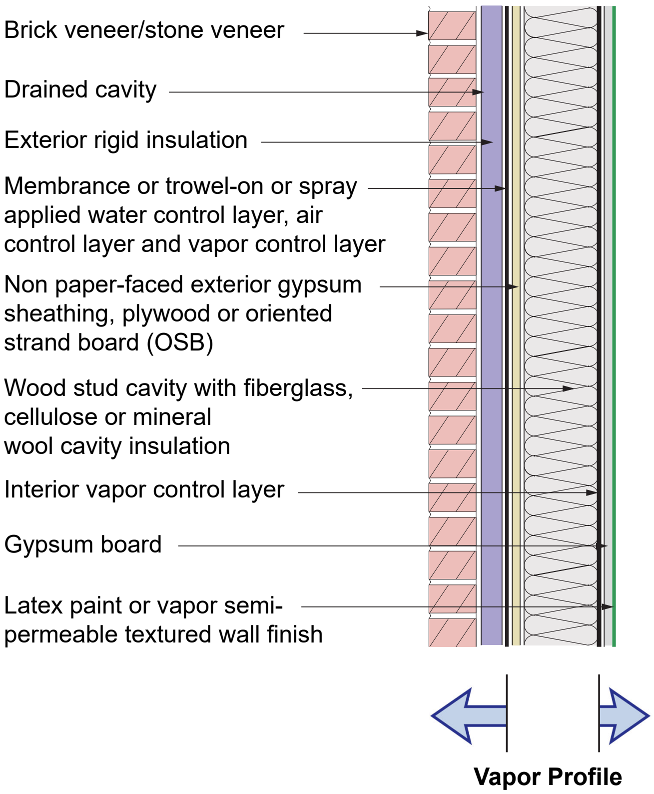


Figure 4.12: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and an Interior Vapor Control Layer

Figure 4.12: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and an Interior Vapor Control Layer

Applicability

OK: cold and very cold regions
NO: hot-dry, hot-humid, mixed-dry, mixed-humid, marine, and subarctic/arctic regions
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description

This wall is a variation of Figure 4.10, but with an interior vapor control layer. This wall has a combined air/vapor/water control layer at the exterior sheathing, inboard of continuous exterior insulation. The sheathing can be non-paper-faced exterior gypsum, plywood, fiberboard, or oriented strand board. This wall assembly will dry from the vapor control layer inwards and will dry from the vapor control layer outwards.

Drainage cavity

Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Exterior Insulation
Vapor impermeable (foil-faced poly-isocyanurate) or vapor semi-impermeable (extruded polystyrene) acceptable.

Water control layer
Combined air/vapor/water control layer at the exterior sheathing. Can be fully adhered sheet membrane, trowel-on or spray applied coating, mechanically attached sheet, or integral water control layer within the sheathing.

Air control layer
Combined air/vapor/water control layer at the exterior sheathing (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior sheathing (see above); vapor impermeable layer at exterior of wall.

Vapor Control Layer (Interior) and Condensation Control
This wall assembly has an interior vapor control layer ; therefore, the wall assembly cannot dry to the interior. Nor can this wall assembly dry to the exterior. Therefore, this wall assembly is limited to interior climate class I and II buildings, and is limited to cold, very cold and colder hygro-thermal regions.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

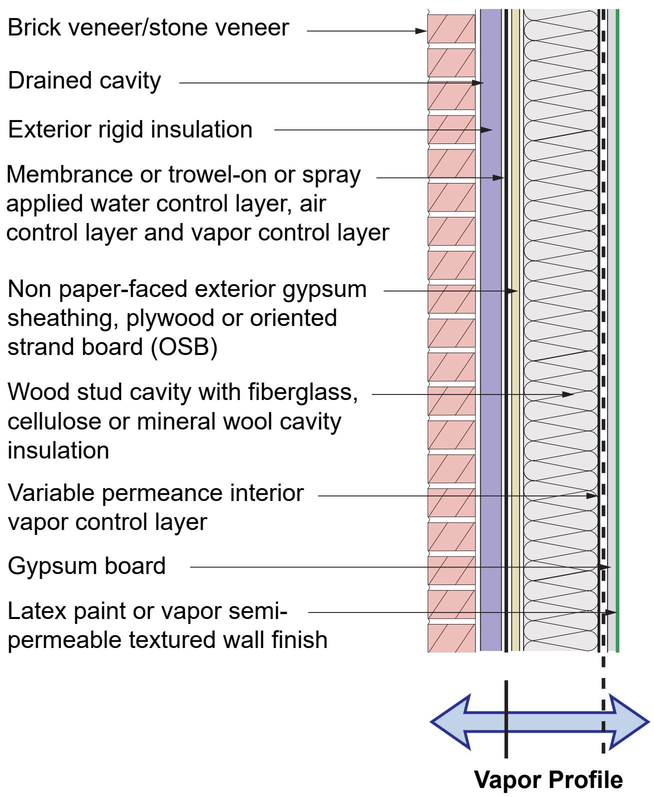


Figure 4.13: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and a Variable Permeance Interior Vapor Control Layer or Kraft Faced Cavity Insulation

Figure 4.13: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and a Variable Permeance Interior Vapor Control Layer or Kraft Faced Cavity Insulation

Applicability

OK: Marine, Cold, Very Cold, and colder hygro-thermal regions

OK: All rain exposure zones and interior climate classes I and II.

NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description

This wall is a variation of Figure 4.12, but with a variable permeance vapor control layer or kraft faced batt insulation (also a variable permeance vapor control layer). This wall is designed to dry to the interior. The sheathing can be non-paper-faced exterior gypsum, plywood, fiberboard, or oriented strand board.

Drainage cavity

Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Exterior Insulation

Vapor impermeable (foil-faced poly-isocyanurate) or vapor semi-impermeable (extruded polystyrene) acceptable.

Water control layer
Combined air/vapor/water control layer at the exterior sheathing. Can be fully adhered sheet membrane, trowel-on or spray applied coating, mechanically attached sheet, or integral water control layer within the sheathing.

Air control layer
Combined air/vapor/water control layer at the exterior sheathing (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior sheathing (see above); vapor impermeable layer at exterior of wall.

Vapor Control Layer (Interior) and Condensation Control
This wall assembly has a variable permeance vapor control layer or kraft-faced batt insulation (also a variable permeance vapor control layer). This layer changes its vapor transmission based on interior relative humidity. It therefore allows inward drying during the summer months, or if the wall cavity becomes wet from exterior sources. Even with inward drying, this wall assembly should be limited to interior climate class I and II buildings. Despite the effectiveness of the variable permeance interior vapor control layer, this wall assembly should still be limited to marine, cold, very cold, and colder hygro-thermal regions.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

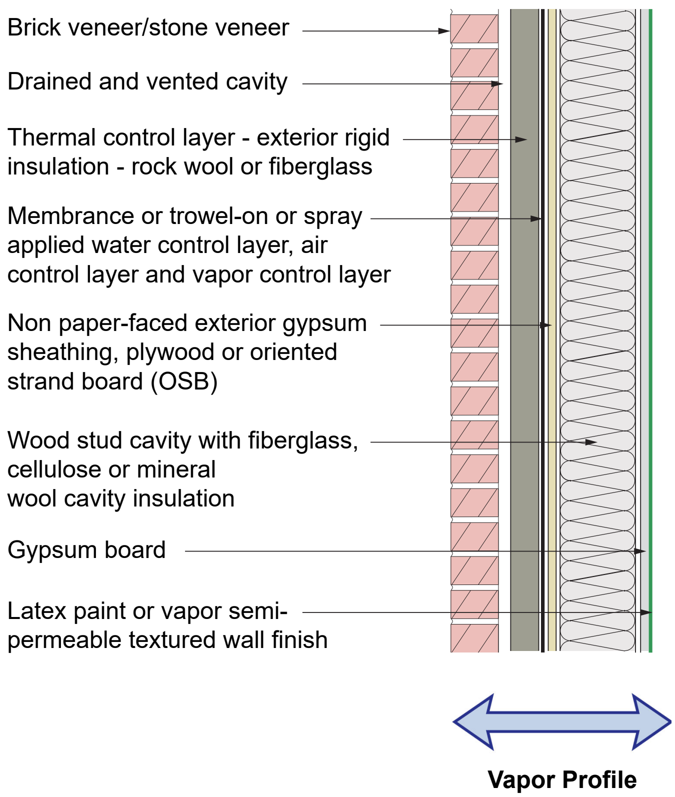


Figure 4.14: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and No Interior Vapor Control Layer

Figure 4.14: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and No Interior Vapor Control Layer

Applicability
OK: All hygro-thermal regions
OK: All rain exposure zones and interior climate classes I and II.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall assembly is a flow through assembly that can dry in both directions. The sheathing can be non-paper-faced exterior gypsum, plywood, fiberboard, or oriented strand board.

Drainage cavity
Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer. Alternately, in milder or lower-rainfall climates, a ¼ inch drainage mat or drainable insulation can be substituted for the 1 inch air cavity. This option should not be used in IECC Climate Zone 5 and higher, with rainfall over 20 inches per year (due to freeze-thaw risks).

Exterior Insulation
Vapor permeable (mineral wool or rigid fiberglass insulation) required.

Water control layer
Combined air/vapor/water control layer at the exterior sheathing. Can be fully adhered sheet membrane, trowel-on or spray applied coating, mechanically attached sheet, or integral water control layer within the sheathing.

Air control layer
Combined air/vapor/water control layer at the exterior sheathing (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior sheathing (see above). The vapor control layer is vapor permeable. Where the annual average rainfall exceeds 20 inches and a reservoir cladding such as brick or stone veneer is used, the vapor control layer should be vapor semi permeable (or less in permeance) to control inward vapor drive.

Vapor Control Layer (Interior) and Condensation Control
This wall assembly does not have an interior vapor control layer (Class III latex paint only); therefore, the thermal resistance of the exterior insulation to avoid condensation is specified in Table 3.1. This wall assembly is also limited to interior climate class I and II buildings.

This assembly can dry inwards – therefore vapor impermeable and vapor semi impermeable interior finishes such as vinyl wall coverings, epoxy paints, and alkyd paints should be avoided.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

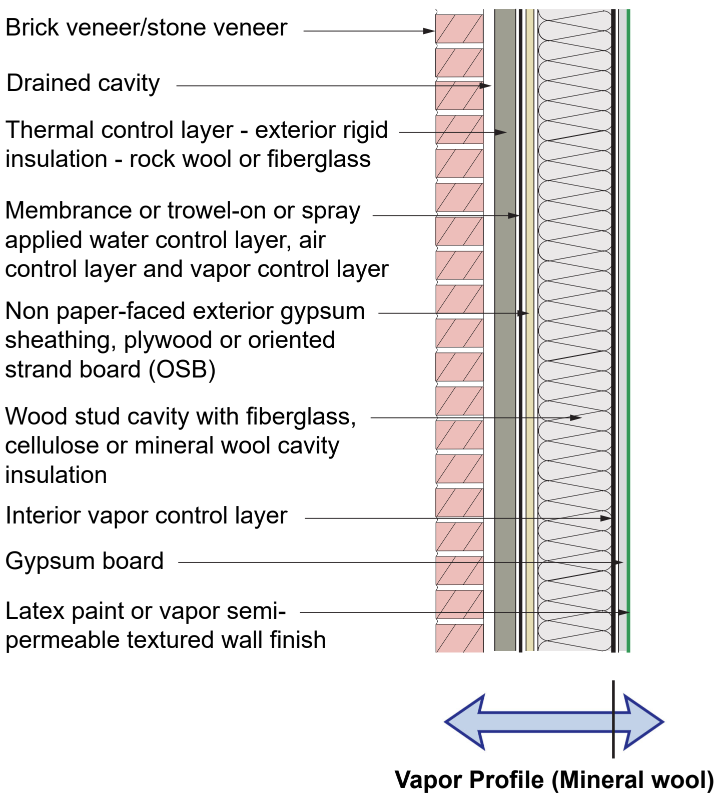


Figure 4.15: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and an Interior Vapor Control Layer

Figure 4.15: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and an Interior Vapor Control Layer

Applicability
OK: Marine, Cold, Very Cold, and colder hygro-thermal regions
OK: All rain exposure zones and interior climate classes I and II.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This wall is a variation of Figure 4.14, but with an interior vapor control layer. The sheathing can be non-paper-faced exterior gypsum, plywood, fiberboard, or oriented strand board.

Drainage cavity
Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Exterior Insulation
Vapor permeable (mineral wool or rigid fiberglass insulation) required.

Water control layer
Combined air/vapor/water control layer at the exterior sheathing. Can be fully adhered sheet membrane, trowel-on or spray applied

coating, mechanically attached sheet, or integral water control layer within the sheathing.

Air control layer
Combined air/vapor/water control layer at the exterior sheathing (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior sheathing (see above). The vapor control layer is vapor permeable. Where the annual average rainfall exceeds 20 inches and a reservoir cladding such as brick or stone veneer is used, the vapor control layer should be vapor semi permeable (or less in permeance) to control inward vapor drive.

Vapor Control Layer (Interior) and Condensation Control
Although this wall assembly includes an interior vapor control layer , the recommended construction uses thermal resistance of exterior insulation to control condensation, as specified in Table 3.1. This wall assembly is also limited to interior climate class I and II buildings.

This wall assembly has an interior vapor control layer; therefore, the wall assembly cannot dry to the interior. However, this wall assembly can dry to the exterior. Because of the interior vapor control layer, this wall assembly should be limited to cold, very cold, and colder hygro-thermal regions.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

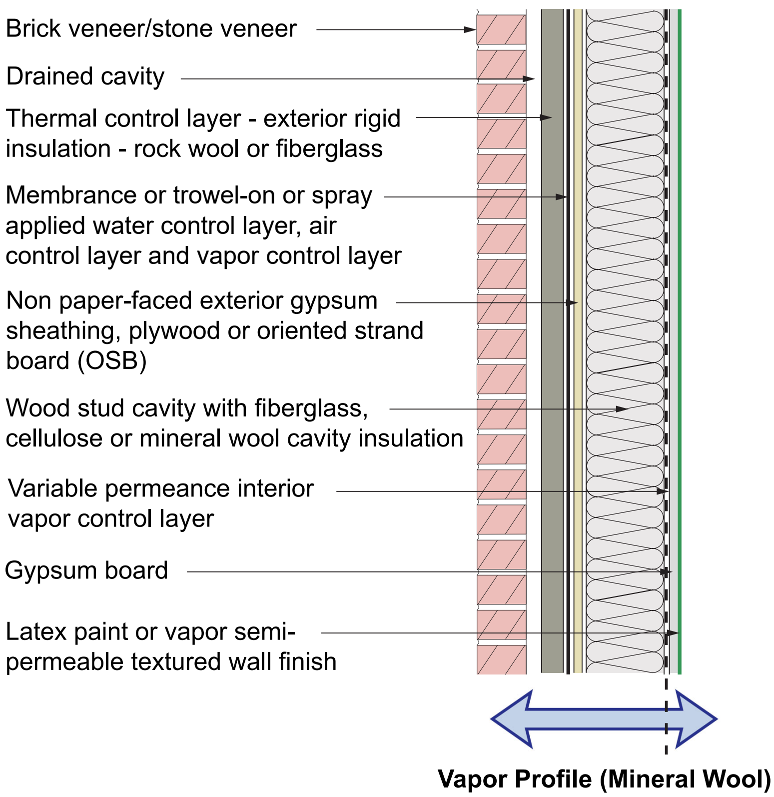


Figure 4.16: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and a Variable Permeance Interior Vapor Control Layer or Kraft Faced Cavity Insulation

Figure 4.16: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Brick or Stone Veneer and a Smart Interior Vapor Control Layer or Kraft Faced Cavity Insulation

Applicability

OK: Marine, Cold, Very Cold, and colder hygro-thermal regions

OK: All rain exposure zones and interior climate classes I and II.

NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description

This wall is a variation of Figure 4.15, but with a variable permeance vapor control layer or kraft faced batt insulation (also a variable permeance vapor control layer). This wall is designed to dry to the interior. The sheathing can be non-paper-faced exterior gypsum, plywood, fiberboard, or oriented strand board.

Drainage cavity

Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Exterior Insulation

Vapor permeable (mineral wool or rigid fiberglass insulation) required.

Water control layer
Combined air/vapor/water control layer at the exterior sheathing. Can be fully adhered sheet membrane, trowel-on or spray applied coating, mechanically attached sheet, or integral water control layer within the sheathing.

Air control layer
Combined air/vapor/water control layer at the exterior sheathing (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior sheathing (see above). The vapor control layer is vapor permeable. Where the annual average rainfall exceeds 20 inches and a reservoir cladding such as brick or stone veneer is used, the vapor control layer should be vapor semi permeable (or less in permeance) to control inward vapor drive.

Vapor Control Layer (Interior) and Condensation Control
This wall assembly has a variable permeance vapor control layer or kraft-faced batt insulation (also a variable permeancea vapor control layer). This layer changes its vapor transmission based on interior relative humidity. It therefore allows inward drying during the summer months, or if the wall cavity becomes wet from exterior sources. Even with inward drying, this wall assembly should be limited to interior climate class I and II buildings. Despite the effectiveness of the variable permeance interior vapor control layer, this wall assembly should still be limited to marine, cold, very cold, and colder hygro-thermal regions.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

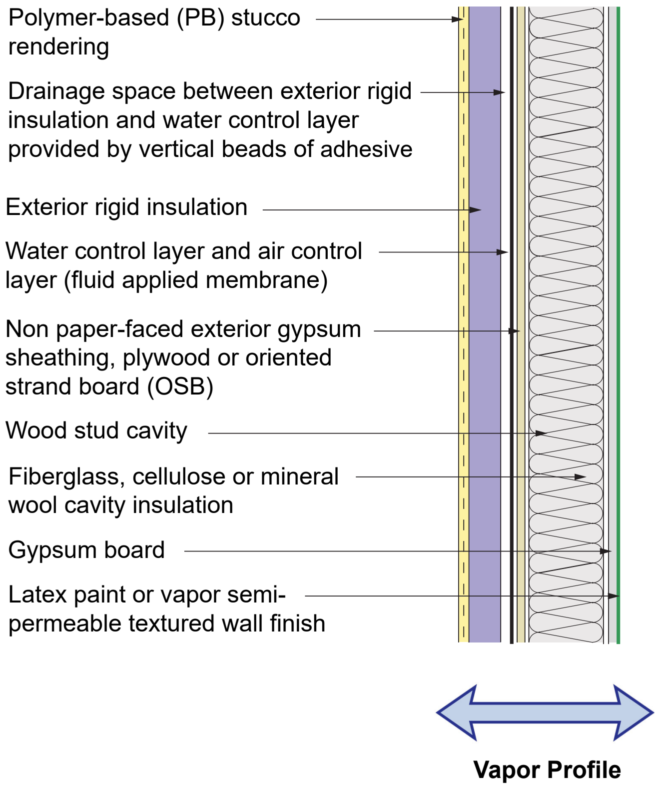


Figure 4.17: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Stucco

Figure 4.17: Wood Frame Assembly With Exterior Insulation and Interior Cavity Insulation With Synthetic Stucco (EIFS)

Applicability
OK: All hygro-thermal regions except subarctic/arctic
OK: All rain exposure zones and interior climate classes I and II.
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures.

Description
This is a water managed exterior insulation finish system (EIFS) wall. Unlike "face-sealed" EIFS, this wall has a water control layer inboard of the exterior stucco skin that is drained to the exterior. It is also a flow through assembly that can dry to both the exterior and the interior.

Drainage cavity
This wall assembly requires a drainage space between the exterior rigid insulation and the water control layer. This can be accomplished by installing vertical beads of adhesive to adhere the exterior rigid insulation to the sheathing.

Exterior Insulation
Vapor semi-permeable (expanded polystyrene/EPS) required.

Water control layer
Combined air/water control layer at the exterior sheathing; fluid applied membrane compatible with EIFS system adhesive.

Air control layer
Combined air/water control layer at the exterior sheathing (see above).

Vapor Control Layer (Interior) and Condensation Control
This wall assembly does not have an interior vapor control layer (Class III latex paint only); therefore, the thermal resistance of the exterior insulation to avoid condensation is specified in Table 3.1. This wall assembly is also limited to interior climate class I and II buildings. In hot-humid climates, any moisture that condenses on the exterior side of the water control layer will be drained to the exterior. This assembly can dry inwards – therefore vapor impermeable and vapor semi impermeable interior finishes such as vinyl wall coverings, epoxy paints, and alkyd paints should be avoided.

Thermal control layer
Stud bay cavity insulation and exterior rigid insulation.

Figure 4.18: Concrete Masonry Unit (CMU) With Exterior Insulation and Brick or Stone Veneer and Vapor Impermeable/Semi-Permeable Insulation

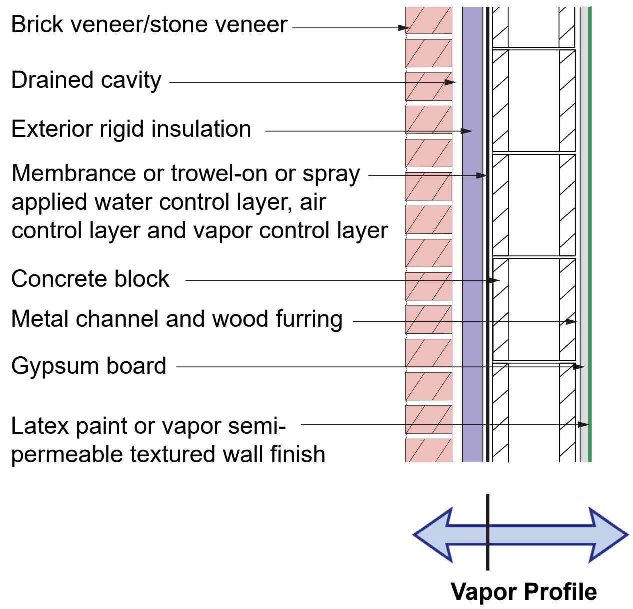


Figure 4.18: Concrete Masonry Unit (CMU) With Exterior Insulation and Brick or Stone Veneer

Applicability
OK: All hygro-thermal regions
OK: All rain exposure zones
OK: All interior climate (classes I, II, and III)

Description
This wall is an implementation of the 'perfect wall,' with all insulation outboard of the structure, and a combined air/vapor/water control layer at the CMU surface, inboard of continuous exterior insulation.

Drainage cavity
Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Exterior Insulation
Vapor impermeable (foil faced polyisocyanurate) or vapor semi-impermeable (extruded polystyrene) acceptable.

Water control layer
Combined air/vapor/water control layer at the exterior of CMU. Can be fully adhered sheet membrane or trowel-on or spray applied coating.

Air control layer
Combined air/vapor/water control layer at the exterior of CMU (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior of CMU (see above); vapor impermeable.

Vapor Control Layer (Interior) and Condensation Control
Interior latex paint (Class III) on interior finishes. In cold climates, condensation is limited on the interior side of the air/water/vapor control layer by installing all of the thermal insulation on the exterior side of these control layers. In hot-humid climates, any moisture that condenses on the exterior side of the air/water control layer will be drained to the exterior. This wall assembly will dry from the vapor control layer inwards and will dry from the vapor control layer outwards.

Thermal control layer
Continuous exterior rigid insulation

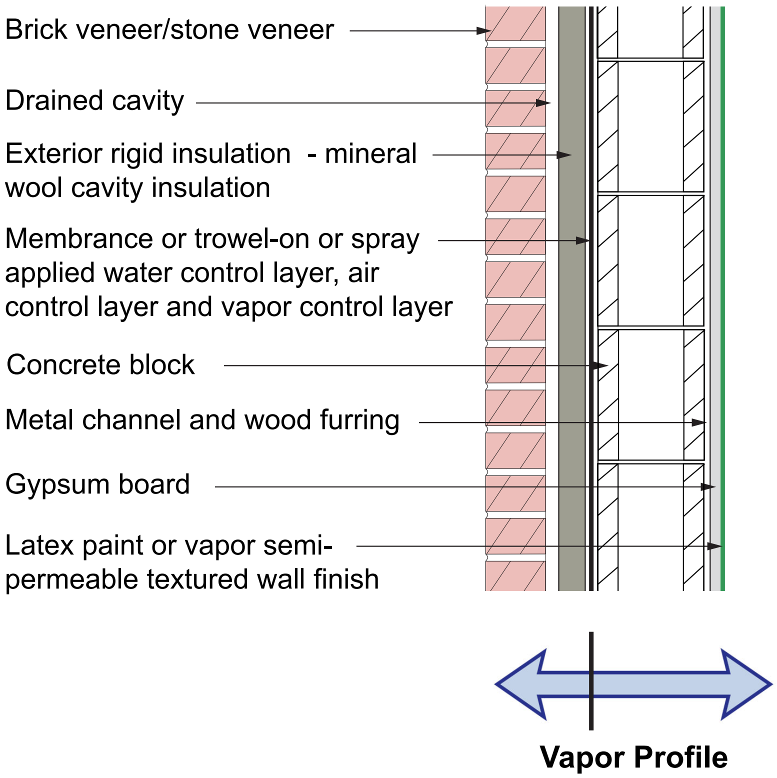


Figure 4.19: Concrete Masonry Unit (CMU) With Exterior Insulation and Brick or Stone Veneer

Figure 4.19: Concrete Masonry Unit (CMU) With Exterior Insulation and Brick or Stone Veneer and Vapor Permeable Insulation

Applicability
OK: All hygro-thermal regions
OK: All rain exposure zones
OK: All interior climate (classes I, II, and III)

Description
This wall is an implementation of the 'perfect wall,' with all insulation outboard of the structure, and a combined air/vapor/water control layer at the CMU surface, inboard of continuous exterior insulation.

Drainage cavity
Hydrostatic pressure is controlled by providing a drainage space behind the cladding. The ideal solution is to decouple the exterior brick veneer (a "reservoir" cladding) from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 1 inch wide and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer.

Exterior Insulation
Vapor permeable (mineral wool or rigid fiberglass insulation) required.

Water control layer
Combined air/vapor/water control layer at the exterior of CMU. Can be fully adhered sheet membrane or trowel-on or spray applied coating.

Air control layer
Combined air/vapor/water control layer at the exterior of CMU (see above).

Vapor control layer (Exterior)
Combined air/vapor/water control layer at the exterior of CMU (see above). The vapor control layer can either be vapor impermeable or vapor permeable. Where the annual average rainfall exceeds 20 inches and a reservoir cladding such as brick or stone veneer is used, the vapor control layer should be vapor semi permeable (or less in permeance) to control inward vapor drive.

Vapor Control Layer (Interior) and Condensation Control
Interior latex paint (Class III) on interior finishes. In cold climates, condensation is limited on the interior side of the air/water/vapor control layer by installing all of the thermal insulation on the exterior side of these control layers. In hot-humid climates, any moisture that condenses on the exterior side of the air/water control layer will be drained to the exterior. This wall assembly will dry from the vapor control layer inwards and will dry from the vapor control layer outwards. If a vapor permeable vapor control layer is used coupled with mineral wool insulation through wall vapor flow occurs – the wall assembly dries in both directions depending on the moisture gradient.

Thermal control layer
Continuous exterior rigid insulation.

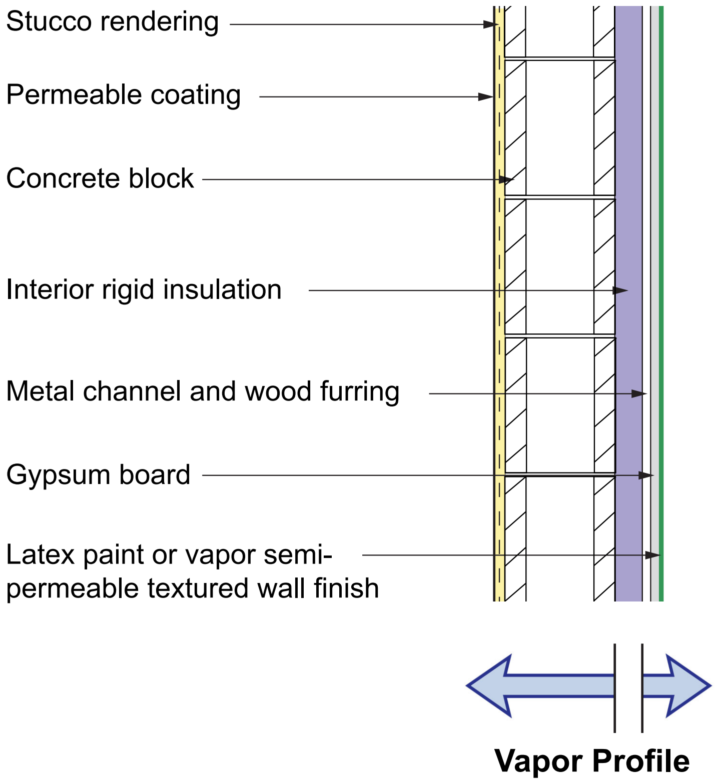


Figure 4.20: Concrete Masonry Unit (CMU) With Interior Rigid Insulation and Stucco

Figure 4.20: Concrete Masonry Unit (CMU) With Interior Rigid Insulation and Stucco

Applicability
OK: All hygro-thermal regions except subarctic/arctic
OK: All rain exposure zones and interior climate classes I and II
OK: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures in hot-dry, hot-humid, and mixed-dry hygro-thermal regions
NO: Interior climate class III buildings such as hospitals, museums, and swimming pool enclosures in all other hygro-thermal regions

Description
This wall has continuous rigid insulation on the inboard side of the CMU wall. This wall assembly therefore has all of the thermal insulation installed to the interior of the water, air, and vapor control layers. This wall assembly will dry from the vapor control layer inwards and will dry from the vapor control layer outwards.

Drainage cavity
n/a

Exterior Insulation
n/a

Water control layer
Painted stucco rendering on CMU. The CMU wall behaves as a "mass wall," storing moisture during rain events, then drying during more favorable periods.

Air control layer
Painted stucco rendering on CMU.

Vapor Control Layer and Condensation Control

Extruded polystyrene insulation (XPS) inboard of CMU wall. The thermal insulation is not air permeable and is vapor semi impermeable. Therefore, it can also be used in marine, cold regions or colder with the limitation of interior climate class I and II buildings.

Thermal control layer

Continuous interior rigid insulation; extruded polystyrene insulation (XPS) inboard of CMU wall.

CHAPTER 5

Roof Assemblies

Attics or roofs can be designed and constructed to be either vented or unvented in any hygro-thermal zone (**Figure 1.1** and **Figure 1.3**). The choice of venting or not venting is a design and construction choice not a requirement determined by physics or by the building code. The model codes allow both vented and unvented roof assemblies. The applicable physics impacts the design of attic or roof systems as does the applicable building code but neither limit the choice.

Attics or roofs can be insulated on the top of ceilings or attic floors. Additionally, attics or roofs can be insulated on the top of a roof deck, on the bottom of a roof deck or both on the top and bottom of a roof deck. Insulation added on the top of ceilings or attic floors or on the top of a roof deck can be vapor impermeable or vapor permeable. Insulation added on the top of ceilings or attic floors or the bottom of a roof deck can be air impermeable, air permeable, or a combination of both. Insulation added on both the top and bottom of a roof deck can be a combination of all the above.

In cold climates, the primary purpose of attic or roof ventilation is to maintain a cold roof temperature to control ice dams created by melting snow, and to vent moisture that moves from the conditioned space to the attic. Heat loss from the conditioned space to the attic is due to a combination of air leakage and conductive losses. The air leakage is due to exfiltration from the conditioned space (often because a ceiling air barrier is not present) leaky supply ductwork, often because ductwork located in attics is not sealed; and from penetrations like non-airtight recessed lights. The conductive losses are usually from supply ductwork and equipment located in attic spaces above ceiling insulation (ductwork is typically insulated only to R-6 – whereas ceiling insulation levels are above R-30). Conductive losses also occur directly through insulation, or where insulation is damaged, missing or thin.

In hot climates, the primary purpose of attic or roof ventilation is to expel solar-heated hot air from the attic to lessen the building cooling load. The amount of attic cavity ventilation is specified by numerous ratios of free vent area to insulated ceiling area ranging from 1:150 to 1:600 depending on building code version with the 1:300 ratio being the most common.

Control of moisture accumulation, heat gain, and to a lesser extent ice dams can also be successfully addressed by unvented attic or roof design.

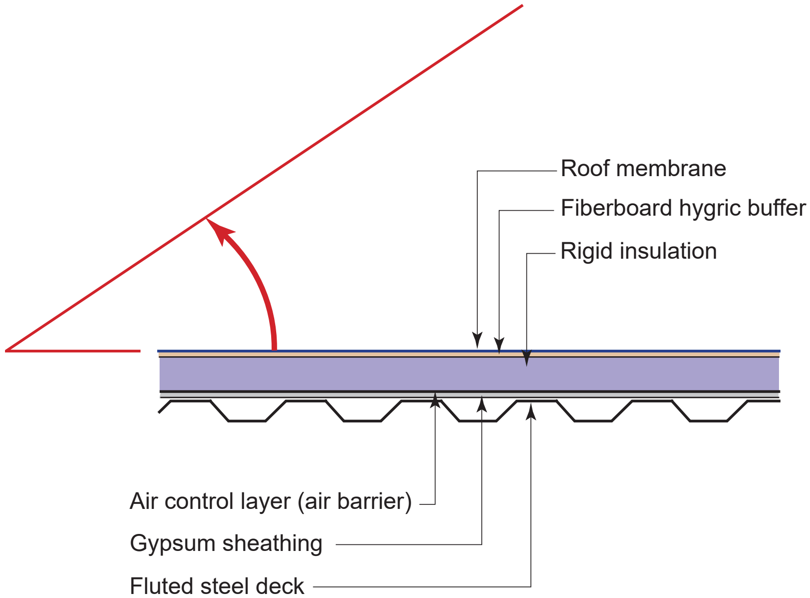


Figure 5.1: Unvented Roof – Standard commercial compact roof design

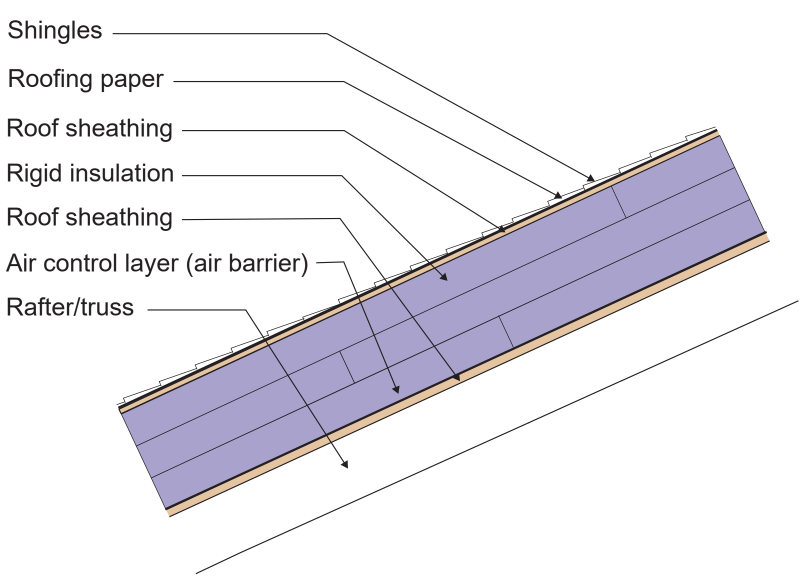


Figure 5.2: Unvented Roof – Sloping roof with all insulation located above the roof deck.

Vented vs Unvented

The most robust design approach is the first method developed historically. Place all the insulation on the top of the roof deck in an unvented configuration, an approach that is common in standard commercial compact roof design. This approach can be applied to sloping roofs not just flat roofs (**Figure 5.1**). In most hygro-thermal regions an air control layer ("air barrier") is necessary in compact roofs under the roof insulation ("Air barrier membrane" in **Figure 5.1**). Historically, air control layers were typically limited to cold climates but with the trend to white roofs in mixed climates such roofs no longer get hot enough to drive interior moisture that migrates upwards during the winter back downward into the conditioned space. As such, air leakage from the interior into the assemblies from the underside must be controlled. Air control layers also are significant in controlling wind uplift.

The principles of standard commercial compact roof design applied to residential construction yields **Figure 5.2**. The key component is the air control layer on the roof deck. In **Figure 5.2** with traditional board sheathing the air control layer should be a fully adhered membrane. Sheet polyethylene does not work as an effective air control layer as it rips, tears, and punctures easily. If the roof deck is built with sheet goods such as plywood or OSB, there are three options. First, go with a fully adhered membrane as you would with traditional board sheathing. Second, apply a fluid applied coating. Third, select a sheet good system that allows you to tape the joints of the sheets to create the air control layer.

Ice dams need to be addressed if the assembly is located in a high snow load zone. A high snow load zone is defined here as a ground snow load of greater than 60 lbs/ft^2. Most model codes provide maps of ground snow loads. The most successful approach in addressing ice dams with unvented compact roof assemblies is to construct a vented "over-roof" over the top of the unvented "under-roof" (**Figure 5.3**). The roofing membrane on the top-side of the unvented "under-roof" should be vapor permeable. Alternatively, a taped plywood or OSB sheathing system that is semi vapor permeable can be used.

Traditional vented attic and roof construction has a long history of successful performance but it is not as robust as the unvented roof approach. However, it is significantly less expensive to construct. Historically, it is the dominant approach used in residential roof and attic construction.

The key to the performance of a vented attic and roof assembly, as in unvented compact roof design, is an air control layer. As the complexity of attic and roof assemblies increases, the difficulty in constructing vented assemblies with an effective air control layer also increases. The more complex a roof geometry, the easier it is to construct the assembly in an unvented conditioned manner. With complex roof designs, multiple dormers, valleys, hips, skylights combined with cathedral construction with interior soffits, tray ceilings, and multiple service penetrations it is often not practical to construct a vented roof assembly with an airtight interior air control layer ("air barrier") at the ceiling plane.

Additionally, it is more common to locate mechanical systems and ductwork in attic spaces. When such ductwork is leaky significant problems can occur (**Figure 5.4**). There are significant energy and durability

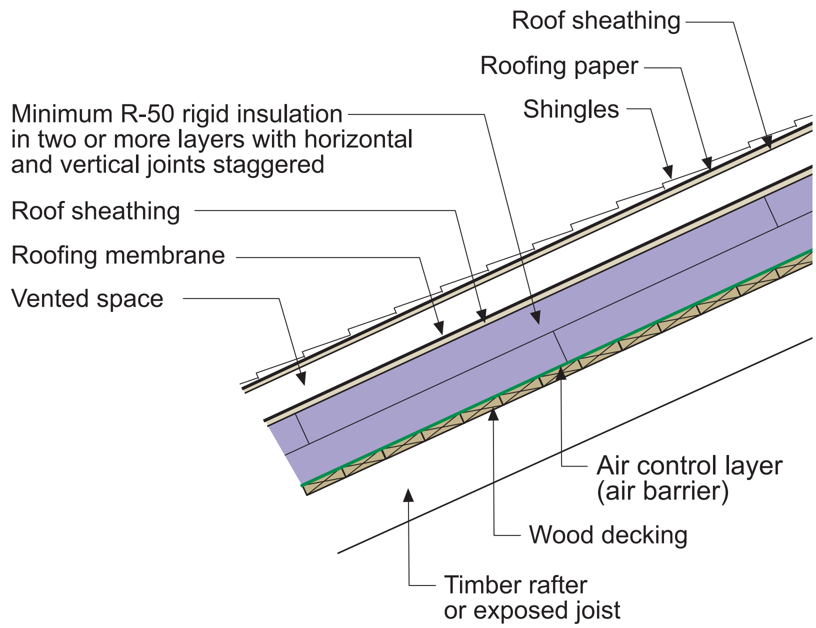


Figure 5.3: Unvented Roof – Vented over-roof constructed over unvented under-roof.

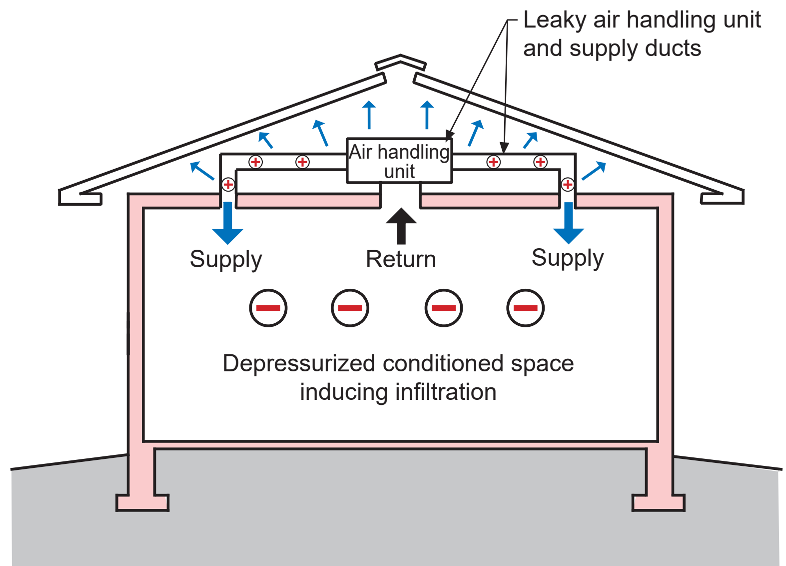


Figure 5.4: Vented Attic – Mechanical system and leaky ductwork located in vented attic space.

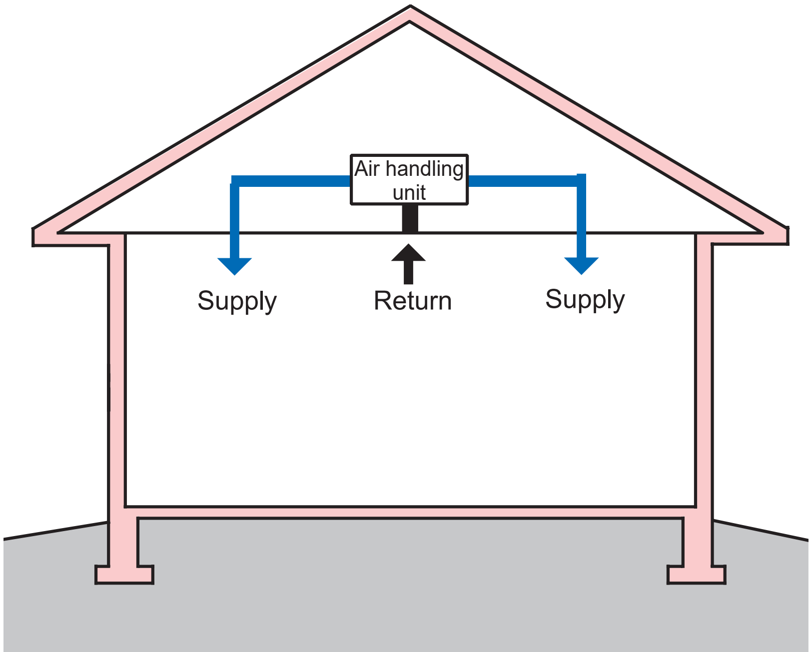


Figure 5.5

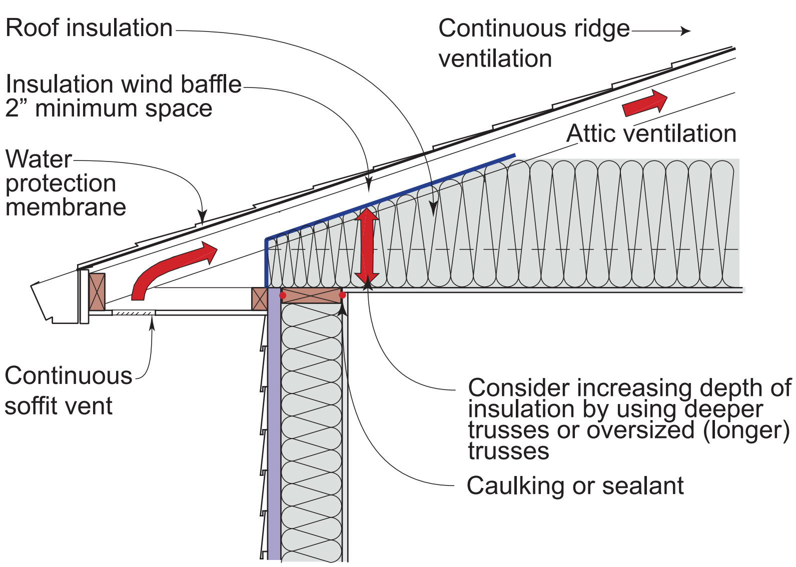


Figure 5.6: Vented Attic – Optimum design where no services such as HVAC distribution ducts, air handlers, plumbing or fire sprinkler systems should be located external to the air control layer.

advantages to move the thermal boundary and pressure boundary (air control layer or "air barrier") to the underside of the roof deck thereby locating these mechanical systems and ductwork within the building conditioned spaces (**Figure 5.5**).

In high wind regions – particularly in coastal areas, wind-driven rain is a problem with vented roof assemblies. Additionally, during high wind events, vented soffit collapse leads to building pressurization and window blowout and roof loss due to increased uplift. Unvented roofs – principally due to the robustness of their soffit construction - outperform vented roofs during hurricanes – they are safer. In coastal areas salt spray and corrosion are a major concern with steel frames, metal roof trusses and truss plate connectors in vented attics.

Finally, in wildfire zones, unvented roofs and attics have significant benefits in terms of fire safety over vented roof assemblies.

Approach

The main strategy to avoid moisture problems, ice dams, and heat loss/gain in roof or attics is to eliminate air movement, particularly exfiltrating air in cold climates and infiltrating air in hot and hot humid climates. This is true regardless of ventilation approach - vented or unvented. This can be accomplished by the installation of an air control layer ("air barrier").

Vapor diffusion should be considered a secondary moisture transport mechanism when designing and building attics and roofs. Specific vapor control layers are often unnecessary, except in cold climates, if air movement is controlled or if condensing surface temperatures are controlled.

Vented Design

Vented attics should not communicate with the conditioned space – they should be coupled to the exterior. Therefore, an air control layer ("air barrier") at the ceiling line – such as sealed gypsum board - must be present to isolate the attic space from the conditioned space. Ideally, no services such as HVAC distribution ducts, air handlers, plumbing or fire sprinkler systems should be located outside the air control layer ("air barrier") (**Figure 5.6**).

The recommended ventilation ratio to provide for vented attic assemblies when an air barrier is present, is the 1:300 ratio (as specified by most building codes). This is based principally on historical experience.

In vented cathedral ceiling assemblies a minimum 2-inch clear airspace is recommended between the underside of the roof deck and the top of the cavity insulation. This is not a code requirement but ought to be (only 1-inch is typically specified in the model codes). It is the authors experience that typical installation practices and construction tolerances do not result in an airspace of at least 1-inch and the airspace is rarely "clear" or free from obstructions created by construction.

In addition to an air control layer ("air barrier") at the ceiling line, a Class II vapor control layer (see below) should be installed in Climate Zones 6 or higher (see **Figure 1.3**).

Class I vapor control layers (i.e. vapor barriers – see below) can be installed in vented attic assemblies in Climate Zones 6 or higher (see **Figure 1.3**) but should be avoided in other climate zones as top side condensation can occur in summer months during air conditioning periods.

No interior attic assembly side vapor control is required or recommended in climate zones other than Climate Zones 6 or higher (see **Figure 1.3**) for vented attic assemblies (note the distinction, this is not the case for unvented attic assemblies). With vented attic assemblies moisture that diffuses into the attic space from the conditioned space is vented to the exterior by attic ventilation.

Class I Vapor Control Layer:
0.1 perm or less
Sheet Polyethylene

Class II Vapor Control Layer:
1.0 perm or less and greater than 0.1 perm
Kraft facing on fiberglass batts
"Membrane" smart vapor barrier
Typical vapor barrier paint

Class III Vapor Control Layer:
10 perm or less and greater than 1.0 perm
Typical latex paint

Class IV Vapor Control Layer:
Greater than 10 perm
Most building papers, housewraps and fluid applied water resistive barriers (WRB)

Vapor Control Layer Definitions

Test Procedure for vapor control layers: ASTM E-96 Test Method A (the desiccant method or dry cup method)

Unvented Design

The key to unvented attic and roof assemblies is to control condensation or moisture accumulation on the underside of the roof sheathing. This can be done several ways. The first is to raise the temperature of the roof sheathing by insulating on the top of the roof sheathing (previously shown in **Figure 5.2**).

If all of the insulation is on the top of the roof sheathing it is clear that the temperature of the roof sheathing is raised sufficiently to control condensation and moisture accumulation. Insulation added on the top of a roof deck can be vapor impermeable or vapor permeable. All of the rigid insulation board products work: foil-faced polyisocyanurate, paper-faced polyisocyanurate, extruded polystyrene, expanded polystyrene, mineral wool (aka "stone wool"), or rigid fiberglass. Expanded polystyrene has a low melting temperature and when coupled with dark colored roofs the assembly may be problematic.

However, there are a few key points. There must be an air control layer ("air barrier") under the rigid insulation boards. The air control layer can be a fully adhered membrane on the roof deck, or the roof deck itself. The rigid board products should be installed in multiple layers with joints offset to address the inherent dimensional instability of almost all rigid board products and to limit three-dimensional airflow networks within the multiple layers of this assembly.

The second way to control condensation or moisture accumulation on the underside of the roof sheathing is to limit the flow of moisture to the underside of the roof sheathing. This can be done by controlling air flow (air can transport a great deal of moisture) to the underside of the roof sheathing as well as by controlling vapor flow (molecular diffusion of water molecules typically through materials due to a concentration gradient) to the underside of the roof sheathing. This can be done with spray polyurethane foam insulation (**Figure 5.7**).

There are two main types of spray polyurethane foam – "high-density" (2 lb/ft^3) low-perm "closed-cell" and low-density (0.5 lb/ft^3) high-perm "open-cell". Both work, but they work differently. Both are good at limiting air flow but they have different properties with respect to vapor flow.

For the remainder of this chapter the two types of spray polyurethane foam will be differentiated using the terms "closed-cell" and "open-cell" as the differences in microstructure define the most significant properties and differences between the numerous manufacturers.

Closed-cell spray polyurethane foam can be used in all climate zones as it controls both air flow and vapor flow to the underside of the roof sheathing. Open-cell spray polyurethane foam can only be used in warm climates and mixed climates because it is "vapor open" (high perm). In cold climates the winters are longer and too much water vapor diffuses upwards into the roof sheathing through the open-cell spray polyurethane foam. The model building codes recognize this and limit open-cell spray polyurethane foam to International Energy Conservation Code (IECC) Climate Zones 1 through 4 (**Figure 1.3**). In contrast, closed-cell spray polyurethane foam can be used in all IECC Climate Zones.

There is an additional issue with open-cell SPF. Some form of moisture removal from the attic space is necessary when open-cell SPF is used. The easiest way to accomplish this is with air change between the attic space and the house – i.e., provide a supply air duct that supplies 50 cfm of supply air for every 1,000 ft^2 of attic area. Note that this is not an issue in hot dry climates and mixed dry climates (IECC Climate Zones 2B, 3B, 4B). However, this is an issue in hot humid climates, mixed humid climates and marine climates (IECC Climate Zones 1, 2A, 3A, 4A and 4C).

The model codes do not use the words "spray foam". The words "air impermeable insulation" are used (see below). Spray polyurethane foam meets the definition of "air impermeable insulation" (0.02 $L/s{\cdot}m^2$ @ 75 Pa).

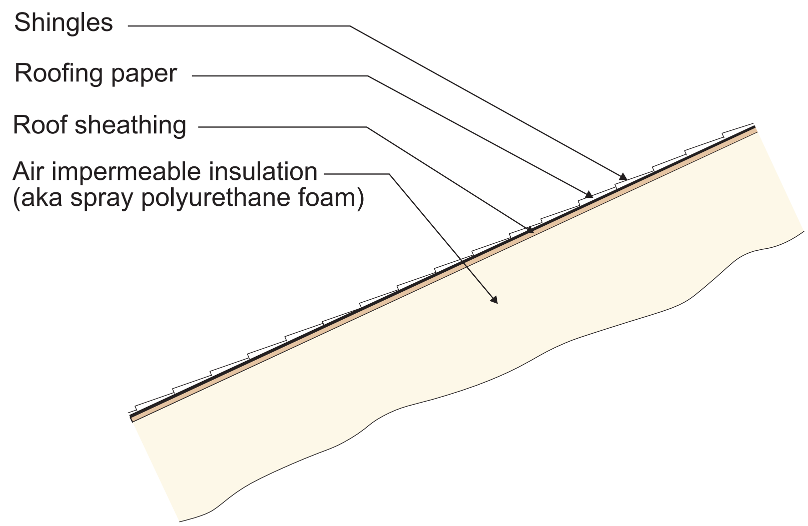


Figure 5.7: Unvented Attic – Roof with all insulation located below the roof deck using spray polyurethane foam insulation**.**

Air-Impermeable and Air-Permeable Definitions

Air-impermeable is defined as having an air permeance of not more than 0.02 $L/s{\cdot}m^2$ at 75 Pa pressure differential as tested according to ASTM E 2178 or E 283.

Air-permeable is defined as having an air permeance of greater than 0.02 $L/s{\cdot}m^2$ at 75 Pa pressure differential as tested according to ASTM E 2178 or E 283.

Note the different approaches between **Figure 5.2** and **Figure 5.7**. In **Figure 5.2**, all of the insulation is on the top of the roof sheathing and in **Figure 5.7** all of the insulation is on the underside of the roof sheathing.

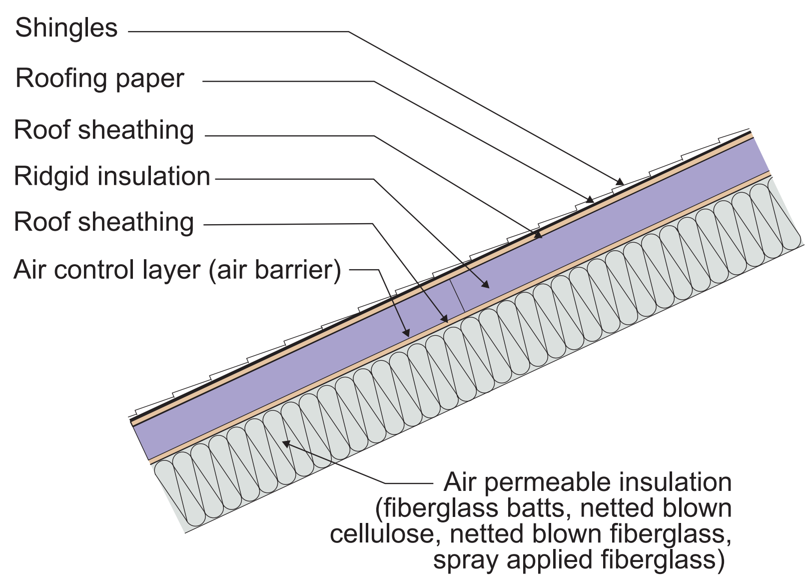


Figure 5.8: Unvented Attic – Roof with some insulation can be located above the top of the roof sheathing and some of the insulation can be located on the underside of the roof sheathing.

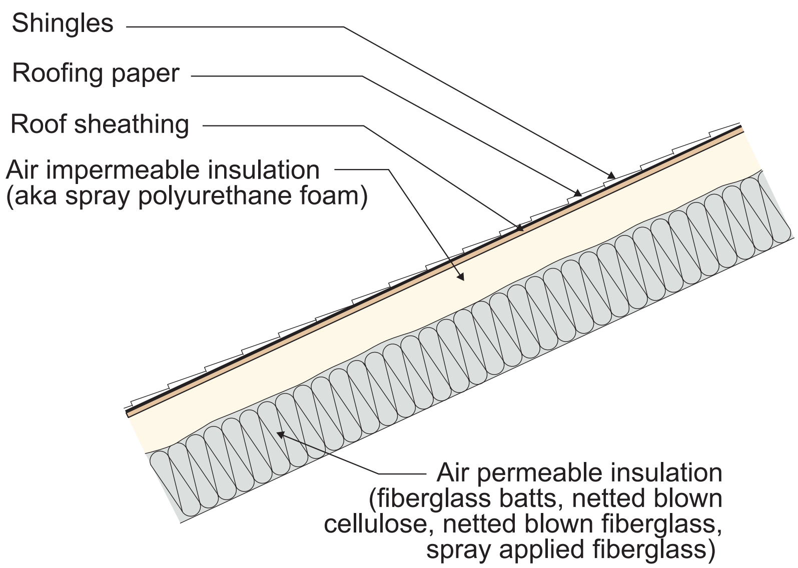


Figure 5.9: Unvented Attic - Spray polyurethane foam on the underside of the roof deck coupled with air permeable insulation. The thermal resistance of the spray polyurethane foam and the thermal resistance of the insulation under it must conform to the ratio stipulated in Table 5.1.

It is not necessary to install all of the insulation on the top of the roof sheathing to elevate its temperature sufficiently to control condensation and moisture accumulation. Insulation can be located both above and below the roof sheathing (**Figure 5.8**). Sufficient insulation should be located above the roof sheathing to keep the moisture content of the sheathing below 20 percent by weight. How much depends on the climate zone and the interior moisture load. The model codes specify the amount of insulation necessary based on climate zone. The model codes assume an interior moisture load based on historical experience and test hut experimentation over several decades.

For the coldest parts of the winter…note that the roof sheathing moisture content drops quite quickly in the spring. The roof sheathing moisture content should remain below 16 percent for the summer and fall. These moisture content limits have been shown to also address mold growth based on historical experience.

The model codes assume a residential occupancy – a moisture load resulting in approximately 35 percent relative humidity at 68° F in winter.

The model codes specify a specific performance requirement – the temperature of the roof sheathing should be maintained above 45° F (7° C). For calculation purposes an interior air temperature of 68° F (20° C) is assumed and the exterior air temperature is assumed to be the monthly average outside temperature of the three coldest months. This is an engineering equation providing boundary conditions derived from observed experimentation and field experience.

This is an "insulation ratio" – the R-value on the top of the roof sheathing compared to the R-value on the underside of the roof sheathing…and the ratio changes based on climate severity. The model codes specify the ratios based on climate zone (**Table 5.1**). Note how the ratio changes from approximately 10 percent to 70 percent as the assembly moves from hot climates to cold climates.

In **Figure 5.8** the rigid insulation can be any type as in **Figure 5.2**. The main stipulation is the thermal resistance of this rigid insulation is based on **Table 5.1**. The "air permeable insulation" can be any insulation product as long as the thermal resistance of this layer complies with the "ratio".

Figure 5.9 is a variation of **Figure 5.8**. The rigid insulation on the top of the roof deck in **Figure 5.8** is replaced with spray polyurethane foam on the underside of the roof deck. The thermal resistance of the spray polyurethane foam and the thermal resistance of the insulation under it must conform to the ratio stipulated in Table 5.1.

In IECC Climate Zone 5 or higher the spray foam must be closed-cell, or open-cell with a Class II vapor retarder coating or covering in direct contact with the underside of the insulation

Figure 5.10 is a variation of **Figure 5.9**. This assembly is a combination of closed-cell spray foam and open-cell spray foam. The thermal resistance of the two layers need to conform to the ratio stipulated in **Table 5.1**.

The third way to control condensation or moisture accumulation on the underside of the roof sheathing is the "flow-through" approach.

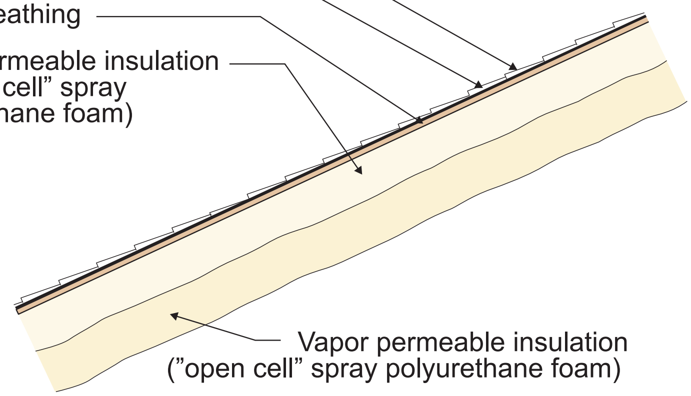


Figure 5.10: Unvented Attic - This assembly is a combination of closed cell spray foam and open cell spray foam. The thermal resistance of the two layers need to conform to the ratio stipulated in Table 5.1.

Climate Zone	Rigid Board or Air Impermeable Insulation	Code Required R-Value	Ratio of Rigid Board Insulation or Air Impermeable R-Value to Total Insulation R-Value
1,2,3	R-5	R-38	10%
4C	R-10	R-49	20%
4A, 4B	R-15	R-49	30%
5	R-20	R-49	40%
6	R-25	R-49	50%
7	R-30	R-49	60%
8	R-35	R-49	70%

Table 5.1: Adapted from Table R806.5 2015 International Residential Code

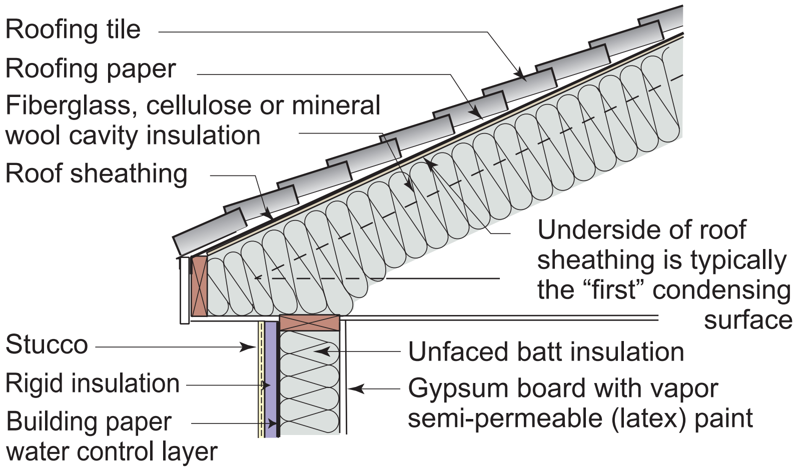


Figure 5.11: Unvented Attic – Flow through approach… limited to hot dry climates such as Las Vegas and Phoenix.

The "flow-through" approach is limited to hot-dry climates such as Las Vegas and Phoenix. The roof cladding needs to be "back-vented" and the roof sheathing and roofing paper, roofing felt, or roofing membrane need to be vapor open. The most typical manifestation of this is a tile roof over batten strips over a roofing felt over plywood or OSB sheathing (**Figure 5.11**). Any moisture that accumulates on the underside of the roof sheathing (the "first condensing surface") can pass through ("flow through") the sheathing and the roofing felt into the air gap under the tile roof, and is vented away. New materials allow the roofing paper or roofing felt to be replaced with a vapor-permeable fully-adhered membrane or a semi-vapor-permeable taped OSB sheathing. The most common insulation is netted cellulose although spray-applied fiberglass, netted fiberglass, and fiberglass batts are also options.

The fourth way to control condensation or moisture accumulation on the underside of the roof sheathing is to remove attic and roof assembly moisture via vapor diffusion rather than air change between the attic and roof assembly and the exterior.

Moisture-laden air is less dense and more buoyant than dry air, which is referred to as – "hygric buoyancy". This appears to be contradictory at first glance. How does adding something (water vapor) to something else reduce its weight? The molecular weight of "dry air" is approximately 29. The molecular weight of "water vapor" is 18. Adding a molecular weight gas of 18 to a gas mixture (nitrogen and oxygen) of molecular weight 29 reduces the combined molecular weight and hence its density.

One of the reasons why moisture accumulates at the ridge in attic spaces and sloping rafter roof assemblies is hygric buoyancy – the other is thermal buoyancy. Installing a "vapor diffusion vent or vapor diffusion port" at the upper part of attic spaces and sloping rafter roof assemblies allows this moisture (in the vapor phase) to exit the attic and roof assembly. In practice this involves installing standard roof vents near the ridge, but covering the vent opening in the roof deck with an airtight but vapor open layer (**Figure 5.12** and **Figure 5.13**). Lower soffit vents are not installed; there is no intent to create "bottom to top" outside airflow in this assembly.

This approach is limited to IECC Climate Zones 1, 2 and 3. It should not be used in colder climate zones.

The vapor permeance of the ridge vent covering should be greater than 20 perms. The ridge vent area should be approximately

1:150 of the ceiling area and the roof needs to be sloped a minimum of 3:12 or greater. Where the insulation is installed on the underside of the roof deck and the insulation is "air permeable" then air should be supplied to the attic space from the interior of the house to remove moisture by providing "conditioning" to the attic space, treating it similar to a room or occupied space. The required conditioning is a minimum of 50 cfm for each 1,000 ft^2 of ceiling area. This airflow does not need to be continuous. The typical 30 percent duty cycle of air-conditioning system operation has been found to be effective. Alternatively, a dehumidifier can be installed in the conditioned attic.

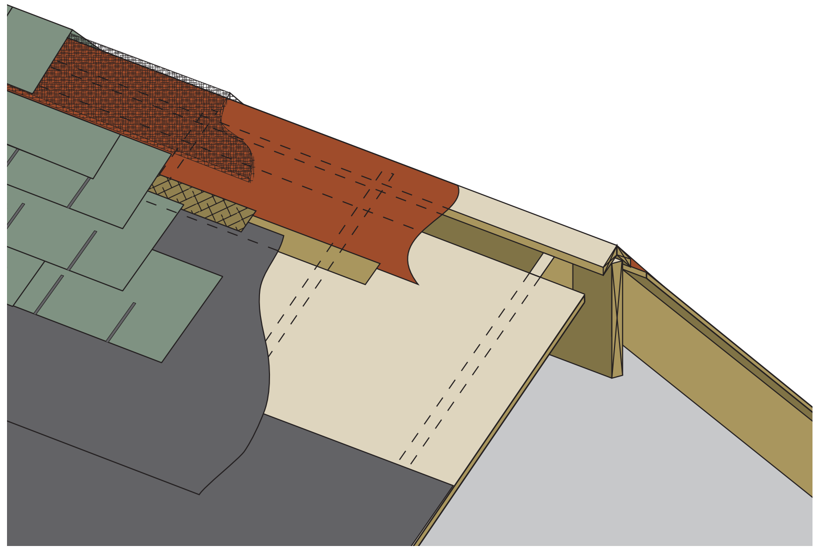


Figure 5.12: Vapor Diffusion Vents – Approach using asphalt shingles.

Hurricanes and Wild Fires

One of the most damaging effects of hurricanes in the southeast is wind-driven rain through roof vents. It is estimated that 20 to 30 percent of hurricane water damage occurs through leaking roof vents. One successful strategy is to construct unvented roof assemblies in these areas. Another successful strategy is to omit soffit vents (or seal existing soffit vents in retrofit applications) and install upper vapor diffusion vents (i.e., sealing the upper vents with a water tight but vapor-open membrane or sheet good in retrofit applications).

In wild fire areas the major concern is embers entering vented roofs carried by air currents. It is possible to seal lower vents and then install a vapor-open membrane or sheet good covering the upper openings that is also fire resistant such as exterior fiber faced gypsum board or a fireproof vapor-open membrane. It is also possible to use fine mesh screens at both soffit and upper vents.

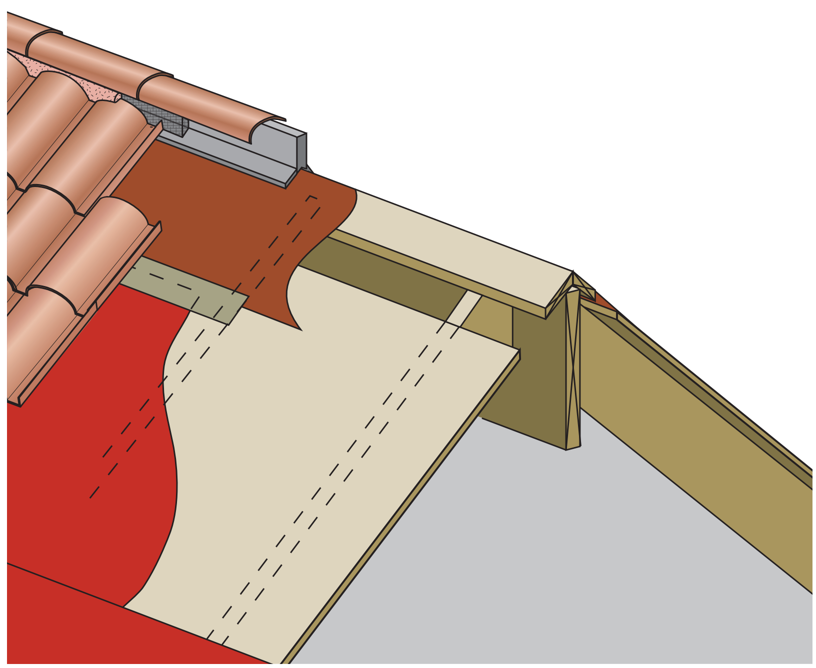


Figure 5.13: Vapor Diffusion Vent – Approach using tile roofing.

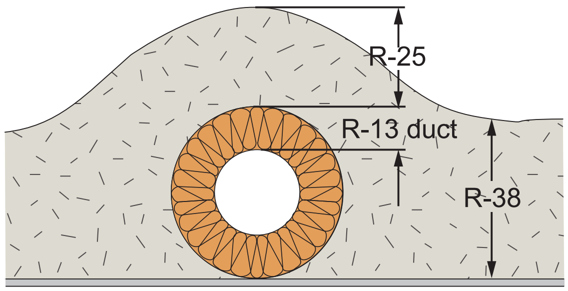


Figure 5.14: Buried Ducts – Approach for hot-humid and mixed-humid climates

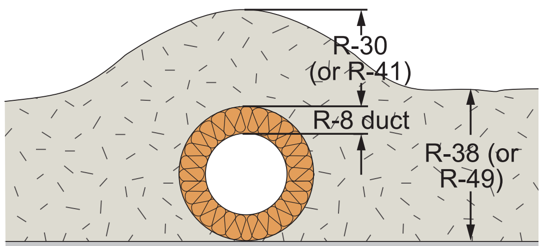


Figure 5.15: Buried Ducts – Approach for colder climates.

Effect on Shingle Life

In general, asphalt shingles installed on unvented attic assemblies operate at a slightly higher temperature. This has impacts on the durability of roof assemblies. A 2 or 3°F. rise in average temperature is typical for asphalt shingles and a corresponding 10 °F. rise in average temperature for sheathing. As such a 10 percent reduction in useful service life for asphalt shingles should be expected. This is comparable to the effect of the installation of radiant barriers. What is more significant is that the color of shingles and roof orientation have a more profound effect on the durability of shingles than the choice of venting or not venting – double or triple the effect of venting/non-venting.

Inward Moisture Drive

Inward moisture drive through asphalt shingles under various configurations/permeabilities of roofing underlayments and under deck insulation systems is not significant to the moisture balance of the roof sheathing from a durability – long term service life perspective or to the latent load of the building or surface condensation.

Burying Ducts

Can ductwork in vented attics be installed underneath insulation….”burying” them? Yes, with some restrictions. The issue is condensation. In order to control condensation the thermal resistance of the ductwork must be increased. The level of thermal resistance is determined by climate zone. In hot-humid and mixed-humid climates – International Energy Conservation Code (IECC) Climate Zones 1A, 2A, 3A and 4A – the ductwork including boots – should be insulated to a minimum of R-13 (**Figure 5.14**). In other climate zones the ductwork including boots should be insulated to a minimum of R-8 (**Figure 5.15**).

The ductwork also must be airtight – less than 4 percent of the rate flow as tested by pressurization to 25 Pascals. Additionally, the ductwork insulation must be less than 1 perm or enclosed in a layer or surface (“jacketed”) that is less than 1 perm. The vapor in attics must be kept away from cold duct surfaces to avoid condensation and moisture issues. Closed-cell spray polyurethane foam can be used to encapsulate R-6 and R-8 ducts in hot humid and mixed humid climates at a little more than 1 inch thick. Open-cell spray polyurethane foam does not work in this role, as it is too vapor open.

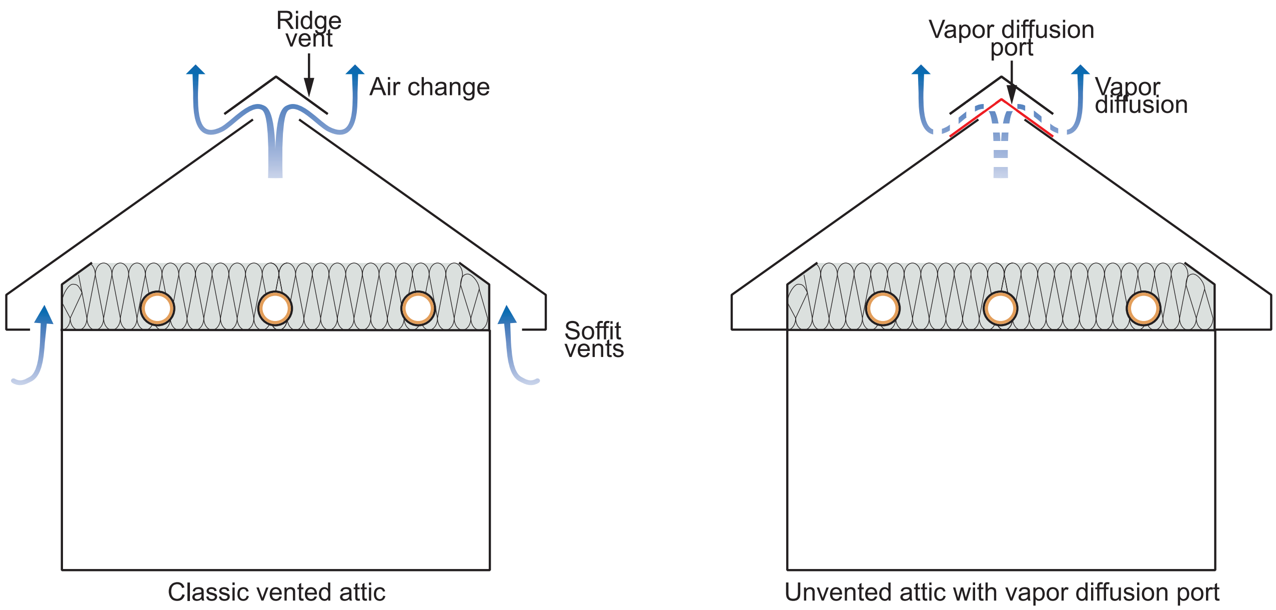


Figure 5.16: Buried Ducts – Alternative approach for hot-humid and mixed-humid climates.

Another approach to controlling ductwork sweating and to burying standard ductwork and boots (insulated to less than R-13 in IECC Climate Zones 1A, 2A, 3A) is to seal (or not install) soffit vents and to install a "vapor diffusion vent or vapor diffusion port" at the upper part of attic spaces and sloping rafter roof assemblies (**Figure 5.16**). Note that this approach is not recommended for Climate Zone 4A (or higher), as it is too cold of a climate for the vapor diffusion approach to function satisfactorily.

Summary

Both vented and unvented attic/roof designs can be used in all hygrothermal regions. However, the designs need to be climate-sensitive.

Control of ice dams, moisture accumulation, and heat gain can be successfully addressed by both vented and unvented attic or roof design.

The choice of the venting approach is up to the designer.

Vented attic/roof designs are well suited to roof designs with less complex geometries, and have the advantage of a long, proven historical track-record. However, they work best with airtight ceiling/attic interfaces and where ductwork and air handlers are not located within attic spaces.

Unvented attic/roof designs are better suited to roof designs with more complex geometries, and have the advantage of providing conditioned spaces for ductwork and air handlers. However, they require different approaches in different climate locations.

CHAPTER 6

Foundation Assemblies

The three foundation approaches common to residential construction are basements, crawl spaces, and slabs. Each can be built with concrete or masonry. Each can be insulated on the inside or the outside. However, they all have to:

- Control liquid flow due to groundwater
- Control liquid flow due to capillarity
- Control soil gas
- Keep the water vapor out
- Let the water vapor out if it gets in

Groundwater control is principally accomplished by draining groundwater away from foundation wall perimeters, using free-draining materials such as sand, gravel, or drainage boards. Groundwater entry is reduced by draining surface water away from the building and foundation.

Capillary control is principally accomplished by installing capillary breaks to fill the pores in capillary susceptible materials such as concrete and masonry. The most common capillary break used in residential foundation construction is dampproofing. The dampproofing fills the pores in the concrete and masonry to control capillarity. Under concrete floor slabs, the stone layer combined with sheet polyethylene serves a similar function. Dampproofing the joint between the footings and the foundation walls controls capillarity at this location. Soil gas control (radon, water vapor, methane, herbicides, termiticides) is principally accomplished by controlling/limiting holes and controlling the pressure difference. Locating a granular drainage pad under concrete slabs can be integrated into a sub-slab ventilation system to control soil gas migration by creating a zone of negative pressure under the slab. A vent pipe connects the sub-slab gravel layer to the exterior through the roof (**Figure 6.1**, **Figure 6.2** and **Figure 6.3**). An exhaust fan can be added later, if necessary.

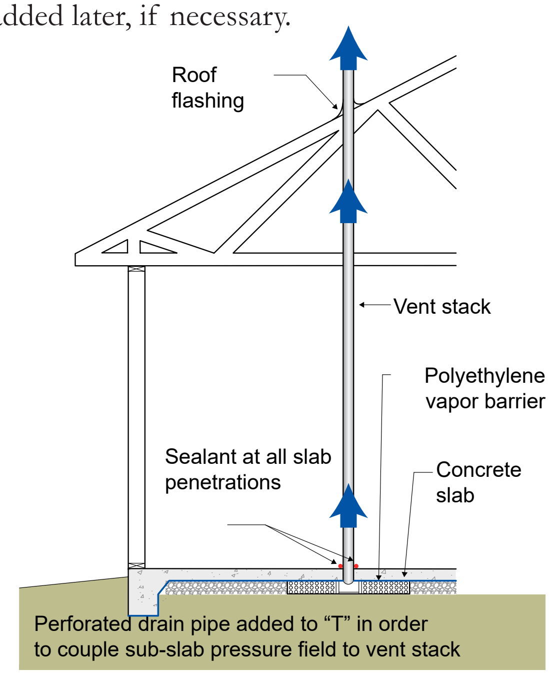


Figure 6.1: Soil Gas Control – Approach for slab foundations.

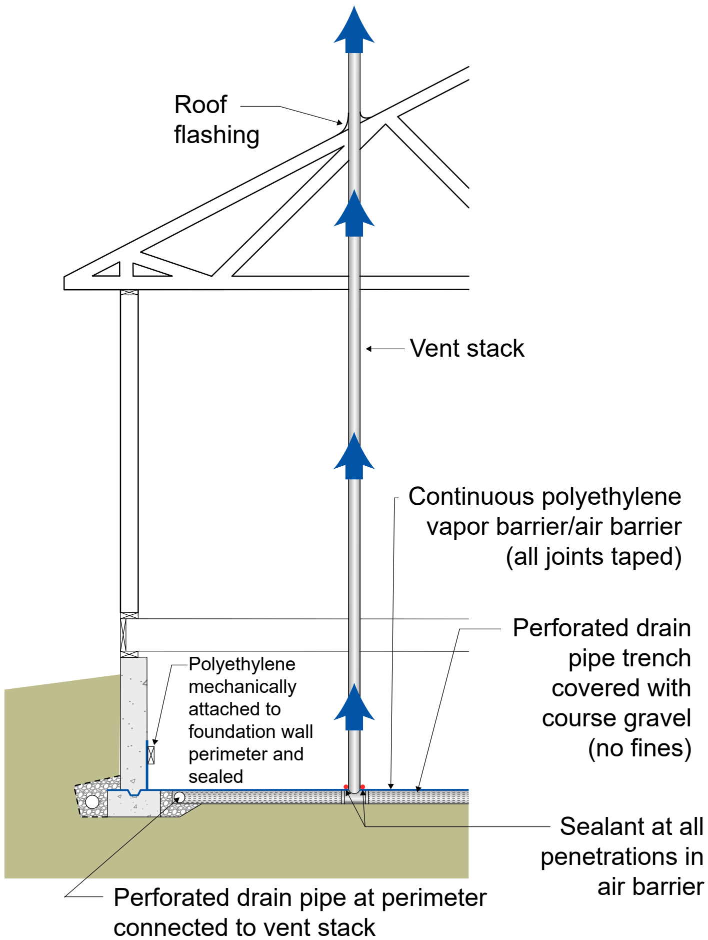


Figure 6.2: Soil Gas Control – Approach for crawl space foundations.

Moisture Vapor Control and Stored Moisture

Controlling water vapor in foundations relies first on keeping it out, and second, on letting it out when it gets in. The issue is complicated by the use of concrete and masonry because there are thousands of pounds of water stored in freshly cast concrete and freshly laid masonry to begin with. This moisture of construction has to dry to somewhere, and it usually (but not always) dries to the inside.

For example, we put coarse gravel (no fines) and a polyethylene vapor control layer under a concrete slab to keep the water vapor and water in the ground from getting into the slab from underneath. The gravel and polyethylene do nothing for the water already in the slab. This water can only dry into the building. Installing flooring, carpets or tile over this concrete before it has dried sufficiently is a common mistake that leads to mold, buckled flooring, and lifted tile. When installing these finishes over a wet slab, these problems can be solved by installing a top side vapor control layer.

Similarly, we install dampproofing on the exterior of concrete foundation walls, and provide a water managed foundation system to keep water vapor and water in the ground from getting into the foundation from the exterior. Again, this does nothing for the water already in the foundation wall, typically initial construction moisture. Concrete and masonry when cast or constructed contain a great deal of water. It is not usually practical to allow this moisture to dry prior to installing interior surfaces. The installation of interior insulation and finishes on the interior of a foundation wall must be done in a manner that protects moisture sensitive materials, such as wood framing, gypsum board, and air permeable insulations. This can be accomplished several ways.

One way is to install a layer of insulation in a manner that is air tight—such as rigid sheet insulation materials like extruded polystyrene, expanded polystyrene, foil faced polyisocyanurate— with all seams and joints sealed, preventing interior air from contacting the interior surface of concrete and masonry foundation walls. Similarly, a layer of high density closed cell polyurethane spray foam insulation can be applied to the interior surface of concrete and masonry walls.

These materials limit the ability of the concrete or masonry foundation wall to dry to the interior. This does not damage either concrete or masonry. Over time the foundation walls can dry upwards and outwards at grade.

Letting interior air (that is usually full of moisture, especially in the humid summer months) touch cold foundation surfaces will cause condensation and wetting. If a frame wall is built inboard of the air tight insulation layer described above, the frame wall cavities should either be left uninsulated, or insulated without installing an interior vapor barrier (such as sheet polyethylene), thereby allowing the frame wall assembly to dry to the interior, as it is unable to dry to the exterior.

Basement Foundations

The traditional approach to basement moisture control has been to locate the water control on the outside and then allow drying to the inside. Drainage, water control layers (water-proofing), capillary control layers (damp-proofing), and vapor control layers (damp-proofing) have historically been located on the outside of basement perimeter walls and crushed stone layers and plastic vapor barriers have been located under concrete slabs. The operative principle has been to keep the liquid flow due to groundwater and capillarity out of the structure and locate vapor control layers (vapor barriers) on the outside – therefore allowing inward drying to the basement space where moisture can be removed by ventilation or dehumidification.

Two generic basement foundation approaches are typical: insulate the inside or insulate the outside. The most logical location from the physics perspective is to locate the insulation on the outside. By locating the insulation layer outward of the structure and outward of the control layers the foundation is kept at a constant temperature and the insulation system does not interfere with the inward drying of the assembly. Exterior basement insulation is completely compatible with the traditional approach for foundation water control.

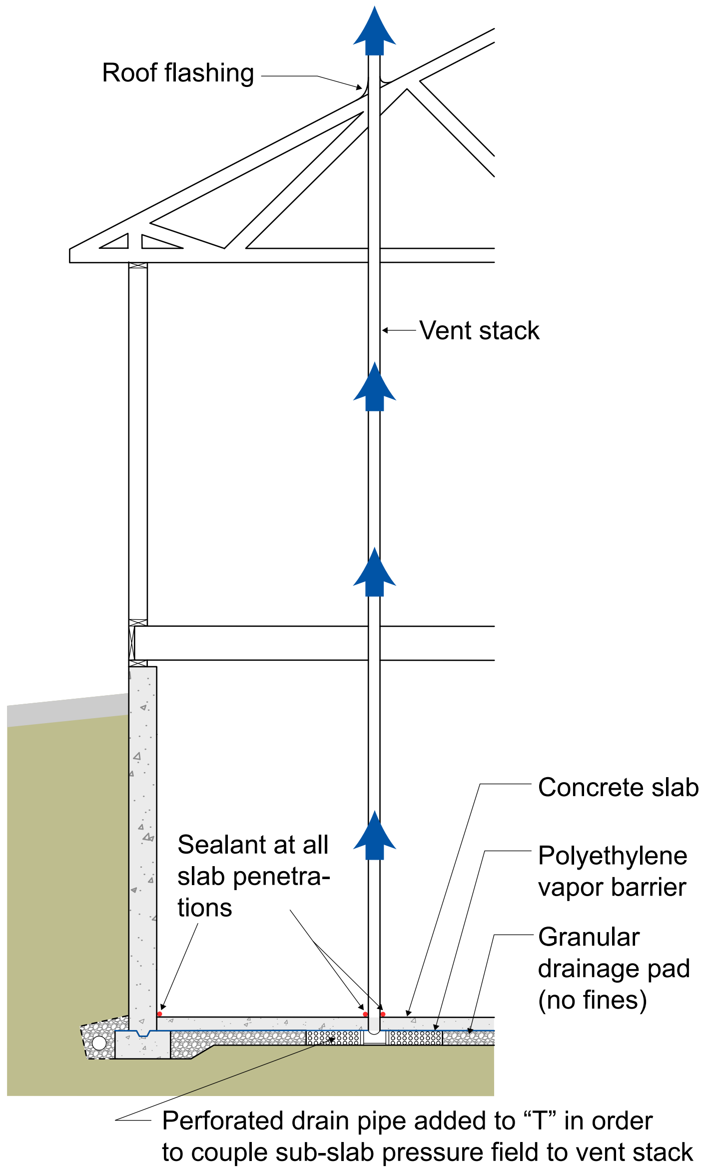


Figure 6:3: Soil Gas Control – Approach for basement foundations.

Unfortunately, exterior basement foundation insulation can have significant application problems that often make it impractical to employ. The first is the difficulty in protecting the insulation layer during the construction process and subsequently during its useful service life. The second is insect control. Exterior insulation can be an "insect interstate" that provides a direct pathway into the structure.

These factors have resulted in primarily locating insulation layers on the interior. However, locating insulation layers on the interior often conflicts with the traditional approach of foundation water control – namely inward drying. Building a frame wall with fibrous cavity insulation with an interior plastic vapor barrier is common, but often leads to odor, mold, decay, and corrosion problems.

Examples of common residential basement foundations using recommended configurations of control layers and control approaches follow.

Figure 6.4: Concrete Basement With Interior Rigid Insulation

Applicability – all hygro-thermal regions

The key to this assembly is the use of non-water sensitive rigid insulation on the interior that still permits drying to the interior. The recommended permeance of the interior rigid insulation layer is approximately 1 perm. This typically limits the thermal resistance of the interior rigid insulation layer (R-4 to R-5, below 2015 IECC requirements for Zone 5 or colder). An insulated frame wall assembly can be located to the interior of the interior rigid insulation. No interior vapor control layer is located within the frame wall thereby permitting inward drying. All interior concrete surfaces are wrapped with the rigid insulation layer – particularly at the top of the wall and at foundation "step downs". Exterior rigid insulation is located at the rim joist floor framing to control summer condensation. When insulating sheathing is not used, rigid insulation should be installed to the interior of the rim joist or an air impermeable insulation be applied at the rim joist assembly. Note the capillary break at the top of the footing. Further note the air sealing of the rigid insulation at the top of the concrete floor slab – a sealant is used to seal the top of the concrete slab to the rigid insulation and an additional sealant is used to seal the rigid insulation to the interior of the concrete perimeter foundation wall. These two seals are necessary to control soil gas ingress.

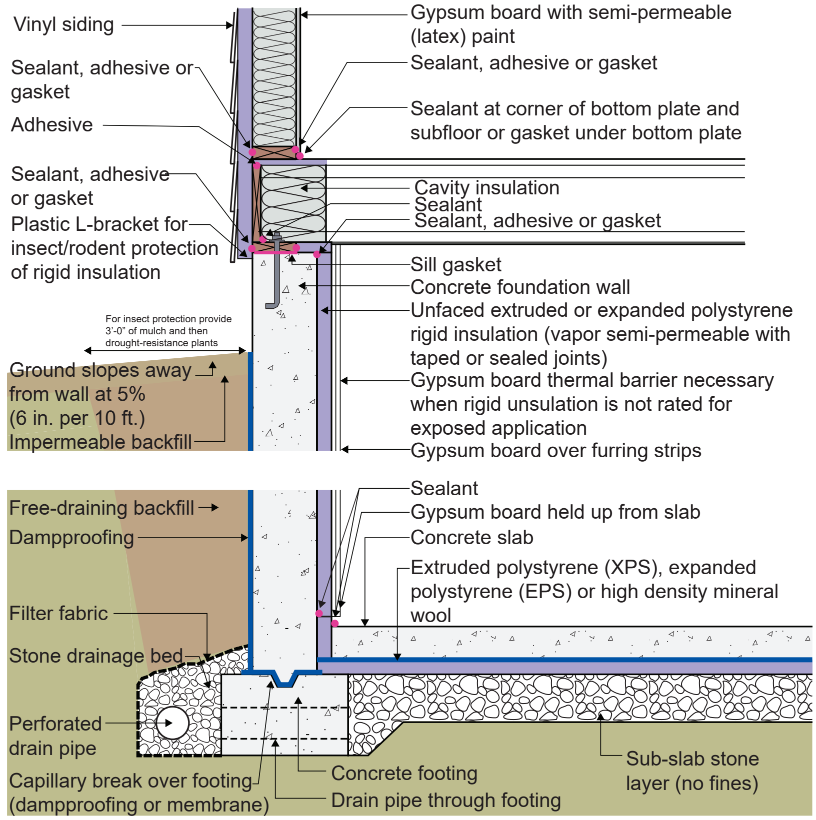


Figure 6.4: Concrete Basement With Interior Rigid Insulation

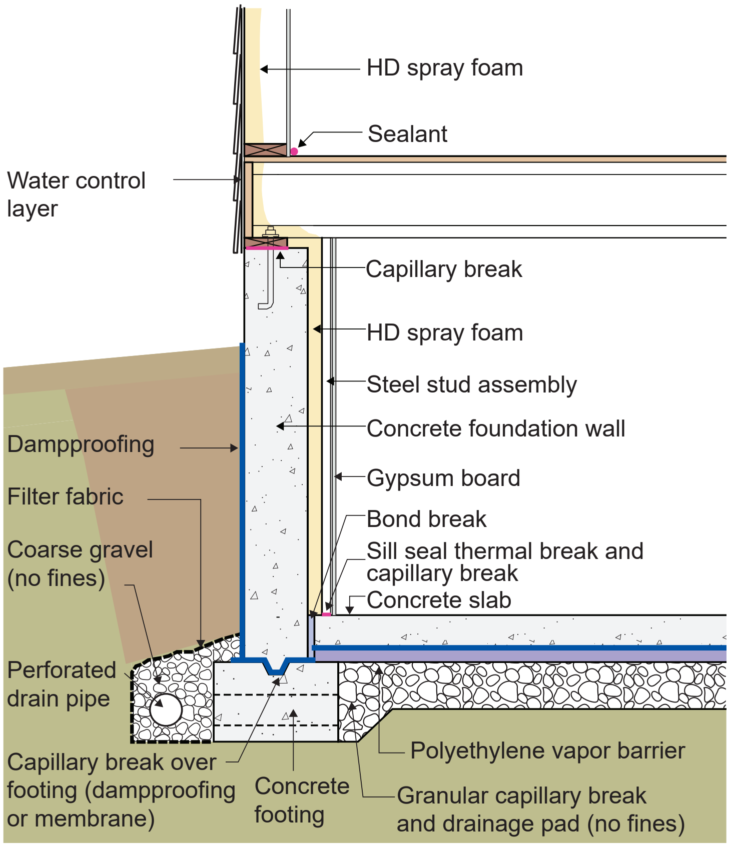


Figure 6.5: Concrete Basement With Interior Spray Polyurethane Foam Insulation

Figure 6.5: Concrete Basement With Interior Spray Polyurethane Foam Insulation

Applicability – all hygro-thermal regions

Polyurethane spray foam insulation can be directly applied to the interior of concrete foundation walls. High density closed cell spray foam should be used. The recommended permeance of the interior spray foam insulation layer is approximately 1 perm (~R-12). This typically limits the thermal resistance of the interior spray foam insulation layer (~R-12). An insulated frame wall assembly can be located to the interior of the interior spray foam insulation to increase the assembly thermal resistance. No interior vapor control layer should be located within the frame wall thereby permitting inward drying. All interior concrete surfaces are wrapped with the spray foam insulation layer – particularly at the top of the wall and at foundation "step downs". Note the spray foam insulation applied at the rim joist assembly. Note the capillary break at the top of the footing. Further note the air sealing of the spray foam insulation connecting the concrete floor slab to the perimeter concrete foundation wall to control soil gas ingress.

Figure 6.6: Concrete Basement With Interior Rigid Insulation and an Interior Insulated Frame Wall

Applicability – all hygro-thermal regions

The key to this assembly is the use of non-water sensitive rigid insulation on the interior that still permits drying to the interior. The recommended permeance of the interior rigid insulation layer is approximately 1 perm. This typically limits the thermal resistance of the interior rigid insulation layer (R-4 to R-5, below 2015 IECC requirements for Zone 5 or colder); however, an insulated frame wall assembly can be located to the interior of the interior rigid insulation. No interior vapor control layer is located within the frame wall thereby permitting inward drying. All interior concrete surfaces are wrapped with the rigid insulation layer – particularly at the top of the wall and at foundation “step downs”. Exterior rigid insulation is located at the rim joist floor framing to control summer condensation. When insulating sheathing is not used, rigid insulation should be installed to the interior of the rim joist or an air impermeable insulation be applied at the rim joist assembly. Note the capillary break at the top of the footing. Further note the air sealing of the rigid insulation at the top of the concrete floor slab – a sealant is used to seal the top of the concrete slab to the rigid insulation and an additional sealant is used to seal the rigid insulation to the interior of the concrete perimeter foundation wall. These two seals are necessary to control soil gas ingress.

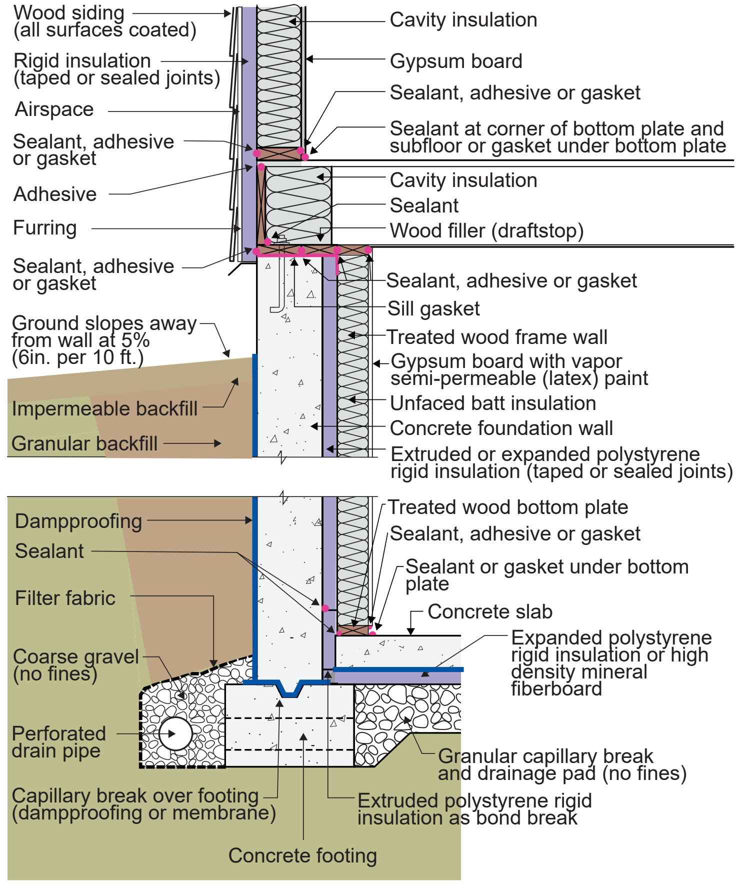


Figure 6.6: Concrete Basement With Interior Rigid Insulation and an Interior Insulated Frame Wall

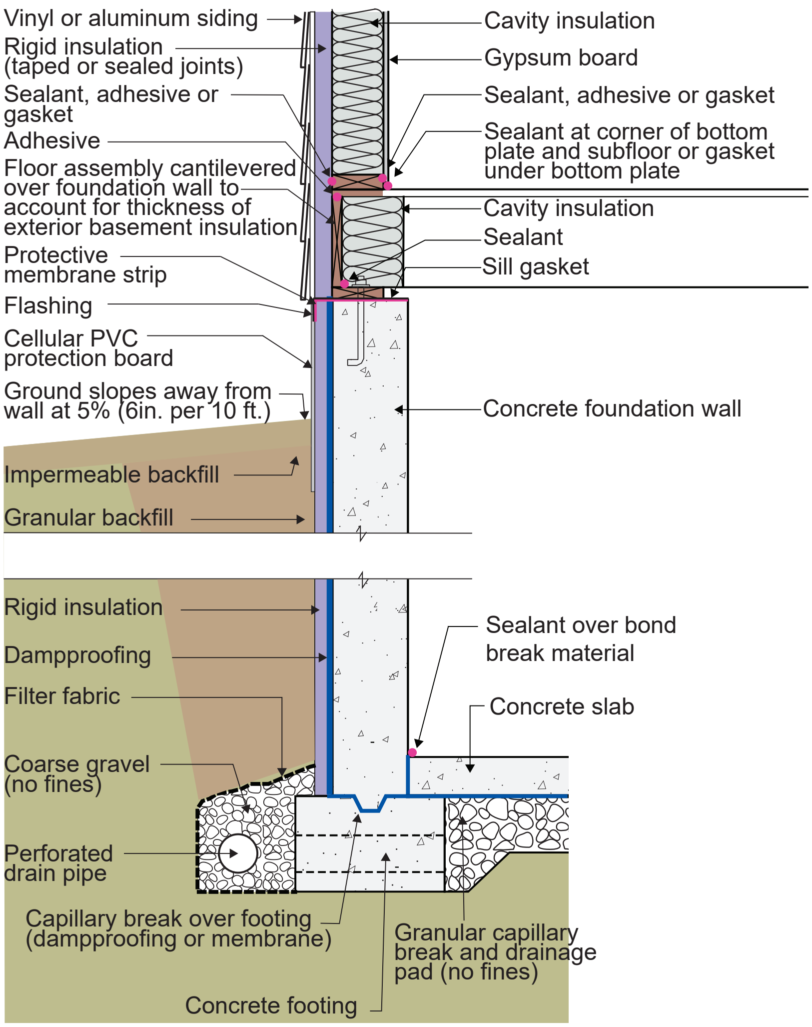


Figure 6.7: Concrete Basement With Exterior Rigid Insulation

Figure 6.7: Concrete Basement With Exterior Rigid Insulation

Applicability – all hygro-thermal regions

The exterior insulation layer is protected with a sealed cement board protecting the insulation layer during the construction process and subsequently during its useful service life. Note the protective membrane strip sealed to the top of the foundation wall for insect control. Exterior rigid insulation is located at the rim joist floor framing to control summer condensation. When insulating sheathing is not used, rigid insulation should be installed to the interior of the rim joist or an air impermeable insulation be applied at the rim joist assembly. Note the capillary break at the top of the footing. Further note the air sealing of the top of the concrete slab to the interior of the concrete perimeter wall. This seal is necessary to control soil gas ingress.

Crawlspace Foundations

The traditional approach to crawlspace moisture control has been to vent them – connect them to the outside. In the past when crawlspace sub-floors were not insulated and the occupied spaces above them were heated but not air conditioned the sub-floor framing was typically warmer than the ground and framing remained dry. With the advent of installing thermal insulation in floor framing and air conditioning, vented crawlspace construction became more complex. The crawlspace needed to be completely disconnected from a moisture perspective from the occupied space. The alternative was to completely connect the crawlspace to the occupied space – in essence construct it like a mini-basement and condition it.

Two fundamental approaches to crawlspace construction and moisture control exist. The crawlspace is either "vented" and "not conditioned" and connected to the "outside"…or…the crawlspace is "not vented" and "conditioned" and connected to the "inside".

When crawlspaces are completely connected to the house (or building) they must be conditioned. There has to be a means of removing moisture from the crawlspace when the crawlspace is connected to the house, like the requirement to remove moisture from any room in the house. In the rooms and spaces in houses we do it with controlled air change during heating seasons and dehumidification via air conditioning (or via a dehumidifier) during cooling seasons. Houses are "conditioned" and conditioning means controlling temperature and relative humidity.

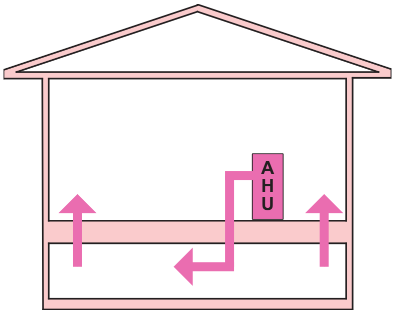


Figure 6.8a

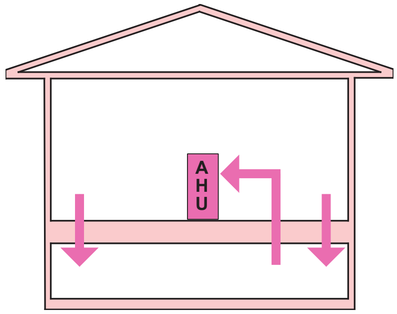


Figure 6.8b

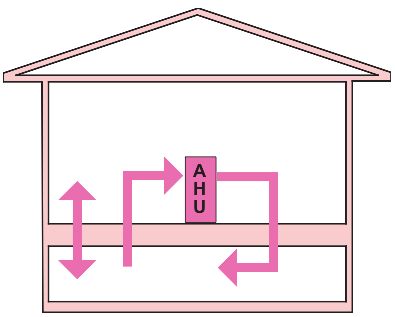


Figure 6.8c

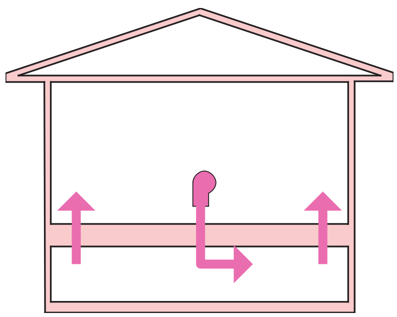


Figure 6.8d

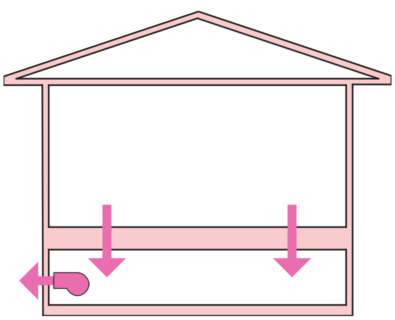


Figure 6.8e

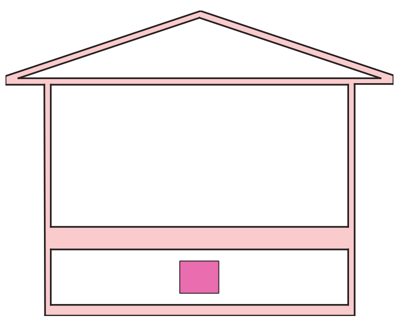


Figure 6.8f

Conditioning Crawlspaces

Conditioning crawlspaces is typically accomplished two ways: air change between the crawlspace and the house or dehumidification. Typical air flow rates providing air change between the crawlspace and the house are 50 cfm per 1,000 ft^2 of supply air.

The following approaches can be used. When air is supplied to the crawlspace from an air conditioner or furnace (**Figure 6.8a**) a return flow path should be provided. A transfer grille is can be used to serve this function. If air is returned from the crawlspace with a return duct (**Figure 6.8b**) a supply flow path should be provided - a transfer grille can also be used.

If supply and return air to the crawlspace from an air conditioner or furnace is provided (**Figure 6.8c**) the air flows should be balanced to avoid pressure differences. A transfer grille is recommended to facilitate balancing.

Conditioning can be done without a ducted furnace or air conditioner by using a supply fan (**Figure 6.8d**) and by providing a pathway back to the house via a transfer grille.

An exhaust fan can be used to pull air out of the crawlspace and exhaust this air to the exterior pulling air from the house (**Figure 6.8e**). The house is in effect vented through the crawlspace - exhaust only ventilation with make-up air supplied to the crawlspace from the house.

A dehumidifier can also be used to condition the crawlspace (**Figure 6.8f**).

Figure 6.9: Vented Crawlspace – Rigid Insulation

Applicability – all hygro-thermal regions

The key to this assembly is the use of an air control layer and vapor control layer at the underside of the floor framing. The air control layer and vapor control layer can be a layer of insulating sheathing such as foil faced polyisocyanurate. In most regions the exterior air summertime dewpoint is above both the ground surface temperature in crawlspaces and the temperature of the floor assembly. The rigid insulation protects the floor assembly from condensation.

A ground cover is also recommended to limit evaporation of water from the soil. The interior grade should be higher than the exterior grade. Floor cavity insulation should be located in contact with the rigid insulation. Rim joists should be internally insulated with rigid insulation to control condensation or an air impermeable insulation should be applied to the interior of the rim joist. Alternatively, exterior insulating sheathing can be used. A protection board is recommended on the underside of the rigid insulation to protect the insulation layer from insects and rodents.

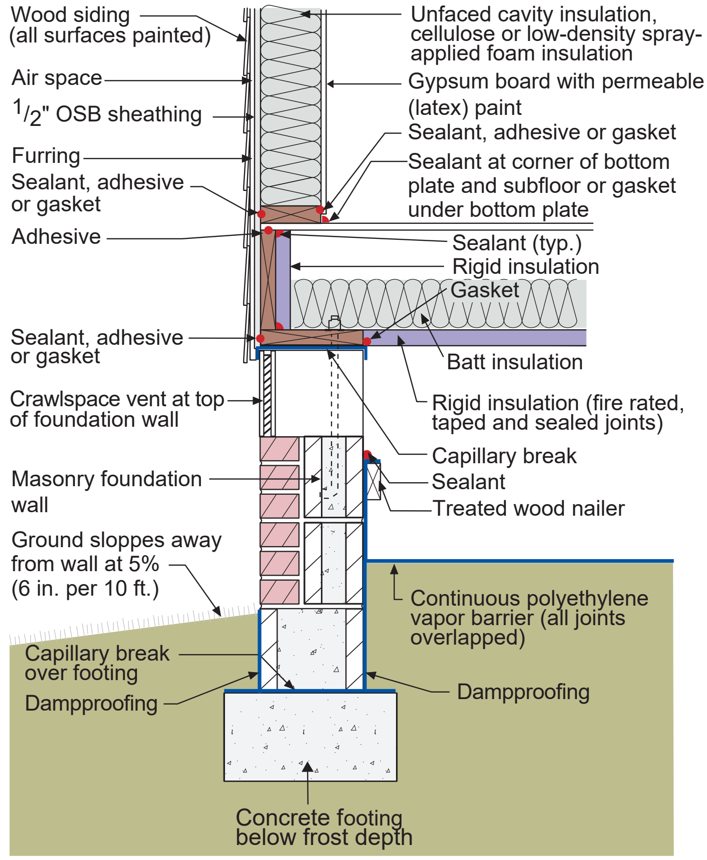


Figure 6.9: Vented Crawlspace – Rigid Insulation

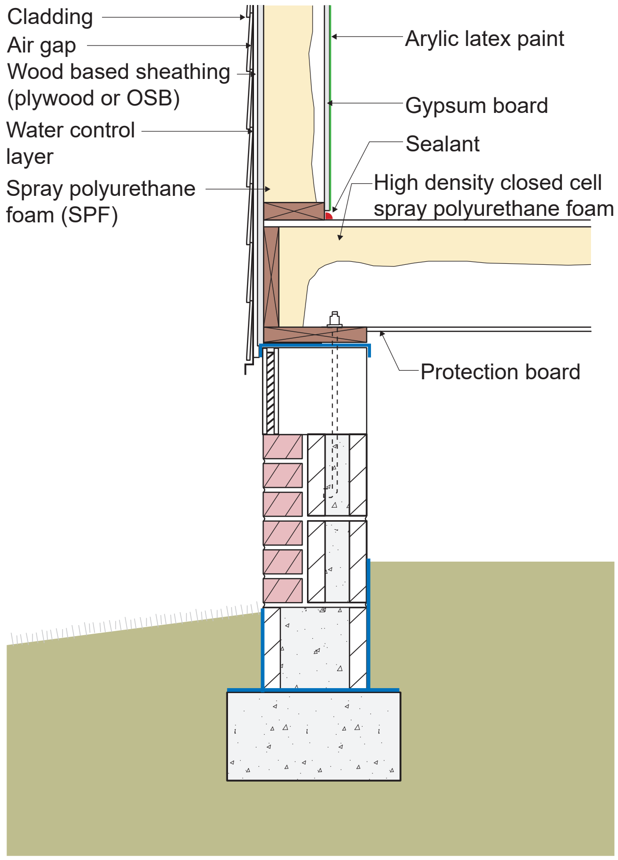


Figure 6.10: Vented Crawlspace – Spray Polyurethane Foam

Figure 6.10: Vented Crawlspace – Spray Polyurethane Foam

Applicability – all hygro-thermal regions

The air control layer and vapor control layer in this assembly is a layer of polyurethane spray foam insulation directly applied to the underside of the floor framing. High density closed cell spray foam should be used. In most regions the exterior air summertime dewpoint is above both the ground surface temperature in crawlspaces and the temperature of the floor assembly. The high density closed cell spray polyurethane foam protects the floor assembly from the condensation.

A ground cover is also recommended to limit evaporation of water from the soil. The interior grade should be higher than the exterior grade. A protection board is recommended on the underside of the floor framing to protect the insulation layer from insects and rodents.

Figure 6.11: Vented Crawlspace – Pier Foundation - Rigid Insulation

Applicability – all hygro-thermal regions

The key to this assembly is the use of an air control layer and vapor control layer at the underside of the floor framing. The air control layer and vapor control layer can be a layer of insulating sheathing such as foil faced polyisocyanurate. In most regions the exterior air summertime dewpoint is above both the ground surface temperature in crawlspaces and the temperature of the floor assembly. The rigid insulation protects the floor assembly from condensation.

A ground cover is also recommended to limit evaporation of water from the soil. The interior grade should be higher than the exterior grade. Floor cavity insulation should be located in contact with the rigid insulation. Rim joists should be internally insulated with rigid insulation to control condensation or an air impermeable insulation should be applied to the interior of the rim joist. Alternatively, exterior insulating sheathing can be used. A protection board is recommend to be installed on the underside of the rigid insulation to protect the insulation layer from insects and rodents.

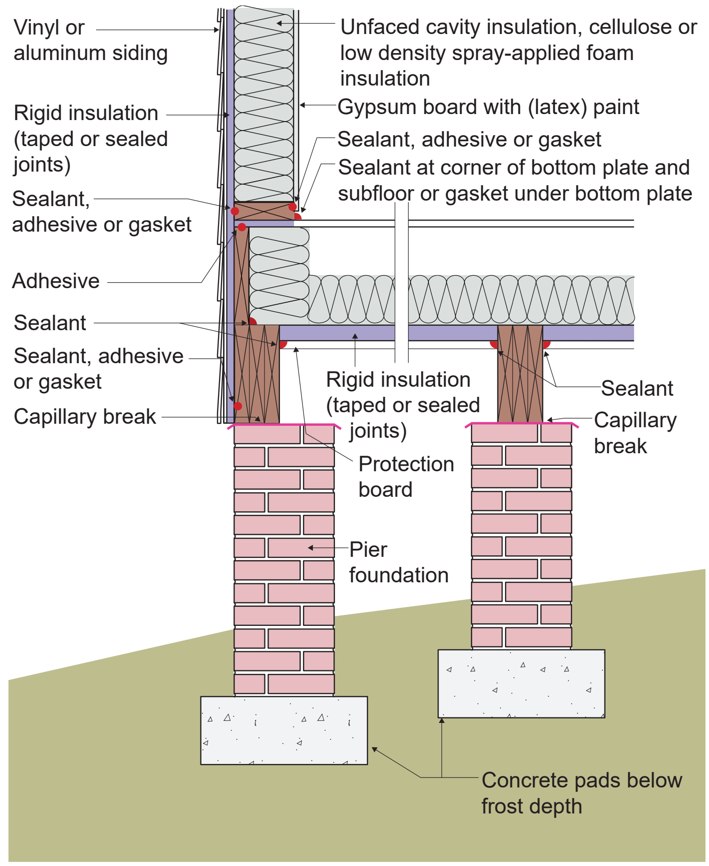


Figure 6.11: Vented Crawlspace – Pier Foundation - Rigid Insulation

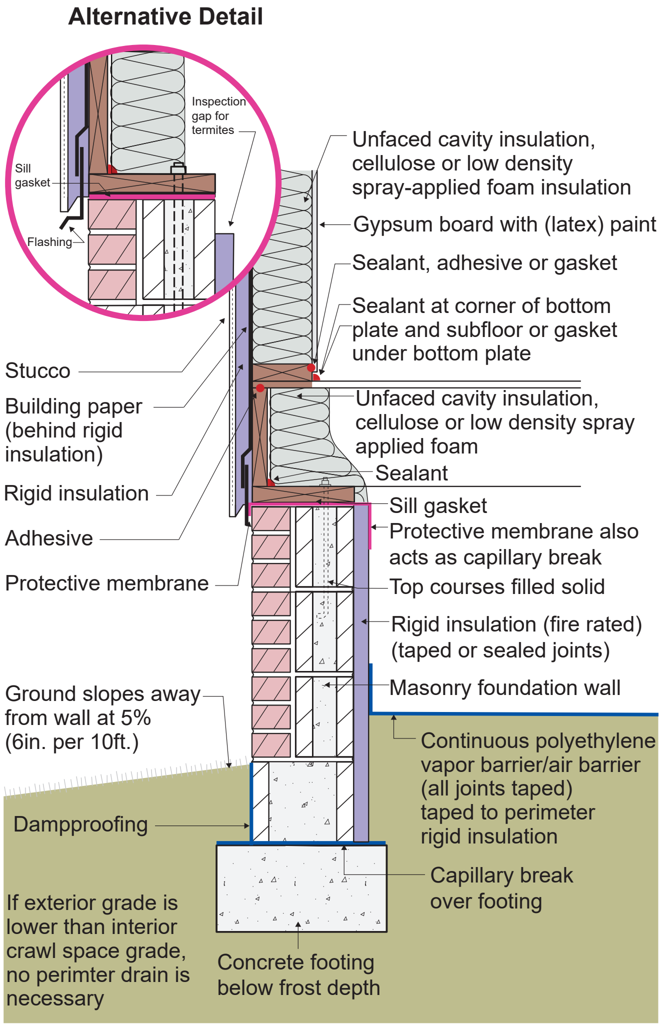


Figure 6.12: Conditioned Crawlspace – Rigid Insulation

Figure 6.12: Conditioned Crawlspace – Rigid Insulation

Applicability – all hygro-thermal regions

A provision for moisture removal must be provided by conditioning the crawl space with a duct distribution system providing supply and return air or by installing a dehumidifier or by exhaust venting the crawlspace with an exhaust fan.

Non-water-sensitive rigid insulation should be installed at the perimeter and rigid insulation should be installed at rim joist areas (either internally or externally). The interior grade should be higher than the exterior grade. A ground cover should be installed to act as both an air control layer and a vapor control layer (vapor barrier).

Figure 6.13: Conditioned Crawlspace – Spray Polyurethane Foam

Applicability – all hygro-thermal regions

A provision for moisture removal must be provided by conditioning the crawl space with a duct distribution system providing supply and return air, by installing a dehumidifier or by exhaust venting the crawlspace with an exhaust fan.

The air control layer in this assembly is a layer of polyurethane spray foam insulation directly applied to the interior of the perimeter crawlspace foundation wall assembly. High density closed cell spray foam should be used.

The interior grade should be higher than the exterior grade. A ground cover should be installed such that it also acts as both an air control layer and a vapor control layer (vapor barrier).

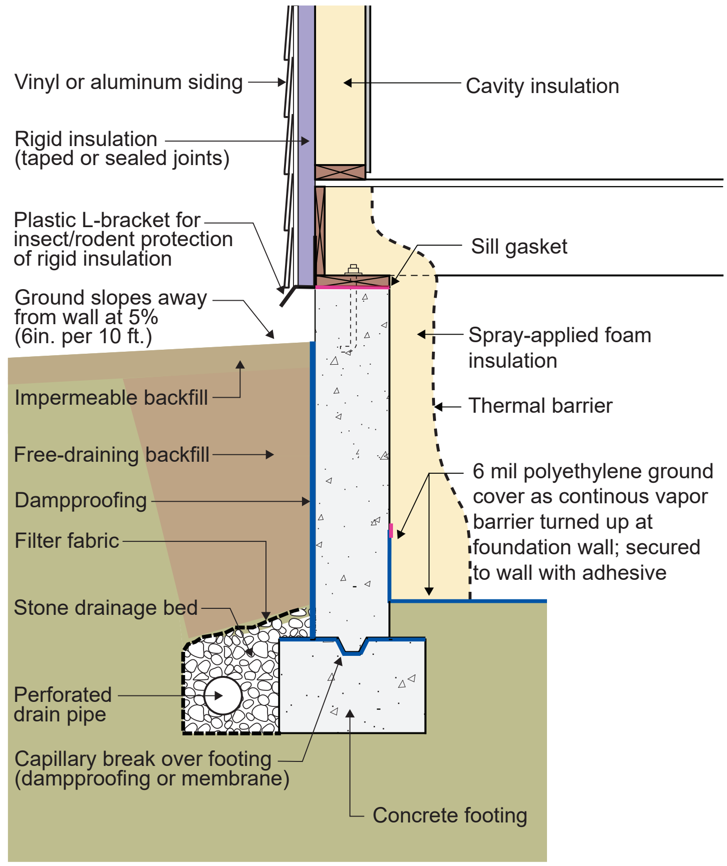


Figure 6.13: Conditioned Crawlspace – Spray Polyurethane Foam

Slab Foundations

Capillary control is necessary for slab-on-grade construction. Stem wall slab foundations require a plastic ground cover/vapor barrier under the interior slab. Monolithic slabs need plastic ground covers that extend under the perimeter grade beam and upwards to grade. Additionally, the exposed portion of the monolithic slab edge that is exposed to the outside should be painted with latex paint to reduce water absorption. In all slab assemblies, a capillary break is required under perimeter wall framing.

Insulation can be installed on the underside of slab foundations, on the perimeter of slab foundations or on the top of slab foundations – or some combination. The key concern is thermal bridging associated with discontinuity of the insulation.

Figure 6.14: Insulated Stem Wall Slab Foundation – XPS and EPS Rigid Insulation

Applicability – all hygro-thermal regions

Note the thermal uncoupling of the concrete slab from the stem wall. The rigid insulation also acts as a bond break disconnecting the concrete slab from the stem wall. The rigid insulation extends inwards horizontally and is located on a granular capillary break. A sheet polyethylene vapor control layer (vapor barrier) is located over the top of the rigid insulation in direct contact with the underside of the concrete slab.

The membrane strip that is sealed with mastic connecting the top of the stem wall to the top of the concrete slab acts as a capillary break as well as an insect barrier.

In this assembly either extruded polystyrene (XPS) or expanded polystyrene (EPS) rigid insulation can be used.

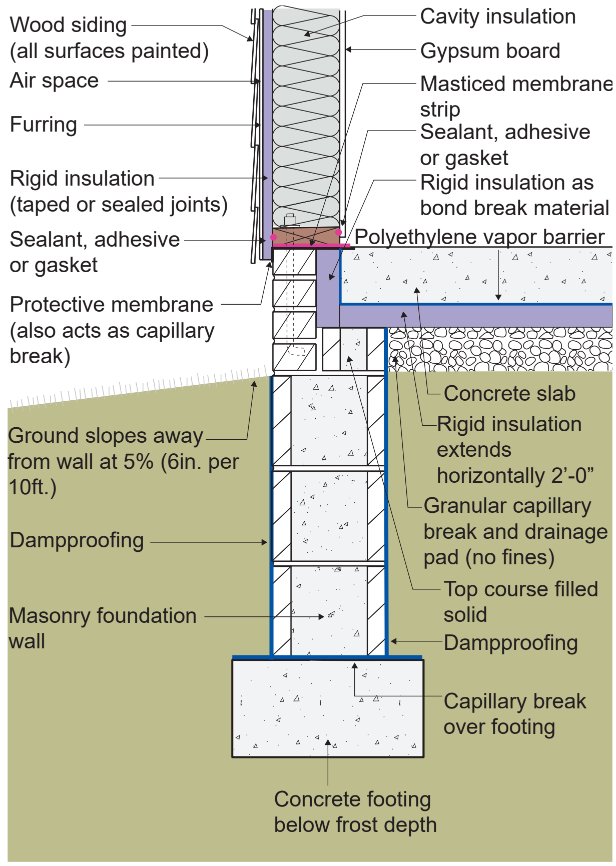


Figure 6.14: Insulated Stem Wall Slab Foundation – XPS and EPS Rigid Insulation

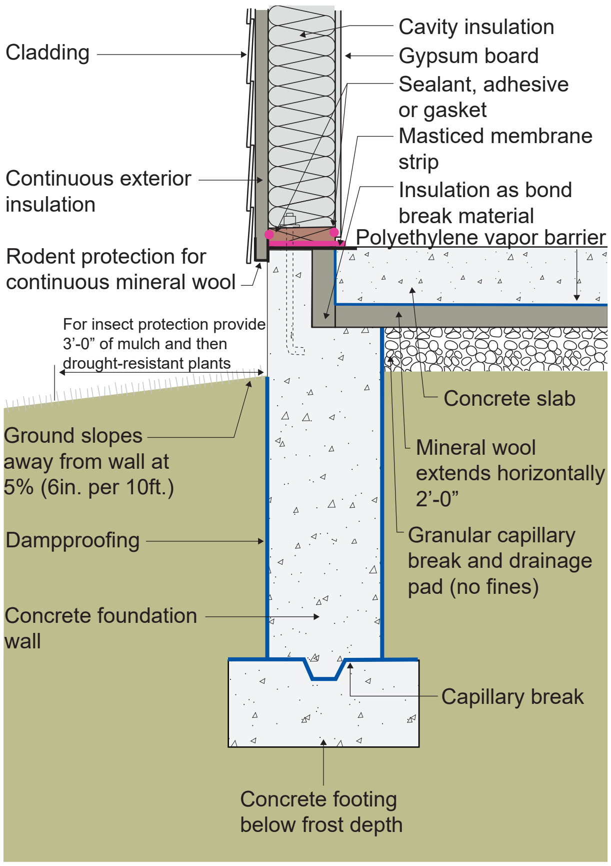


Figure 6.15: Insulated Stem Wall Slab Foundation – Mineral Wool Rigid Insulation

Figure 6.15: Insulated Stem Wall Slab Foundation – Mineral Wool Rigid Insulation

Applicability – all hygro-thermal regions

Note the thermal uncoupling of the concrete slab from the stem wall. The rigid insulation also acts as a bond break disconnecting the concrete slab from the stem wall. The rigid insulation extends inwards horizontally and is located on a granular capillary break. A sheet polyethylene vapor control layer (vapor barrier) is located over the top of the rigid insulation in direct contact with the underside of the concrete slab.

The membrane strip that is sealed with mastic connecting the top of the stem wall to the top of the concrete slab acts as a capillary break as well as an insect barrier.

In this assembly mineral wool rigid insulation can be used.

Figure 6.16: Insulated Stem Wall Slab Foundation – XPS and EPS Rigid Insulation

Applicability – all hygro-thermal regions

Note the thermal uncoupling of the concrete slab from the stem wall. The rigid insulation also acts as a bond break disconnecting the concrete slab from the stem wall. The rigid insulation extends inwards horizontally and is located on a granular capillary break. A sheet polyethylene vapor control layer (vapor barrier) is located over the top of the rigid insulation in direct contact with the underside of the concrete slab.

An additional layer of rigid insulation is located to the interior of vertical surface of the stem wall extending from the top of the footing to the underside of the horizontal rigid insulation under the concrete slab. This vertical stemwall insulation is recommended for climate zones 4 and colder, due to potential occupant comfort concerns.

Note the capillary break on the top of the footing and the interior and exterior dampproofing of the stem wall.

The membrane strip that is sealed with mastic connecting the top of the stem wall to the top of the concrete slab acts as a capillary break as well as an insect barrier.

In this assembly either extruded polystyrene (XPS) or expanded polystyrene (EPS) rigid insulation can be used.

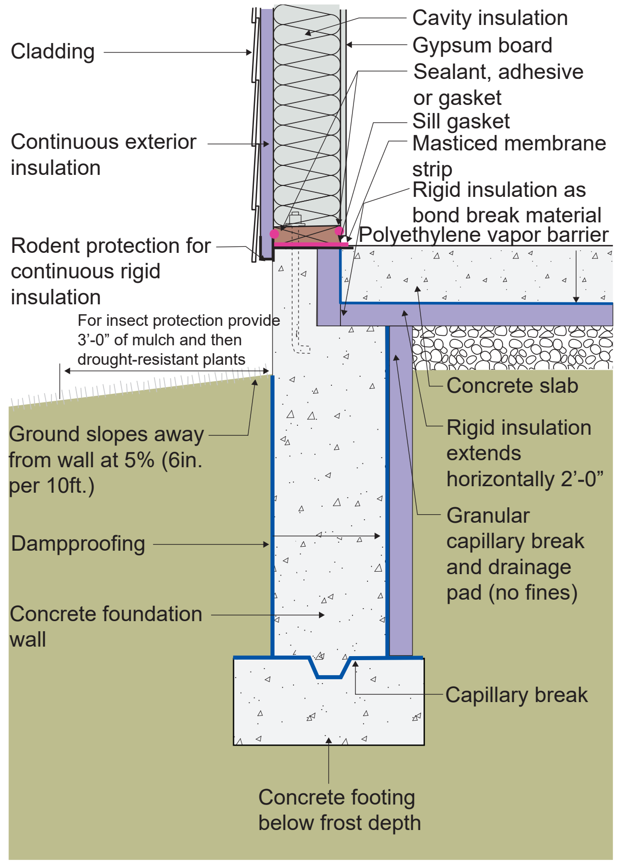


Figure 6.16: Insulated Stem Wall Slab Foundation – XPS and EPS Rigid Insulation

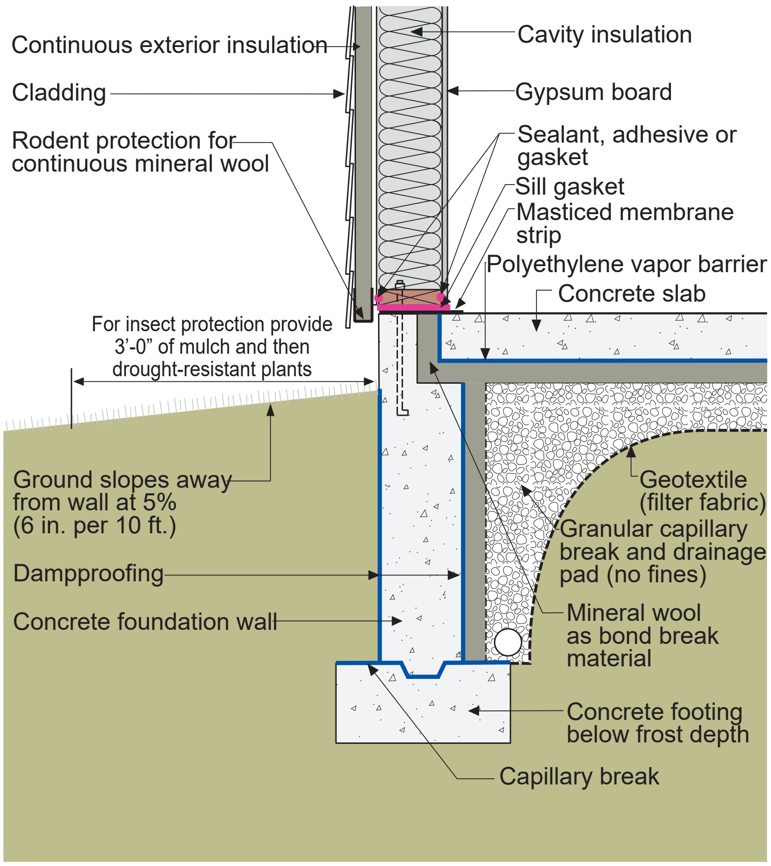


Figure 6.17: Insulated Stem Wall Slab Foundation – Mineral Wool Rigid Insulation

Figure 6.17: Insulated Stem Wall Slab Foundation – Mineral Wool Rigid Insulation

Applicability – all hygro-thermal regions

Note the thermal uncoupling of the concrete slab from the stem wall. The rigid insulation also acts as a bond break disconnecting the concrete slab from the stem wall. The rigid insulation extends inwards horizontally and is located on a granular capillary break. A sheet polyethylene vapor control layer (vapor barrier) is located over the top of the rigid insulation in direct contact with the underside of the concrete slab.

An additional layer of rigid insulation is located to the interior of vertical surface of the stem wall extending from the top of the footing to the underside of the horizontal rigid insulation under the concrete slab. This vertical stemwall insulation is recommended for climate zones 4 and colder, due to potential occupant comfort concerns.

Note the capillary break on the top of the footing and the interior and exterior dampproofing of the stem wall.

The membrane strip that is sealed with mastic connecting the top of the stem wall to the top of the concrete slab acts as a capillary break as well as an insect barrier.

In this assembly mineral wool rigid insulation is used. A granular capillary break and interior perimeter footing drain is installed to protect the mineral wool rigid insulation.

Figure 6.18: Externally Insulated Monolithic Slab Foundation - XPS Rigid Insulation

Applicability – all hygro-thermal regions

The key to this assembly is protecting the exterior rigid insulation with a non-water sensitive protection board such cellular PVC. The insulation and protection board should be installed within the formwork prior to placing the concrete so that the insulation is protected from the start of the project. Additionally, the polyethylene vapor control layer (vapor barrier) should extend under the grade beam so that it can effectively act as a capillary break. The metal flashing that is sealed with mastic connecting the top of the stem wall to the top of the concrete slab acts as a capillary break as well as an insect barrier.

In this assembly extruded polystyrene (XPS) rigid insulation is used.

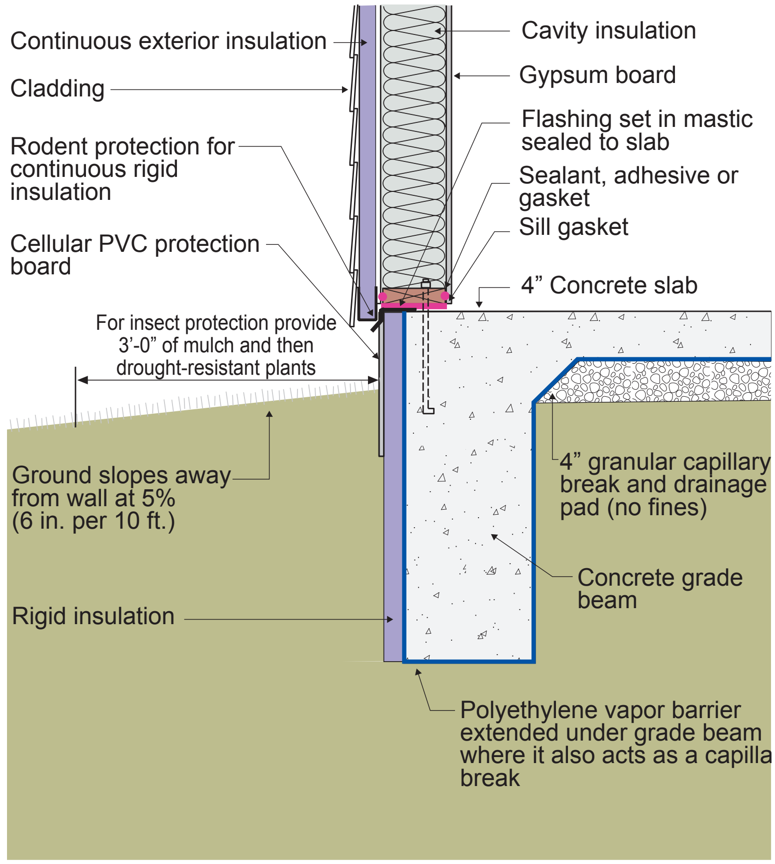


Figure 6.18: Externally Insulated Monolithic Slab Foundation - XPS Rigid Insulation

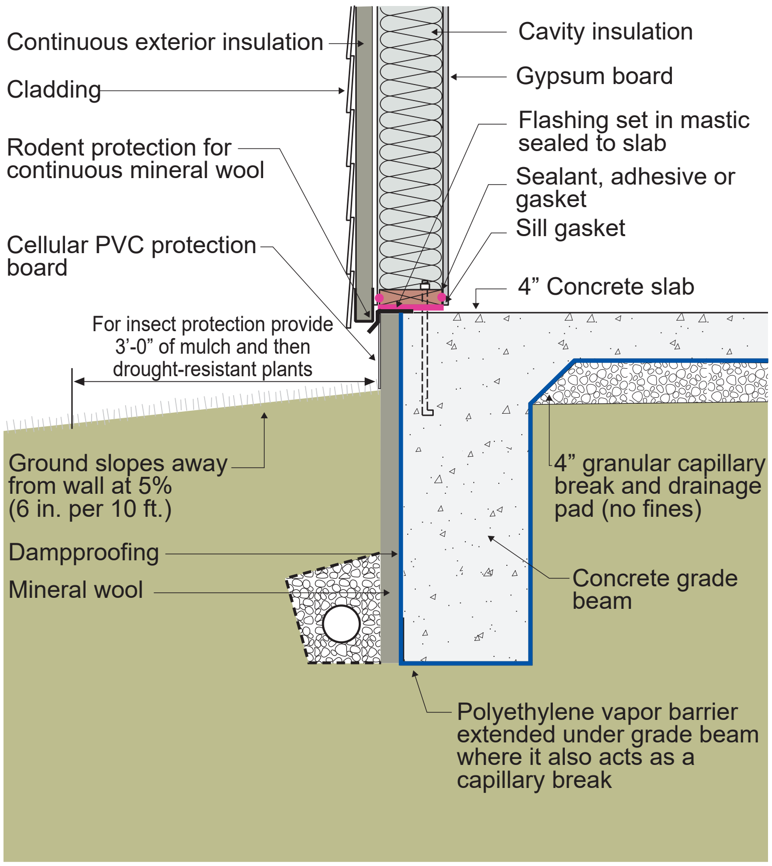


Figure 6.19: Externally Insulated Monolithic Slab Foundation – Mineral Wool Rigid Insulation

Figure 6.19: Externally Insulated Monolithic Slab Foundation – Mineral Wool Rigid Insulation

Applicability – all hygro-thermal regions

The key to this assembly is protecting the exterior rigid insulation with a non-water sensitive protection board such cellular PVC. The insulation and protection board should be installed within the formwork prior to placing the concrete so that the insulation is protected from the start of the project. Additionally, the polyethylene vapor control layer (vapor barrier) should extend under the grade beam so that it can effectively act as a capillary break. The metal flashing that is sealed with mastic connecting the top of the stem wall to the top of the concrete slab acts as a capillary break as well as an insect barrier.

In this assembly mineral wool rigid insulation is used. An exterior perimeter footing drain is installed to protect the mineral wool rigid insulation.

Figure 6.20: Topside Insulated Monolithic Slab Foundation - XPS or EPS Rigid Insulation

Applicability – all hygro-thermal regions

The polyethylene vapor control layer (vapor barrier) under the monolithic slab foundation should extend under the grade beam and the vertically to grade so that it can effectively act as a capillary break.

In this assembly extruded polystyrene (XPS) or expanded polystyrene (EPS) rigid insulation can be used.

A vapor permeable liquid but closed building wrap is recommended under the wood subfloor to protect the insulation layer from topside occupant spillage of water and other fluids.

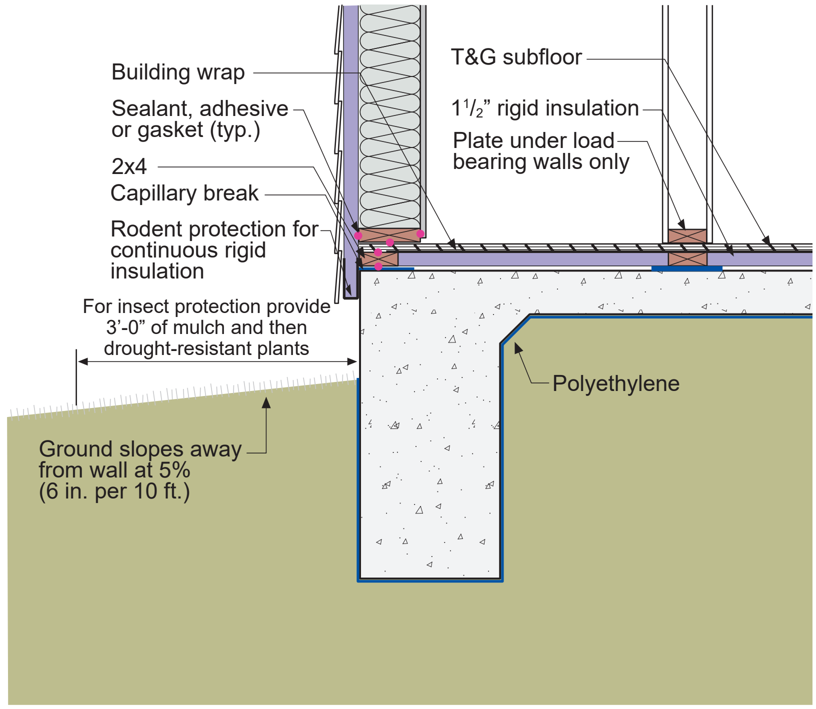


Figure 6.20: Topside Insulated Monolithic Slab Foundation - XPS or EPS Rigid Insulation

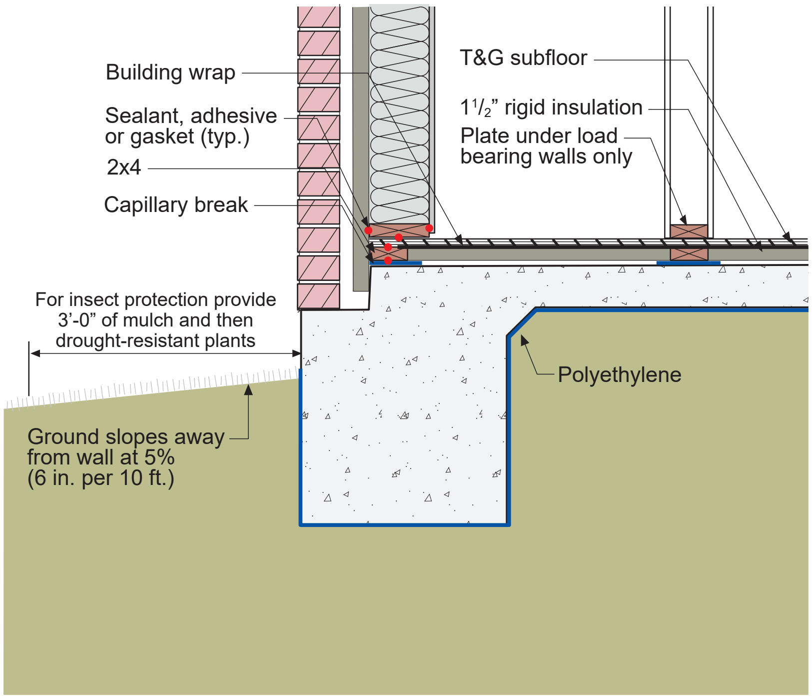


Figure 6.21: Topside Insulated Monolithic Slab Foundation – Mineral Wool Rigid Insulation

Figure 6.21: Topside Insulated Monolithic Slab Foundation – Mineral Wool Rigid Insulation

Applicability – all hygro-thermal regions

The polyethylene vapor control layer (vapor barrier) under the monolithic slab foundation should extend under the grade beam and the vertically to grade so that it can effectively act as a capillary break.

In this assembly mineral wool rigid insulation can be used.

A vapor permeable but liquid closed building wrap is recommended under the wood subfloor, to protect the insulation layer from topside occupant spillage of water and other fluids.

Figure 6.22: Topside Insulated Monolithic Slab Foundation with Brick Veneer - XPS or EPS Rigid Insulation

Applicability – all hygro-thermal regions

The polyethylene vapor control layer (vapor barrier) under the monolithic slab foundation should extend under the grade beam and the vertically to grade so that it can effectively act as a capillary break.

In this assembly extruded polystyrene (XPS) or expanded polystyrene (EPS) rigid insulation can be used.

A vapor permeable but liquid closed building wrap is recommended under the wood subfloor, to protect the insulation layer from topside occupant spillage of water and other fluids.

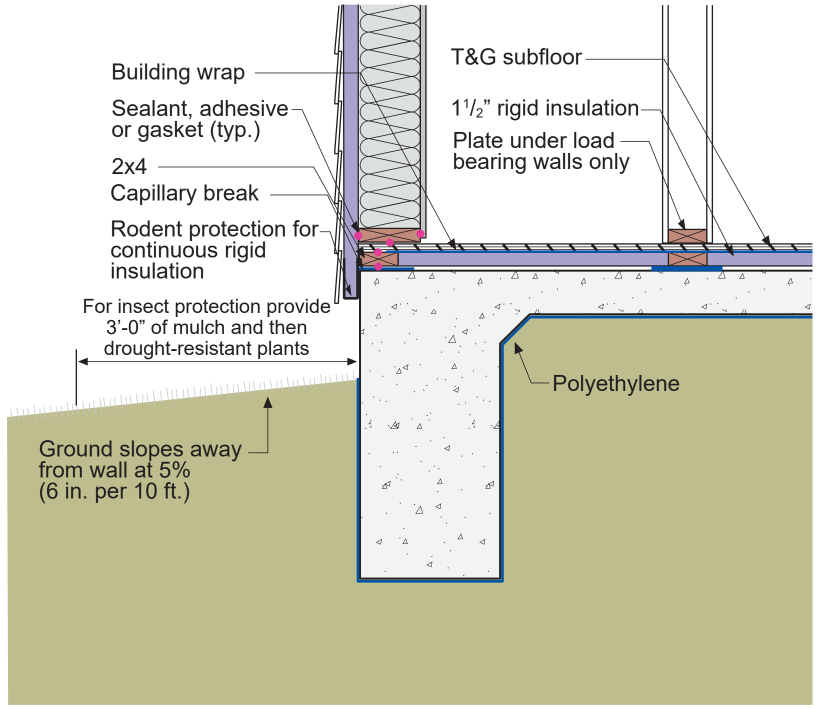


Figure 6.22: Topside Insulated Monolithic Slab Foundation with Brick Veneer - XPS or EPS Rigid Insulation

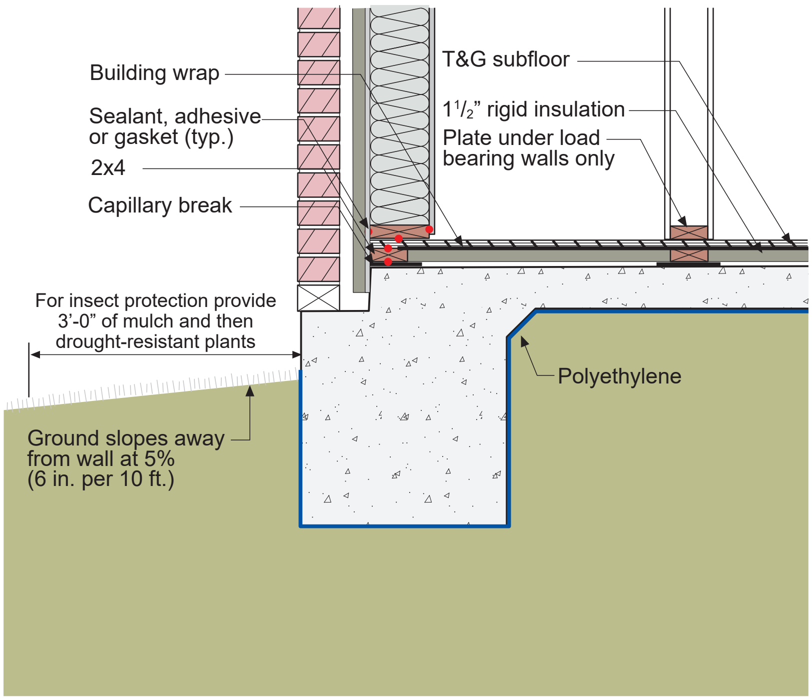


Figure 6.23: Topside Insulated Monolithic Slab Foundation with Brick Veneer – Mineral Wool Rigid Insulation

Figure 6.23: Topside Insulated Monolithic Slab Foundation with Brick Veneer – Mineral Wool Rigid Insulation

Applicability – all hygro-thermal regions

The polyethylene vapor control layer (vapor barrier) under the monolithic slab foundation should extend under the grade beam and the vertically to grade so that it can effectively act as a capillary break.

In this assembly mineral wool rigid insulation can be used.

A vapor permeable but liquid closed building wrap is recommended under the wood subfloor, to protect the insulation layer from topside occupant spillage of water and other fluids.

Figure 6.24: Shallow Frost Protected Slab Foundation – XPS or EPS Rigid Insulation

Applicability - Cold, Very Cold, and colder hygro-thermal regions

Frost protection is provided by horizontal insulation extending outward of the perimeter of the slab foundation. The horizontal extension is typically equal to the frost depth. The horizontal insulation is protected by a concrete skirt cast over a drainage mat. The entire foundation assembly is constructed over a granular capillary break and drainage pad connected to a perimeter drain.

A sheet metal perimeter flashing is sealed with mastic to the concrete slab edge to provide protection from insects.

In this assembly extruded polystyrene (XPS) or expanded polystyrene (EPS) rigid insulation can be used.

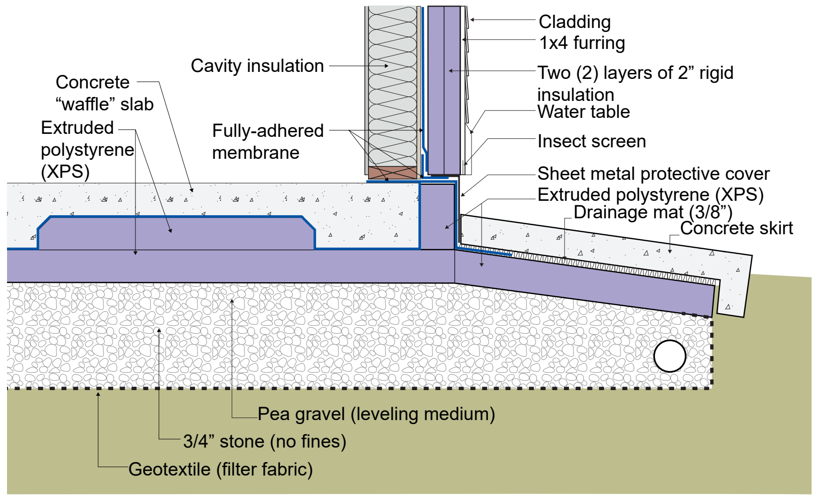


Figure 6.24: Shallow Frost Protected Slab Foundation – XPS or EPS Rigid Insulation

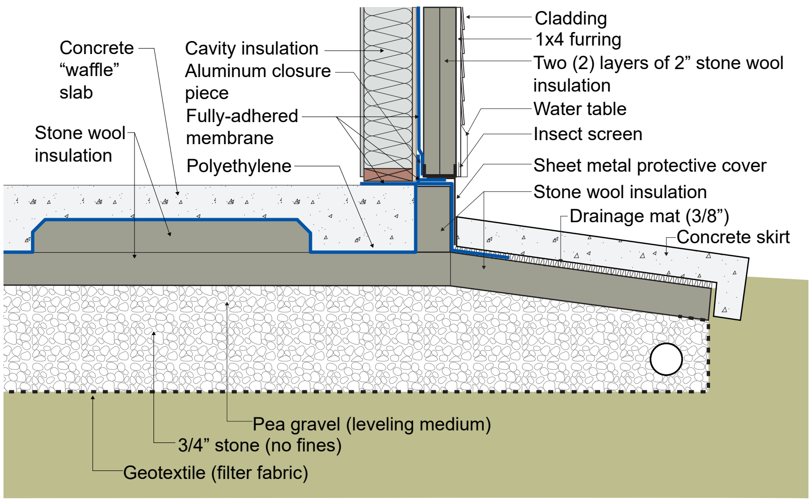


Figure 6.25: Shallow Frost Protected Slab Foundation – Mineral Wool Rigid Insulation

Figure 6.25: Shallow Frost Protected Slab Foundation – Mineral Wool Rigid Insulation

Applicability - Cold, Very Cold and colder hygro-thermal regions

Frost protection is provided by horizontal insulation extending outward of the perimeter of the slab foundation. The horizontal extension is typically equal to the frost depth. The horizontal insulation is protected by a concrete skirt cast over a drainage mat. The entire foundation assembly is constructed over a granular capillary break and drainage pad connected to a perimeter drain.

A sheet metal perimeter flashing is sealed with mastic to the concrete slab edge to provide protection from insects.

In this assembly mineral wool rigid insulation is used.

Building to Garage Foundation Connections

It is becoming increasingly common in Mixed, Marine, Cold, Very Cold, and colder hygro-thermal regions to insulate garage foundations in anticipation of conditioning the garage at a future date. **Figure 6.26** and **Figure 6.27** illustrate two of the typical approaches.

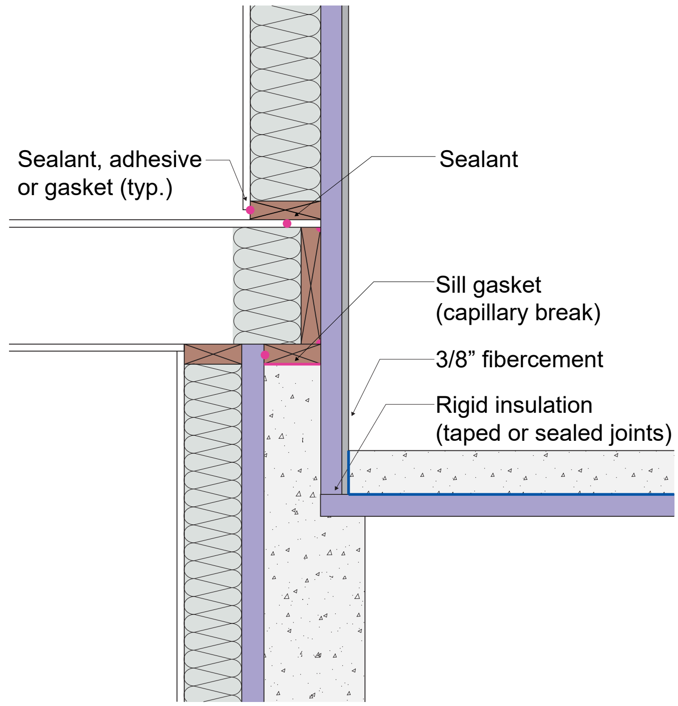


Figure 6.26

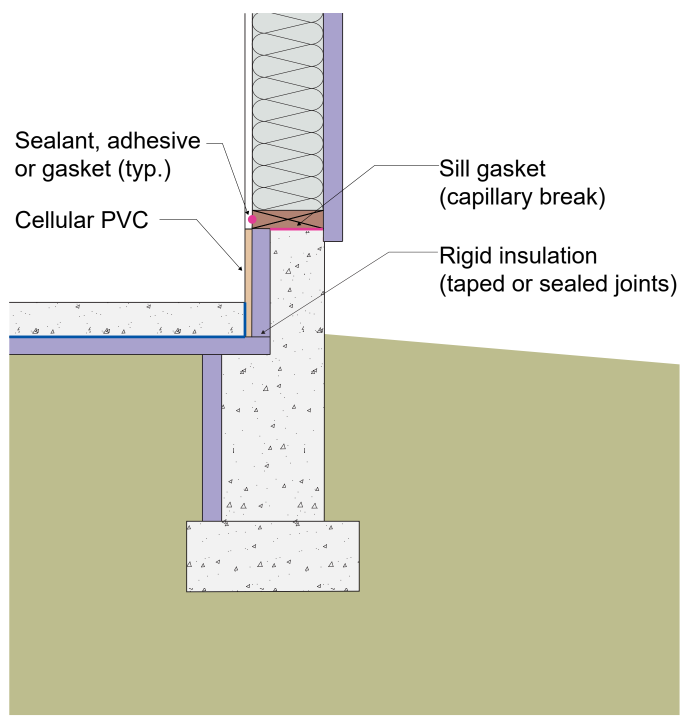


Figure 6.27

CHAPTER 7

Mechanical Systems

Mechanical equipment and ductwork should not be located outside of a home's conditioned space. The conditioned space is enclosed by the building's thermal barrier and air pressure boundary.

The pressure boundary is typically defined by the air control layer (air barrier). The thermal barrier is typically defined by the thermal control layer. Therefore, mechanical equipment and ductwork should not be located in exterior walls, vented attics, vented crawlspaces, garages or at any location exterior to a building's air control layer and thermal control layer. All air distribution systems should be located within the conditioned space. Additionally, ductwork should never be installed in or under floor slabs due to soil gas, radon, moisture condensation issues, and flooding of ductwork.

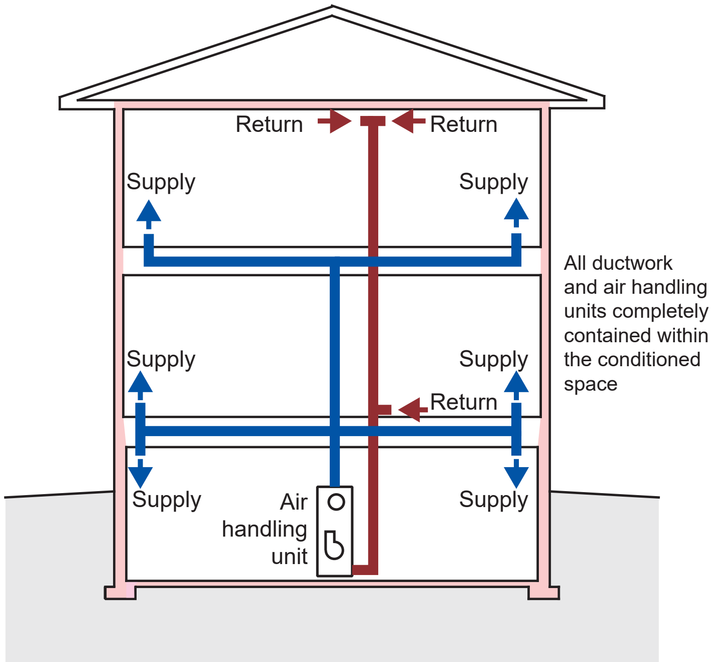
Figure 7.1, **Figure 7.2**, **Figure 7.3**, **Figure 7.4**, **Figure 7.5** and **Figure 7.6** illustrate six approaches that locate air handlers and ductwork completely within conditioned spaces, inside of the building thermal barrier and pressure boundary.

The cold air portion of most air conditioning equipment is internally insulated with insufficient thermal insulation to prevent sweating of the exterior metal cabinet when it is located outside in vented attics, vented (unconditioned) crawlspaces or garages.

Techniques have been developed that allow ductwork and air handlers to be installed in a leak-free manner. Leak-free ductwork and air handler installation is absolutely critical if ductwork and air handlers are installed outside of a building's thermal barrier and air pressure boundary such as in a vented attic. Leak-free ductwork and air handler installation is also recommended if ductwork and air handlers are installed within building thermal barriers and air pressure boundaries. Leakage of ductwork within interior building interstitial cavities can result in carpet dust marking and pollutant transfer as well as affecting thermal performance, moisture control and comfort.

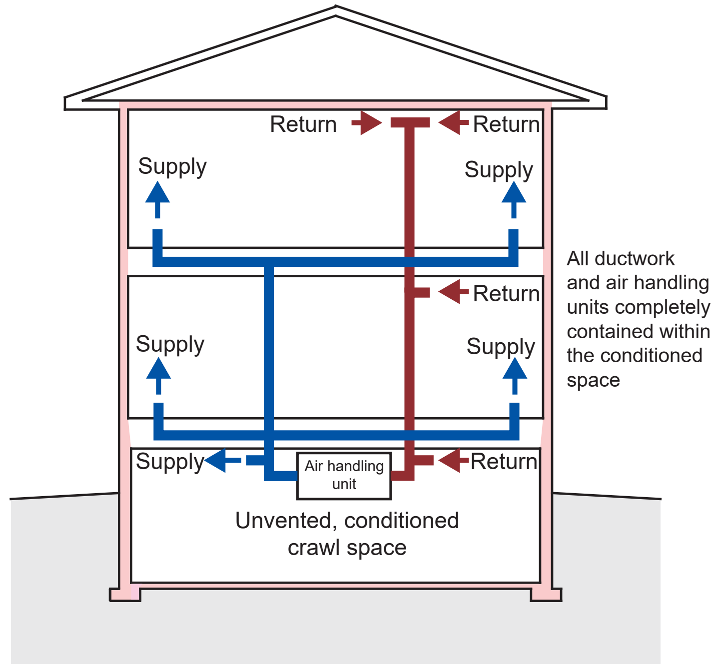
Ventilation

Ventilation is typically provided to protect building occupants and the building. Ventilation controls odors and airborne contaminants. Ventilation also can control interior moisture levels. However, excessive ventilation can contribute to excessive interior moisture levels.



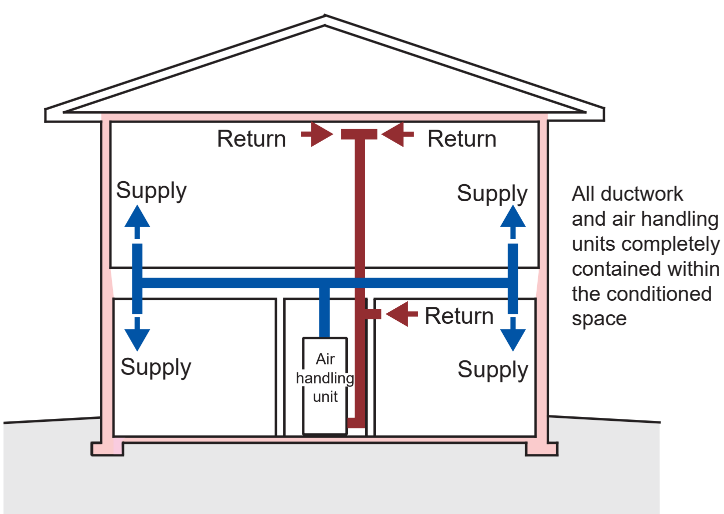
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 7.1: Mechanical System Layout – House with basement foundation and vented attic



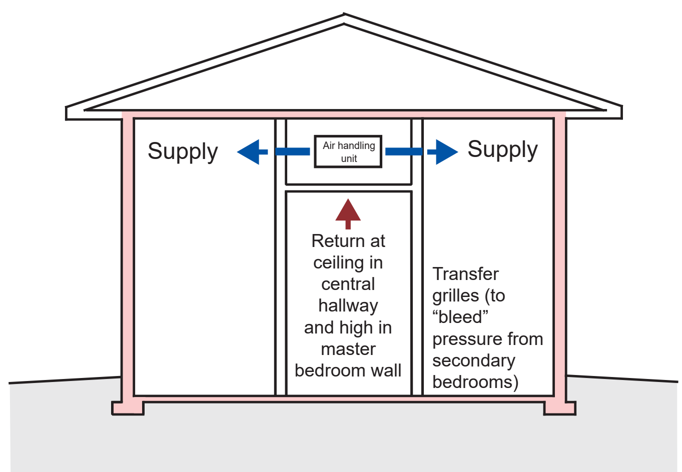
Note: Colored shading depicts the buildings thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space

Figure 7.2: Mechanical System Layout – House with conditioned crawlspace and vented attic.



ote: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 7.3: Mechanical System Layout – House with slab foundation and vented attic.



Note: Colored shading depicts the building's thermal barrier and ressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 7.4: Mechanical System Layout – House with slab foundation, vented attic and dropped ceiling.

Buildings can never be built too tight. However, they can be under-ventilated. The best way to go is to build a tight building enclosure and install controlled ventilation using a fan or several fans which operate when people are present. You don't want to over ventilate during cold weather and under ventilate during warm weather as well as the converse.

How much air should be provided? The model building codes provide the best guidance. Somewhere between 10 cfm and 20 cfm per person when the building is occupied. If a building doesn't have strong interior pollutant sources, as low as 10 cfm per person will work. If a building has strong interior pollutant sources, not even 20 cfm per person will be enough. What are strong interior pollutant sources? Smokers. Unvented gas fireplaces or space heaters. Unusual hobby activities. Gas ovens and gas cooktops. Generally, if you keep the water out of a building, vent combustion appliances to the exterior, don't smoke, and don't have unusual habits or an uncommon lifestyle, 10 cfm per person will be just fine.

How do you decide how many people live in a house? A good rule of thumb is to take the number of bedrooms and add 1. This assumes two people in the master bedroom and one person in each additional bed- room. The following ventilation requirements result when you follow the model building codes.

- 7.5 cfm/person plus 0.01 cfm/ft^2 of conditioned floor area

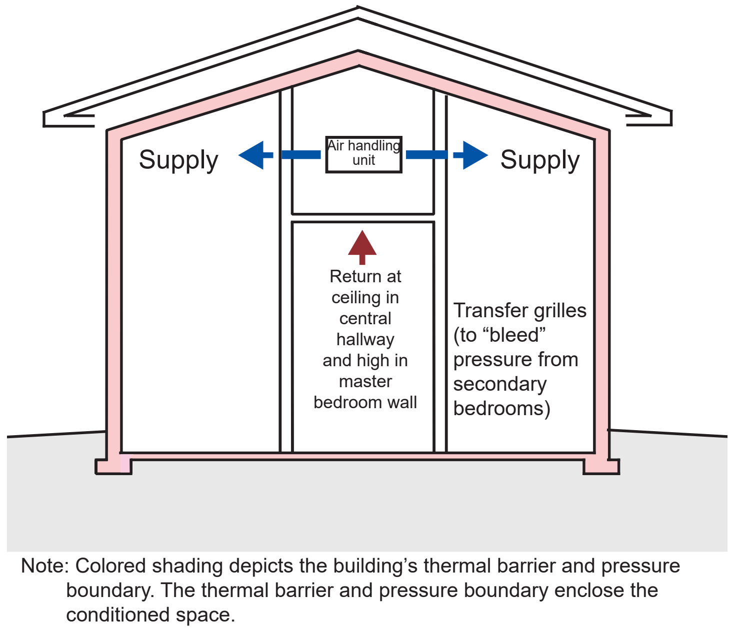


Figure 7.5: Mechanical System Layout – House with slab foundation, vented attic and dropped ceiling.

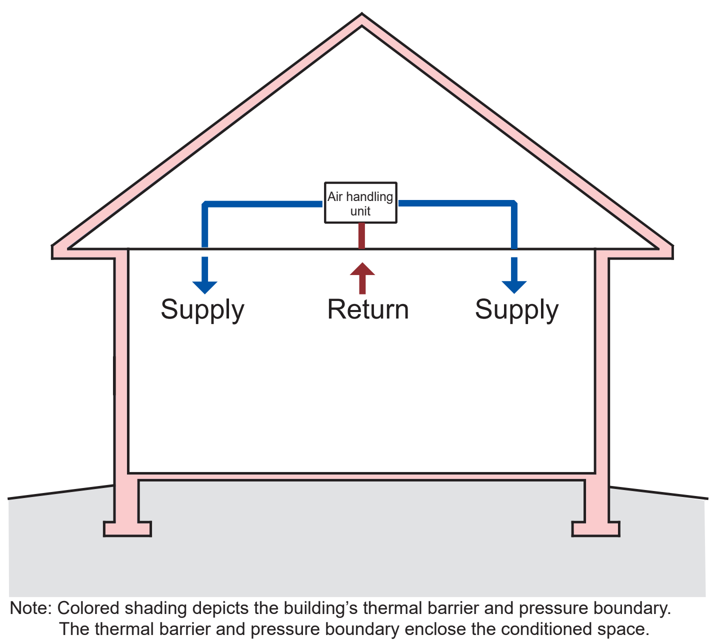


Figure 7.6: Mechanical System Layout – House with slab foundation and conditioned attic.

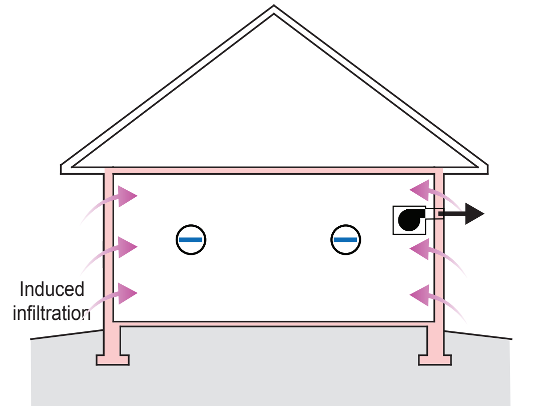


Figure 7.7: Dilution Ventilation – Exhaust system approach.

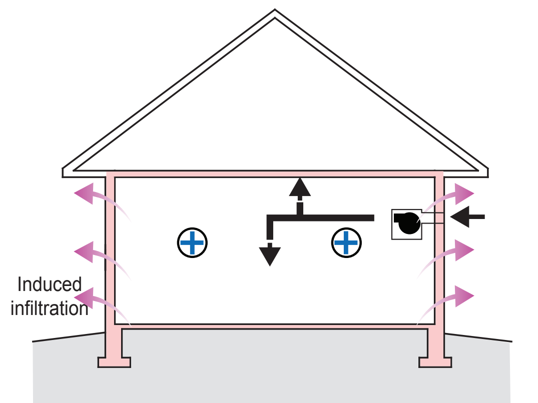


Figure 7.8: Dilution Ventilation – Supply system approach.

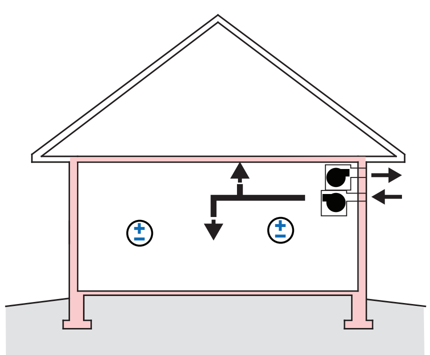


Figure 7.9: Dilution Ventilation – Balanced system approach.

For a 2,000 ft^2 three bedroom house with 4 occupants:

- 4 x 7.5 cfm = 30 cfm (people load)
- 2,000 ft^2 x 0.01 cfm/ft^2 = 20 cfm(house furnishing load)
- 30 cfm (people load) + 20 cfm (house furnishings load) = 50 cfm

Ventilation air should be provided when the building is occupied. Why ventilate when no one is in the building? Ventilation air should also be distributed (circulated) when the building is occupied.

Indoor Humidity and Airborne Pollutants

Indoor humidity and airborne pollutants to a limited extent are both controlled by ventilation. There are two kinds of ventilation: spot ventilation ("point source exhaust") and dilution ventilation. Both are necessary. Spot ventilation deals with point sources of pollution such as bathrooms and kitchens. Dilution ventilation deals with low-level pollutants throughout the home. This ventilation is in addition to the use of operable windows.

Every home should have exhaust from kitchens and from bathrooms. In kitchens, recirculating fans should be avoided because they become breeding grounds for biologicals, a major source of odors, fail to control cooking moisture and in all cases allow grease vapors to coat surfaces throughout the home. Kitchen range hoods should be exhausted to the outside to remove moisture, odors, and other pollutants.

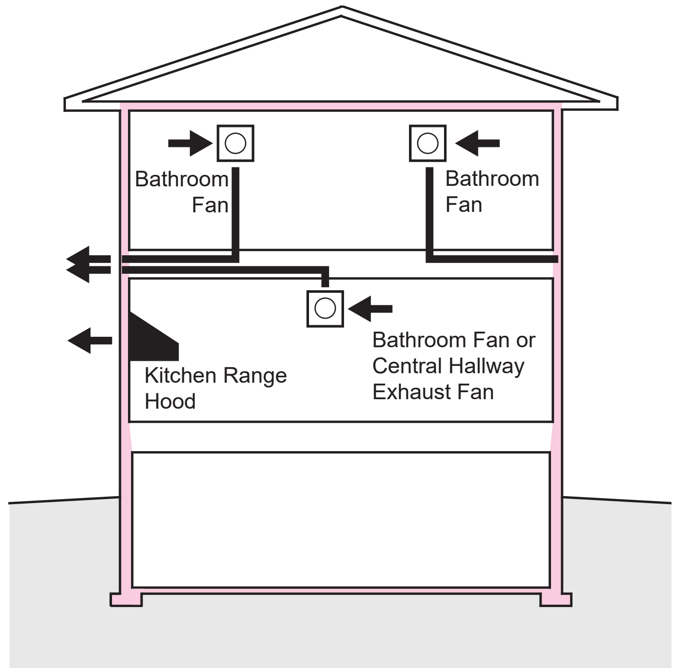
Bathroom fans should exhaust to the exterior — even bathrooms with operable windows. Low-sone fans are recommended because they are quiet (so they are more likely to be used) and more durable (in order to make them quiet they must be made durable).

Dilution ventilation can be provided three ways: exhaust (**Figure 7.7**), supply (**Figure 7.8**) or balanced (**Figure 7.9**).

The key to dilution ventilation is good distribution. Outside air should be provided throughout the house. Forced air duct systems can be excellent distribution systems (either by directly providing outside air or by providing mixing of interior air). Where duct distribution systems do not exist, multiport exhaust strategies can be used.

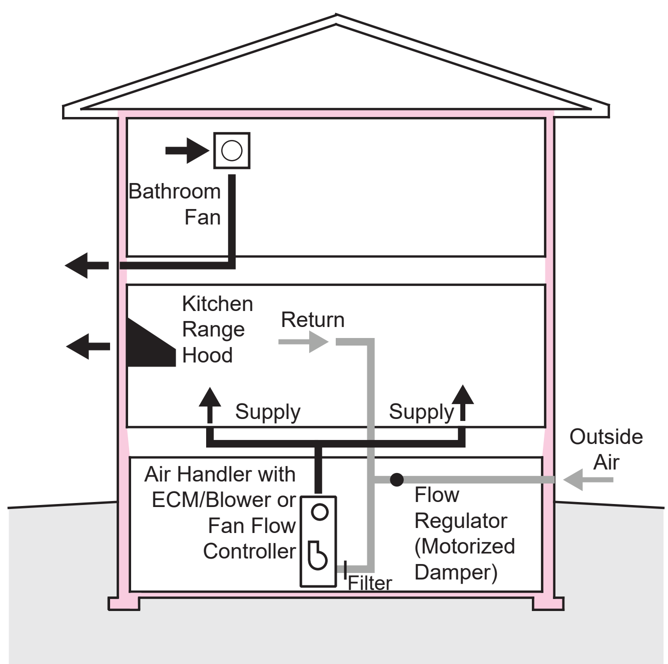
Most individuals are comfortable when the indoor relative humidity is between 20 and 60 percent. In cold climates during the coldest part of the winter, indoor relative humidity should be kept low — but in the comfort range (see **Figure 3.64**). During summer months, indoor relative humidity (in air-conditioned buildings) should not exceed 70 percent for extended periods of time (more than several days). In hot and humid and mixed humid climates this may only be possible with supplemental dehumidification — especially in small energy-efficient buildings.

In general, correctly sized exhaust ventilation systems have a slight depressurization effect on building enclosures; supply ventilation systems have a slight pressurization effect on building enclosures, and balanced ventilation systems do not affect building air pressures. See **Figures 7.10** through **7.15** for more detail on different types of ventilation systems. The best approach is to install balanced ventilation systems that provide mixing and distribution.



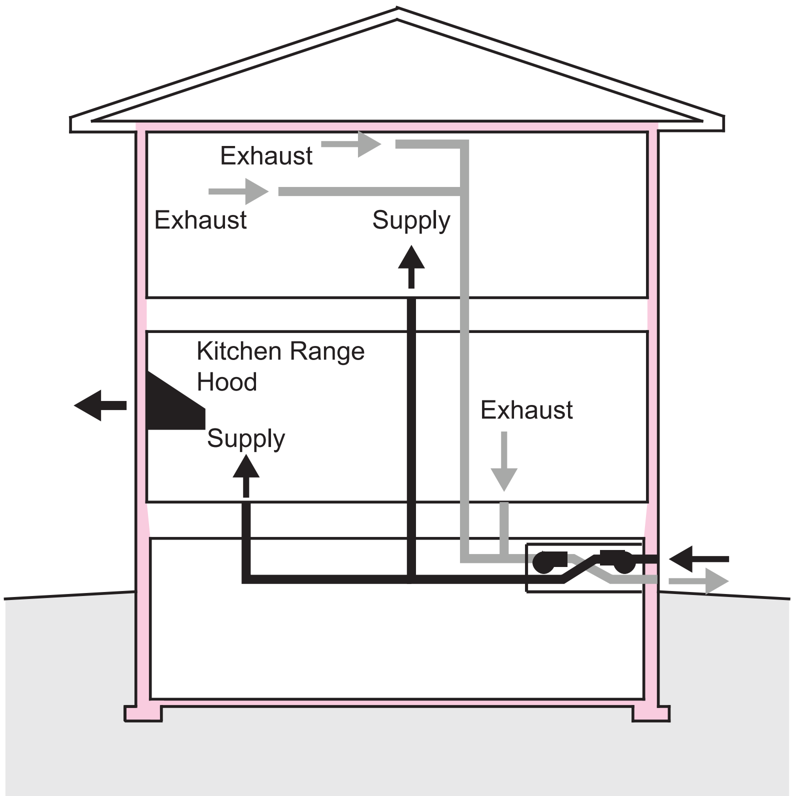
Note: Colored shading depicts the buildings thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space

Figure 7.10: Exhaust Only Ventilation – Approach using bathroom fans and vented range hood.



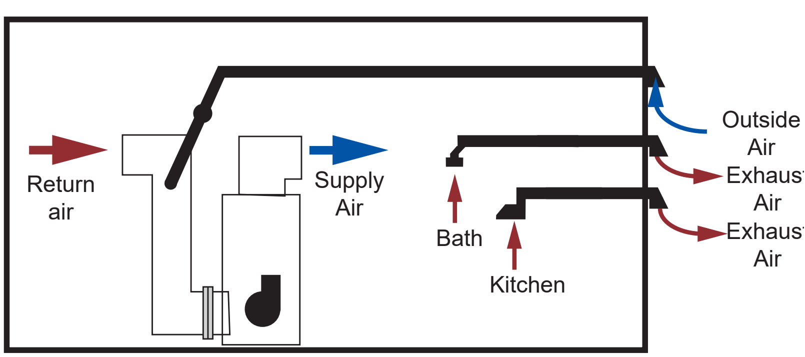
Note: Colored shading depicts the buildings thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space

Figure 7.11: Balanced Ventilation – Approach using outside air to the return side of the air handler coupled with bathroom fans and vented range hood.



Note: Colored shading depicts the buildings thermal barrier and pressure boundary.
The thermal barrier and pressure boundary enclose the conditioned space

Figure 7.12: Balanced Ventilation – Approach using a heat recovery ventilator (HRV) or energy recovery ventilator (ERV) and vented range hood.



Note: Colored shading depicts the buildings thermal barrier and pressure boundary.
The thermal barrier and pressure boundary enclose the conditioned space

Figure 7.13: Balanced Ventilation – Approach using outside air to the return side of the air handler coupled with bathroom fans and vented range hood.

Furnace fans or air handler fans should not run continuously unless at reduced speed using electrically commutated motors (ECM). These types of motors are typically found only on premium units. Even with efficient electric motors and blowers HVAC units should not run continuously if outside air ducted into the air handling system will only occur when the coils are energized. If blowers are run continuously, re-evaporation of condensate off the cooling coil will occur and condensation of humidity contained in the ducted outside air can occur on cold ductwork (i.e. ductwork cooled by cold air coming off energized coils). This can be avoided by cycling the air handler such that once coils are de-energized, blowers are also shutdown for 15 minutes to allow duct- work to warm-up and condensate to drain from the wet coil and drain pans. Continous operation of blowers during the cooling season also greatly diminishes dehumidification capacity of the equipment due to the re-evaporation covered previously.

A flow controller with a motorized damper can be used in a system where outside air is ducted to the return side of the air handler. When the air handler is operating and the motorized damper is open, outside air is brought into the building and distributed. The controller will only operate the blower with the damper open if the coils are energized or with a time-delay where the blower is shutdown for a given period after coils are de-energized to allow for system condensate drainage and duct system warming. This approach will also allow the blower to cycle several minutes each hour even if heating or cooling is not required. This will bring in outside air throughout the year in cases where the outside air supply is provided by the blower independent of thermostat control. The motorized damper prevents overventilation during long blower duty cycles

Exhaust fans extracting less than 50 cfm will typically not increase radon ingress, soil gas ingress or backdrafting problems with fireplaces or wood stoves due to their negligible effect on building air pressures. Larger exhaust air flows may lead to unacceptably high negative air pressures (greater than 5 Pascals negative). A pressure difference of 3 Pascals or less positive or negative is a recommended maximum allowable design metric for pressure differentials.

Spillage or backdrafting of combustion appliances is unacceptable. Only sealed combustion, direct vented, power vented or induced draft combustion appliances should be installed inside conditioned spaces for space conditioning or for domestic hot water. Gas ovens, gas stoves or gas cooktops should only be installed with an exhaust range hood directly vented to the exterior. Wood-burning fireplaces or gas-burning fireplaces should be supplied with glass doors and exterior combustion air ducted to the firebox.

Wood stoves should have a direct ducted supply of combustion air. Unvented (ventless) gas fireplaces or gas space heaters should never be installed. Sealed combustion direct vent gas fireplaces are an acceptable alternative. Portable kerosene heaters should never be used indoors.

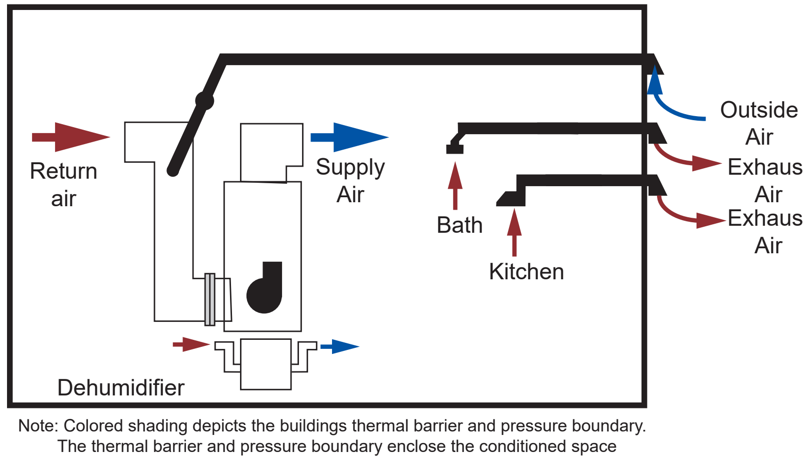


Figure 7.14: Balanced Ventilation – Approach using outside air to the return side of the air handler coupled with bathroom fans, a vented range hood and supplemental dehumidification.

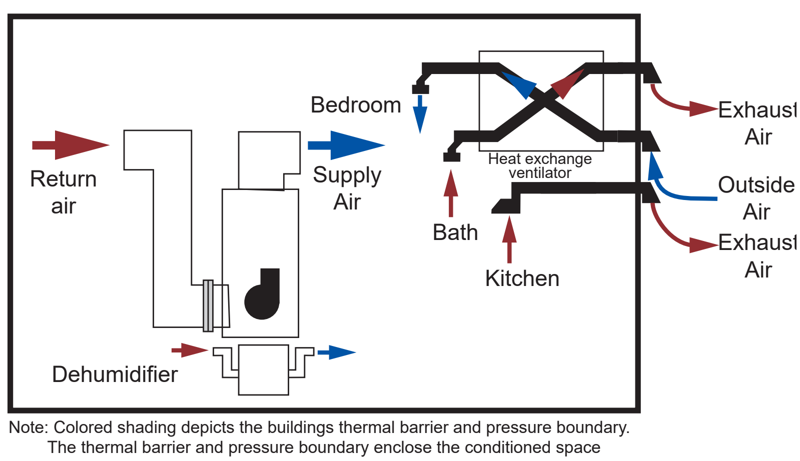


Figure 7.15: Balanced Ventilation - Approach using an energy recovery ventilator (ERV), a vented range hood and supplemental dehumidification.

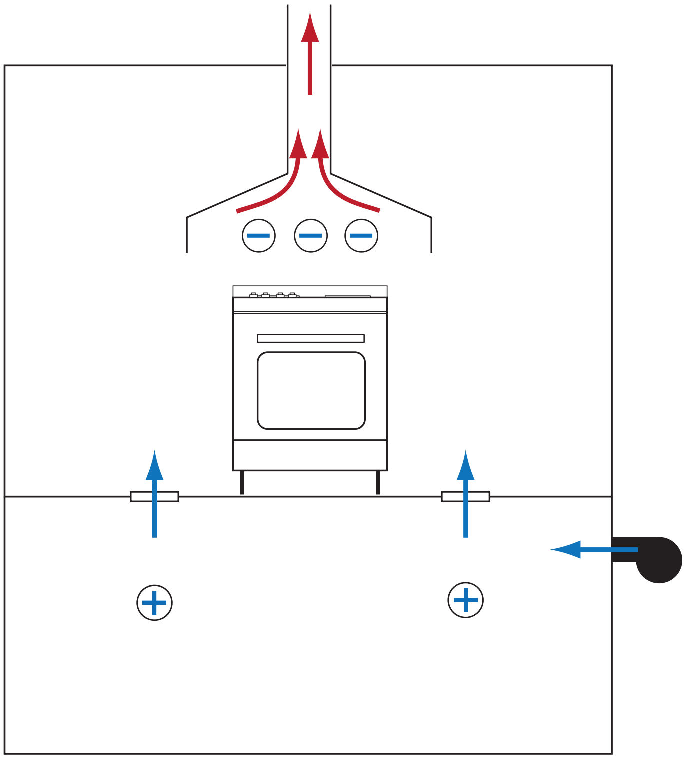


Figure 7.16: Make-Up Air for Vented Kitchen Range Hoods – Approach with basement foundations.

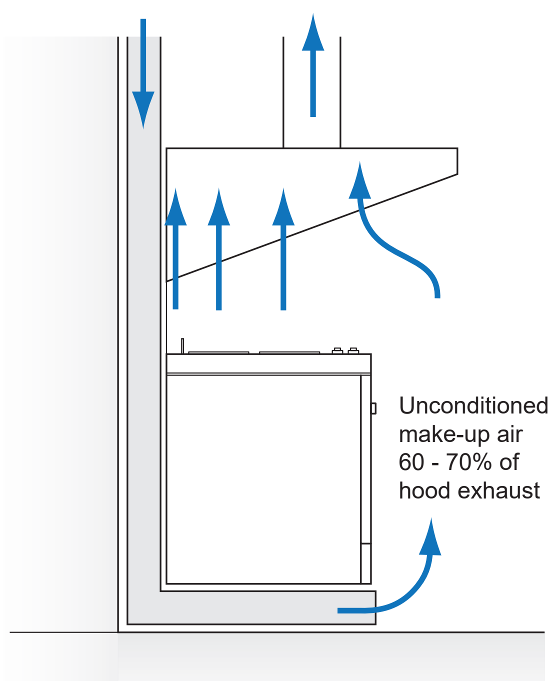


Figure 7.17: Make-Up Air for Vented Kitchen Range Hoods – Approach with slab foundations.

Large Vented Kitchen Range Hoods

A typical source of negative pressure in buildings are large vented range hoods. It is recommended that an interlocked supply fan be used; this is a building code requirement for range hoods over 400 CFM. In cold climates this fan can be located in basements where the incoming air is tempered by the volume of the basement (**Figure 7.16**). In hot-humid and mixed-humid climates the air should be ducted to the cooking appliance (**Figure 7.17**). In hot-humid and mixed-humid climates, if the exhaust hood has an unpowered make-up air opening on the other side of the house, cold supply air registers will sweat along the make-up air's path as it travels through the house on its way to the exhaust hood.

Chapter 7: Bibliography

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CHAPTER 8

Climate Zones 1 and 2

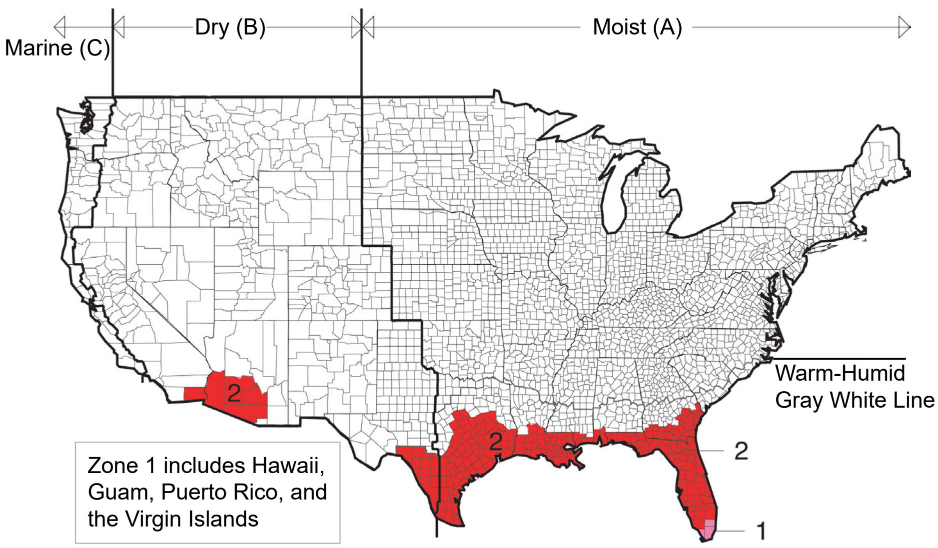

Figure 8.1: Climate Zones 1 and 2

The residential buildings constructed in these two zones (**Figure 8.1**) are principally constructed on slab foundations and crawlspaces due to lack of frost penetration and high ground water.

Where slab foundations are used they are typically uninsulated due to the lack of heat loss and heat gain through these assemblies due to the climate and due to concerns about insect migration. Exterior rigid insulation is often avoided for insect control reasons and constructability. Walls are a combination of wood frame and concrete block – concrete masonry units (CMU). In Florida, CMU construction is common for first-floor assemblies and wood frame for second-floor assemblies from Orlando south. From Orlando north, wood frame predominates as well as throughout the remainder of Climate Zone 2.

Roof construction is predominately vented attics. However, unvented conditioned roof assemblies are becoming more common due to the increasing demand to locate HVAC systems in the conditioned space, and moisture issues related to venting attics with exterior humid air in Climate Zone 2 - Moist (A).

Key Concerns and Control Strategies

In cooling climates, the principal moisture concerns are rain penetration, groundwater, and mold and mildew. High exterior levels of humidity encourage mold and mildew growth, as do cool interior surfaces due to the air conditioning of enclosures.

In cooling climates, wetting from the exterior during the cooling season by air movement is a major concern. In cooling climates, building enclosures are constructed in an airtight manner to control air leakage openings and to facilitate the dehumidification of indoor air, thereby limiting interior moisture levels. Controlled ventilation is also necessary to provide for the dilution of interior pollutants by controlled air change.

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Rain and Groundwater

Rain penetration and groundwater concerns are common to builders in all climates, and the methods of control in these climate zones are similar to those of other climates. Examples include draining claddings, appropriate placement of flashings, gutters, and downspouts which direct water away from foundations, and careful site grading and subgrade drainage.

Another source of external water, air-conditioning condensate drains, should be plumbed directly to graywater systems.

High Interior Humidity

Humidity control within conditioned spaces is accomplished during cooling periods by the dehumidification capabilities of air-conditioning systems and source control. Since latent cooling loads on air-conditioning systems can be higher than sensible cooling loads, proper sizing of air-conditioning systems with consideration of dehumidification capabilities is important. Oversizing of air-conditioning equipment can lead to high interior humidity problems due to a lack of dehumidification capability (oversized air-conditioning equipment will not operate as often and therefore will dehumidify less than properly sized equipment).

Combustion Appliances

Unvented combustion appliances such as gas stoves with standing pilot lights and room space heaters are significant sources of moisture as well as sources for other pollutants and should be avoided. Gas stoves and cook tops without standing pilot lights should be installed in conjunction with vented range hoods or some other vent provision.

Where combustion appliances are installed they should be uncoupled (not influenced by enclosure air pressures or supply air availability) from the conditioned space. In other words, sealed combustion, power-vented, induced draft, condensing, or pulse combustion devices should be used. Devices with traditional draft hoods should be avoided. Where fireplaces are installed, they should have their own supply of air from the exterior as well as tight-fitting glass doors. Wood stoves should also have their own supply of exterior air ducted directly to their firebox.

Foundations

Figure 8.2 is the recommended foundation detail for CMU construction in Climate Zone 1 (South Florida). Note the "seat" in the slab to receive the CMU wall. This seat provides a continuous flashing around the entire perimeter of the building. Also note that the stucco does not extend into the ground. Extending the stucco into the ground is bad practice that results in wicking of moisture into the assembly and provides a pathway for insects. Further note that the under slab polyethylene vapor barrier wraps the grade beam.

Figure 8.3 is the most common foundation detail in Climate Zone 2; it is uninsulated. Note the under slab polyethylene vapor barrier wrapping the grade beam. Further note that the stucco does not extend into the ground.

Figure 8.4 and **Figure 8.5** are effective means of providing a "dry" slab that is also insulated with rigid insulation where the insulation does not act as an insect entry point. A protective membrane strip is used to create a physical barrier to the entry of insects into the building enclosure. Fully adhered membranes are effective means of insect control. Ground treatment is also recommended.

Crawl spaces are common in the Gulf coast regions of Climate Zone 2. They typically are constructed as "vented" crawl spaces and elevated above grade due to high water tables and flooding issues. **Figure 8.6** is an example of recommended vented crawl space construction. Note the continuous rigid insulation on the underside of the floor framing. This rigid insulation's primary function is to protect the floor assembly from moisture. The rigid insulation should be protected with protection board from fire, insects and vermin. Note that the floor cavity insulation is located in direct contact

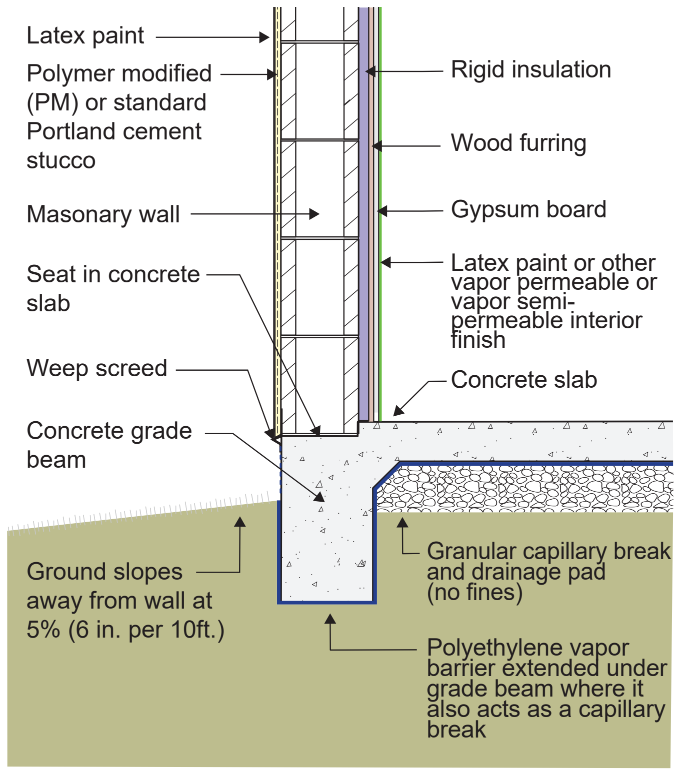

Figure 8.2: Slab Foundation - CMU wall construction.

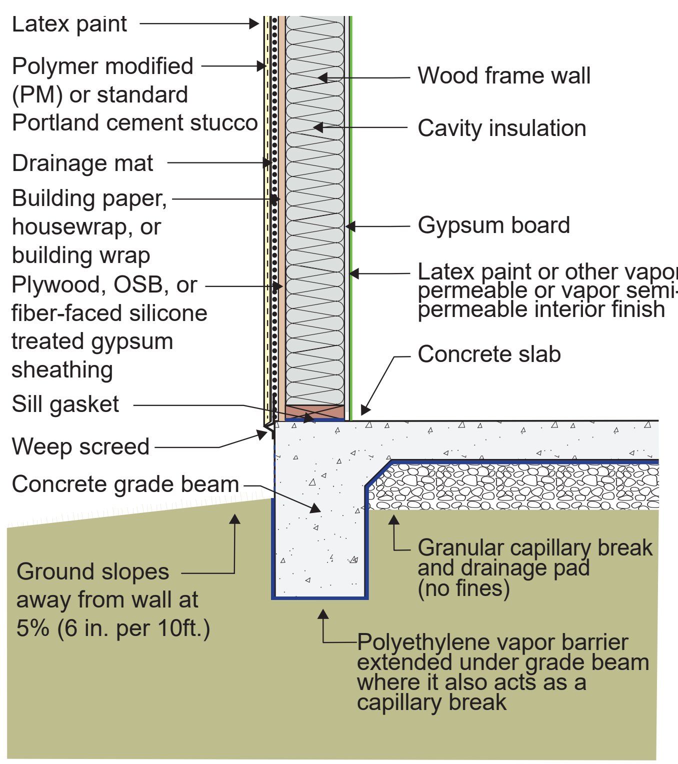

Figure 8.3: Slab Foundation - Frame wall assembly.

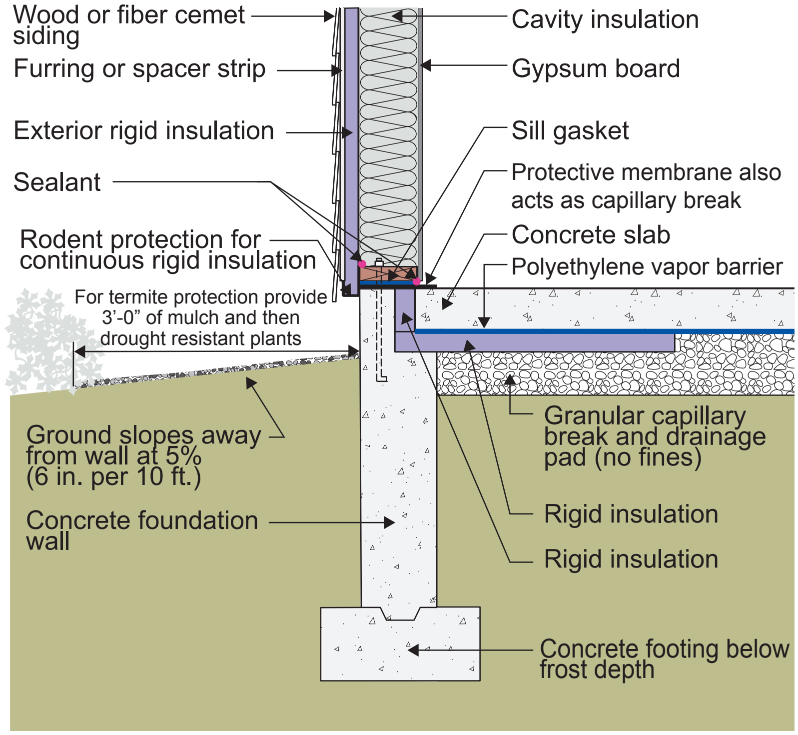

Figure 8.4: Stem Wall Foundation – Internally insulated.

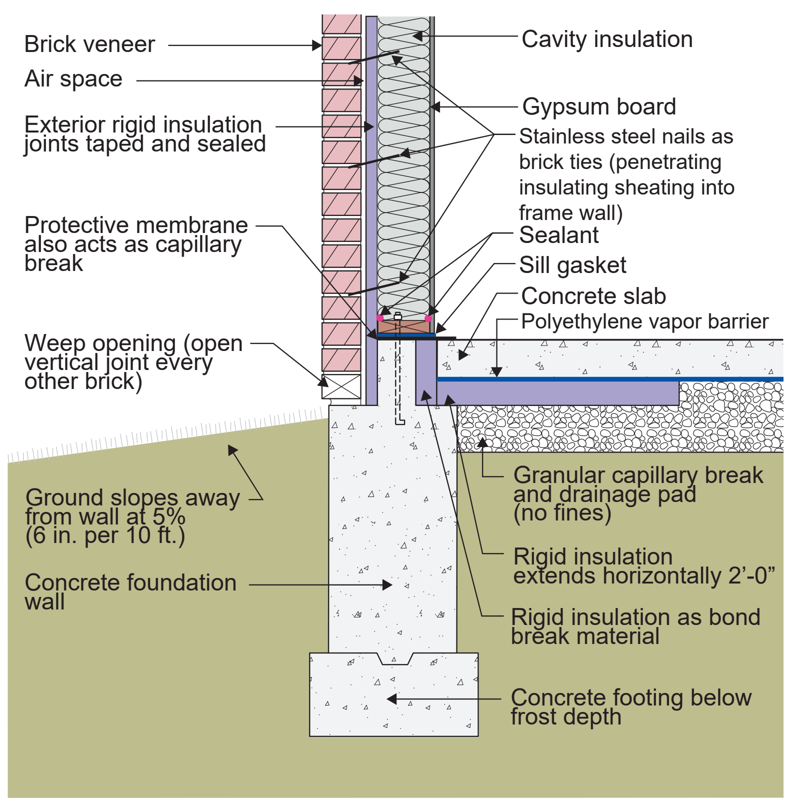

Figure 8.5: Stem Wall Foundation – Internally insulated stem wall foundation with brick veneer.

with the continuous rigid insulation leaving an air space above the cavity insulation. The air space results in a more comfortable floor. It is key with this approach to prevent air entry into the perimeter of the floor framing.

Unvented crawl spaces should only be considered where flooding is not a concern. **Figure 8.7** is a recommended approach to constructing conditioned crawl spaces. Note the fully adhered membrane barrier for insect control. In some jurisdictions an inspection strip or gap is required at the top of the crawl space wall as an insect control mechanism.

Walls

A common approach to construct wood-frame walls in Climate Zone 2 is illustrated in **Figure 8.8**. The key elements of this wall is the gap between the cladding and the rigid insulation used to control hydrostatic pressure. The wall cavity insulation can be fiberglass, cellulose, mineral wool or spray polyurethane foam.

An equally common approach to constructing wood-frame walls is illustrated in **Figure 8.9**. Note the use of plywood or OSB sheathing for structural strength. Also note the gap behind the cladding used to control hydrostatic pressure.

Figure 8.10 is the most typical approach to construct internally insulated CMU walls.

Roofs

The most common approach to roof construction in Climate Zone 1 and Climate Zone 2 is a vented attic. **Figure 8.11**

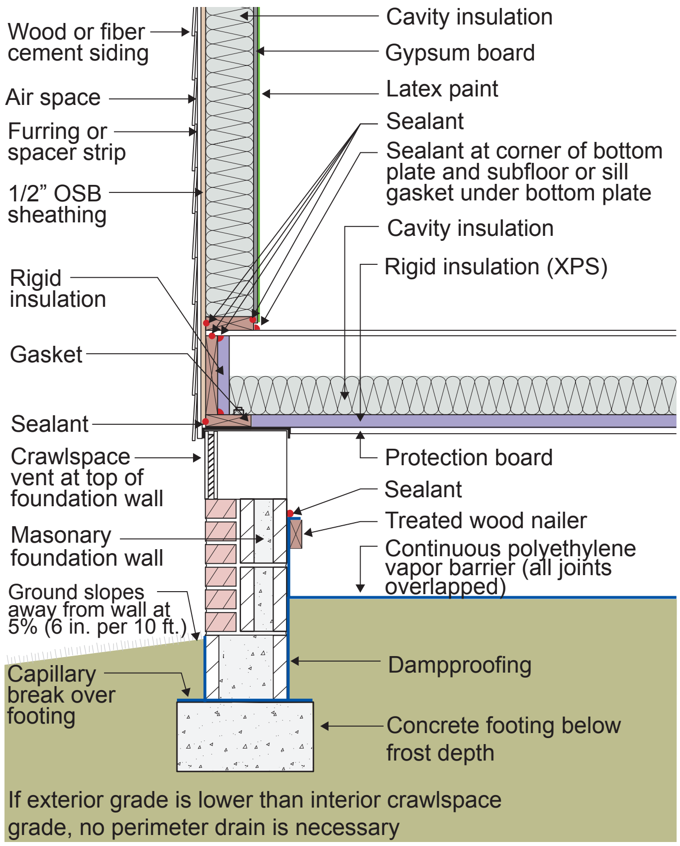

Figure 8.6: Crawl Space Foundation – Vented crawl space.

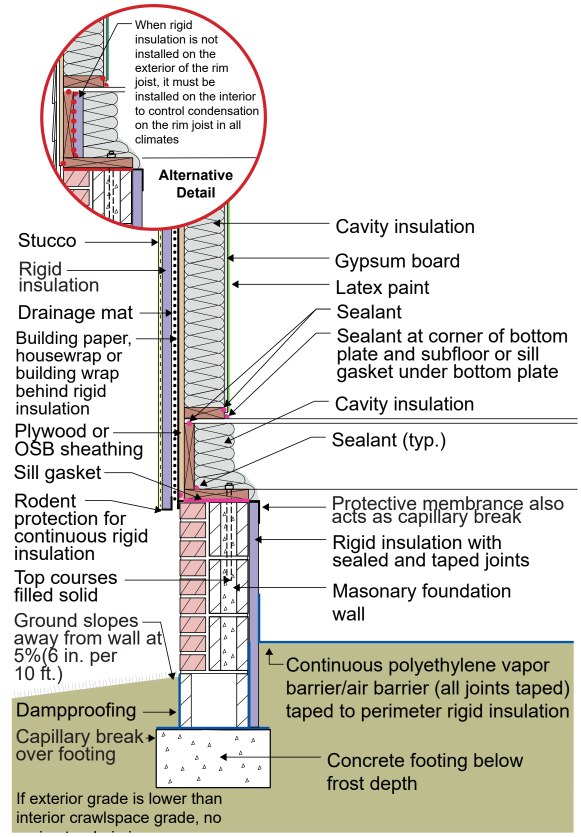

Figure 8.7: Crawl Space Foundation – Conditioned crawl space

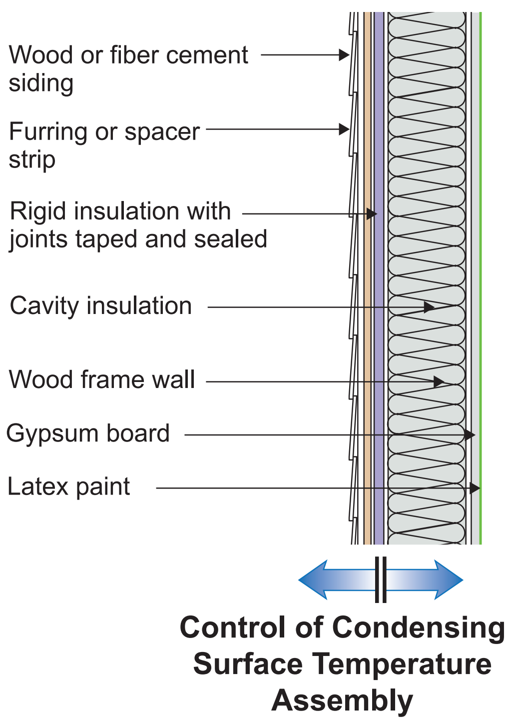

Figure 8.8: Wood Frame Wall – Control of condensing surface temperature assembly.

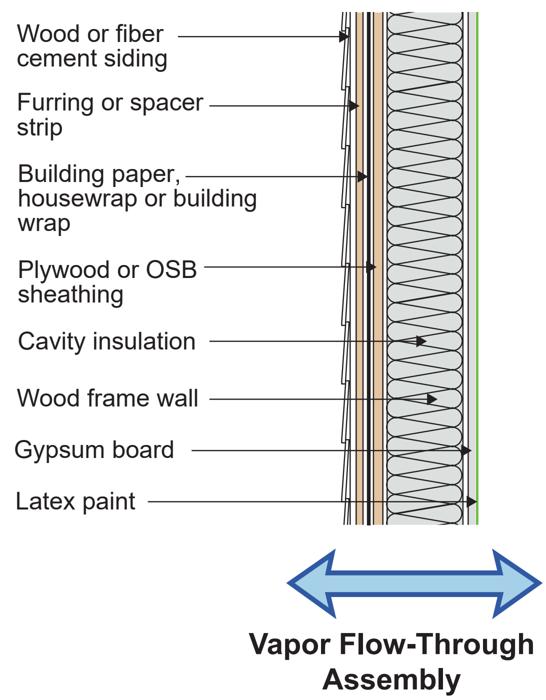

Figure 8.9: Wood Frame Wall – Vapor flow-through assembly.

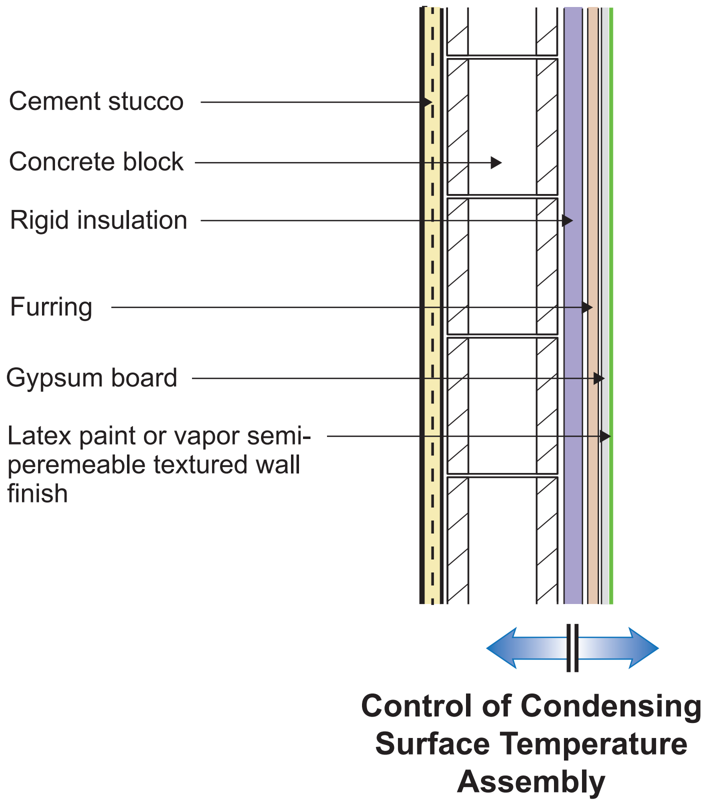

Figure 8.10: CMU Wall – Internally insulated.

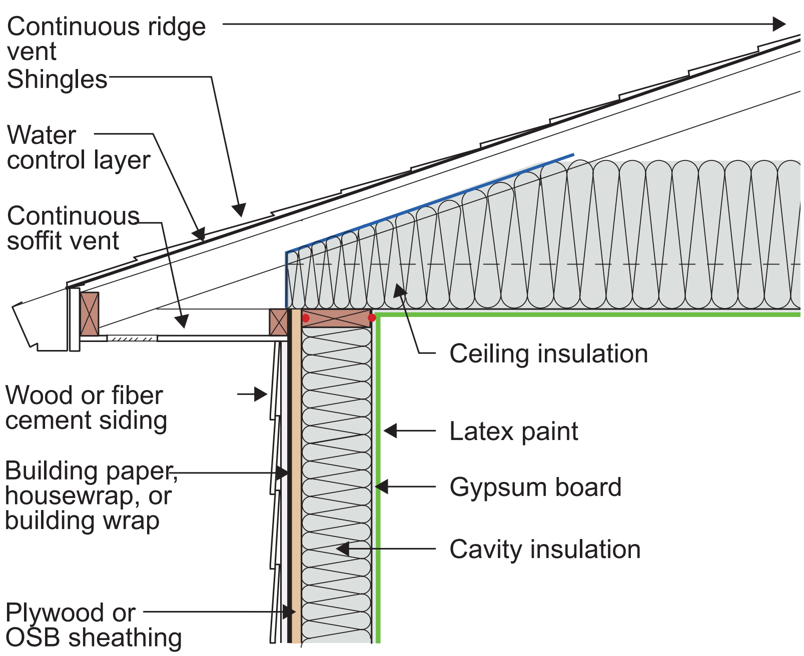

Figure 8.11: Vented Attic – Asphalt shingles.

illustrates the recommended approach to constructing vented attics. Asphalt shingles are the most common type of roof covering on residential roofs.

Balanced attic ventilation (low and high) approaches are more effective than cross-ventilation approaches. Intake vents should be located in the lower section of the roof (typically in the soffit), and exhaust vents located in the upper section of the roof (typically along the ridge).

A vented attic with clay or concrete roof tile covering is presented in **Figure 8.12**. This detail shows a self-adhering membrane under the roof covering. A self-adhered roof membrane is a more robust approach in hurricane zones that have risk of roof cladding tear-off during storm events.

Unvented roofing assemblies are illustrated in **Figure 8.13**, **Figure 8.14** and **Figure 8.15**.

Figure 8.13 uses spray polyurethane insulation to act as the air control layer, vapor control layer and thermal control layer.

The amount of rigid insulation in F**igure 8.14** to control condensation is specified in **Table 5.1**.

Figure 8.15 is an unvented attic approach that can only be used in hot dry climates (Climate Zone 2B). Note that the roofing tiles provide a vented space allowing the roof sheathing to dry into. However, this drying is only possible if the roofing membrane is vapor open (Class III vapor control layer).

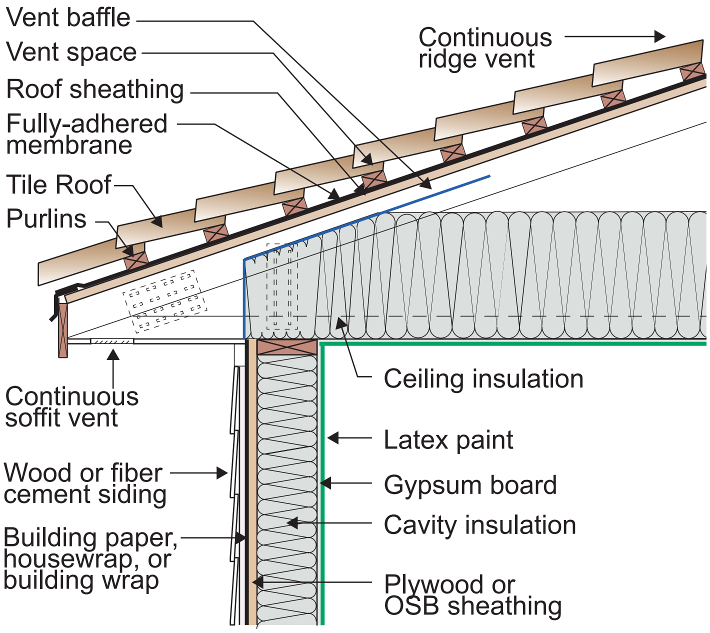

Figure 8.12: Vented Attic – Tile roof covering.

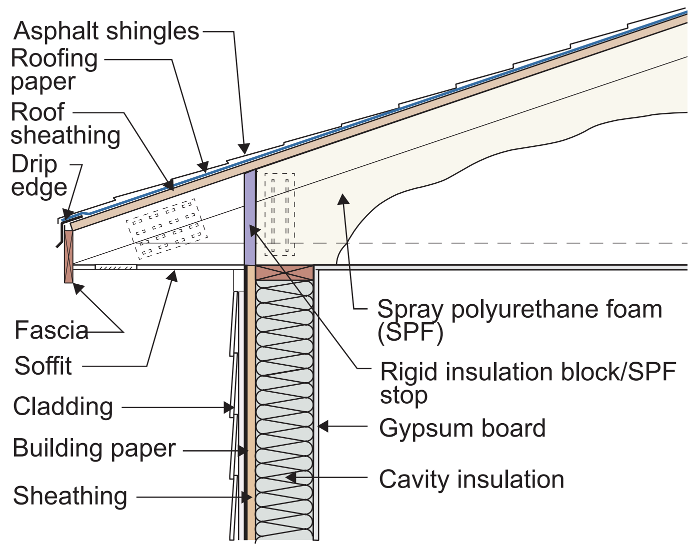

Figure 8.13: Conditioned Attic – Spray polyurethane foam.

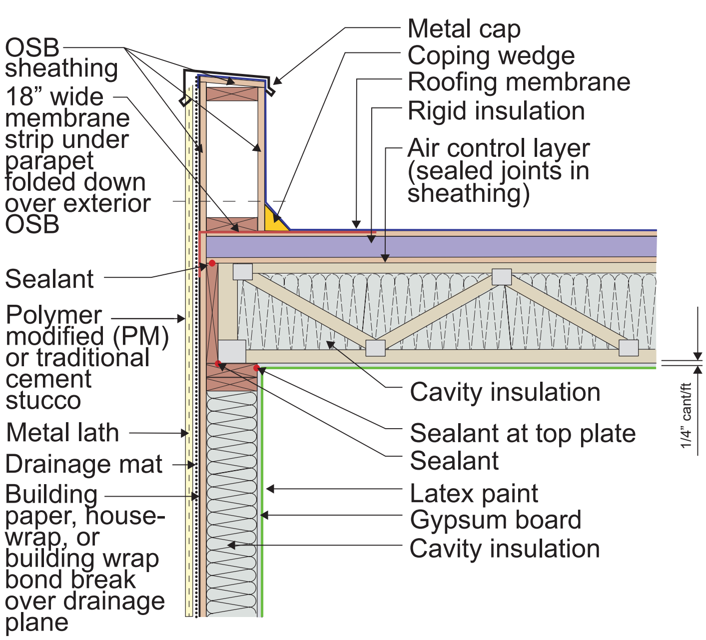

Figure 8.14: Conditioned Attic – Hybrid assembly with insulation located above and below the roof deck.

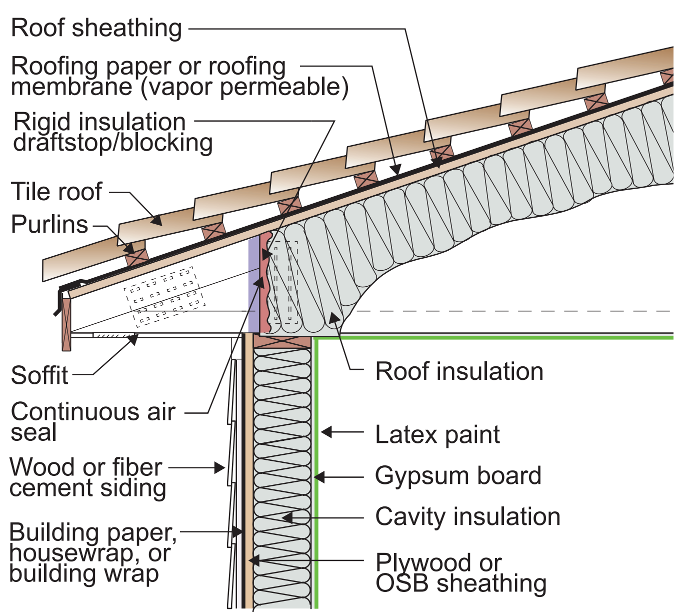

Figure 8.15: Conditioned Attic – Vapor flow-through assembly

Case Studies

Three complete sections are presented as typical for Houston (**Figure 8.16**), Orlando (**Figure 8.17**) and Tucson (**Figure 8.18**).

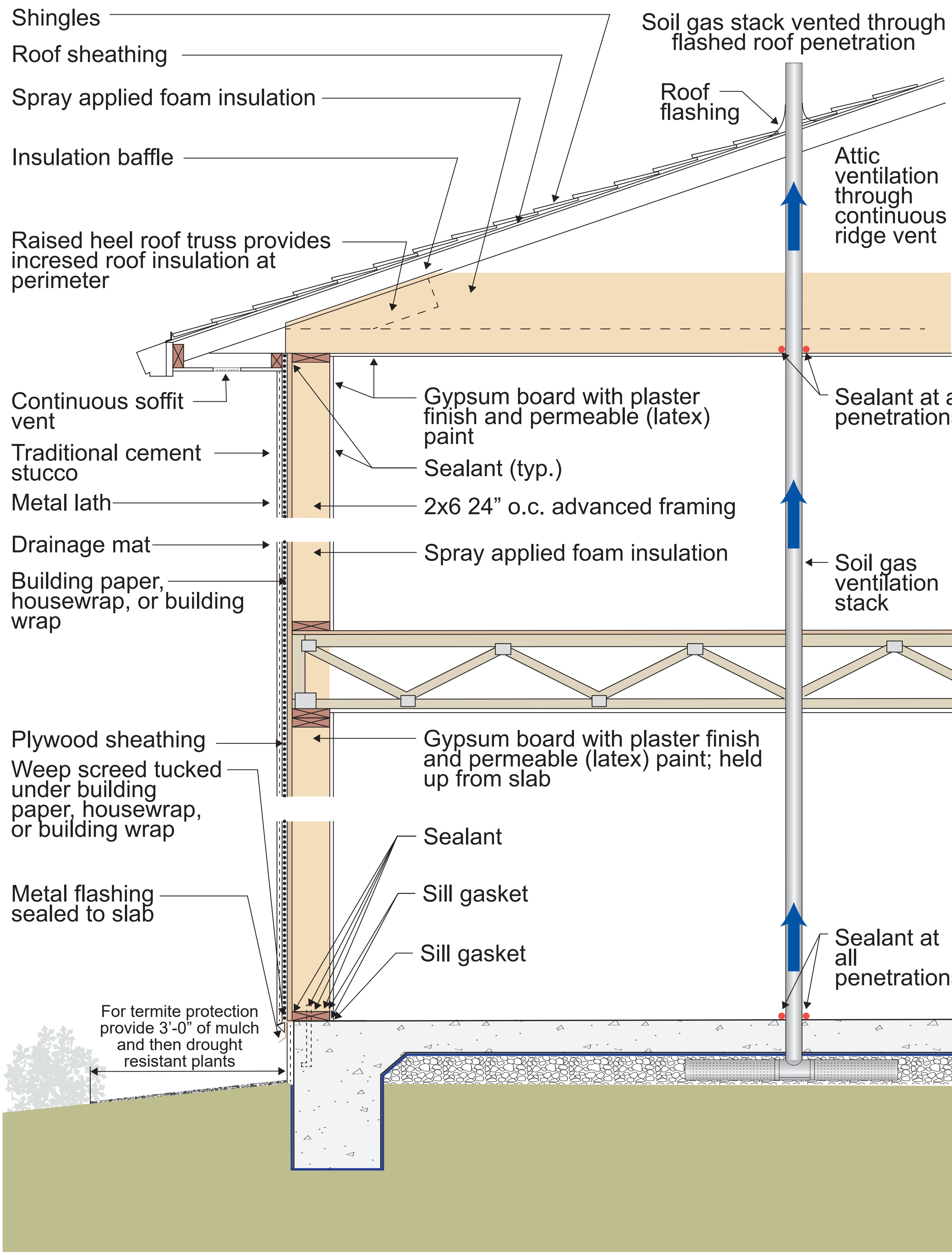

Figure 8.16: Houston

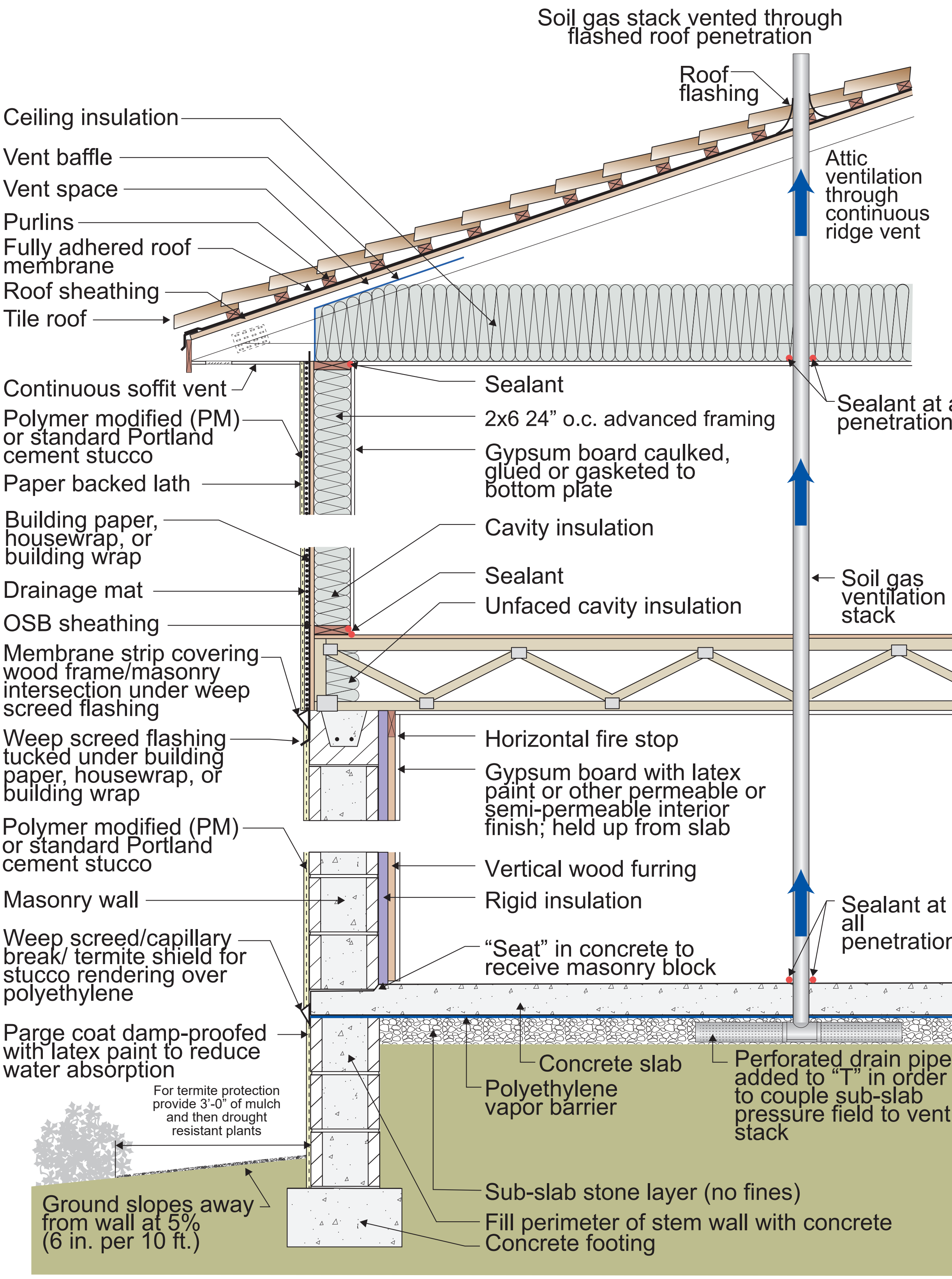

Figure 8.17: Orlando

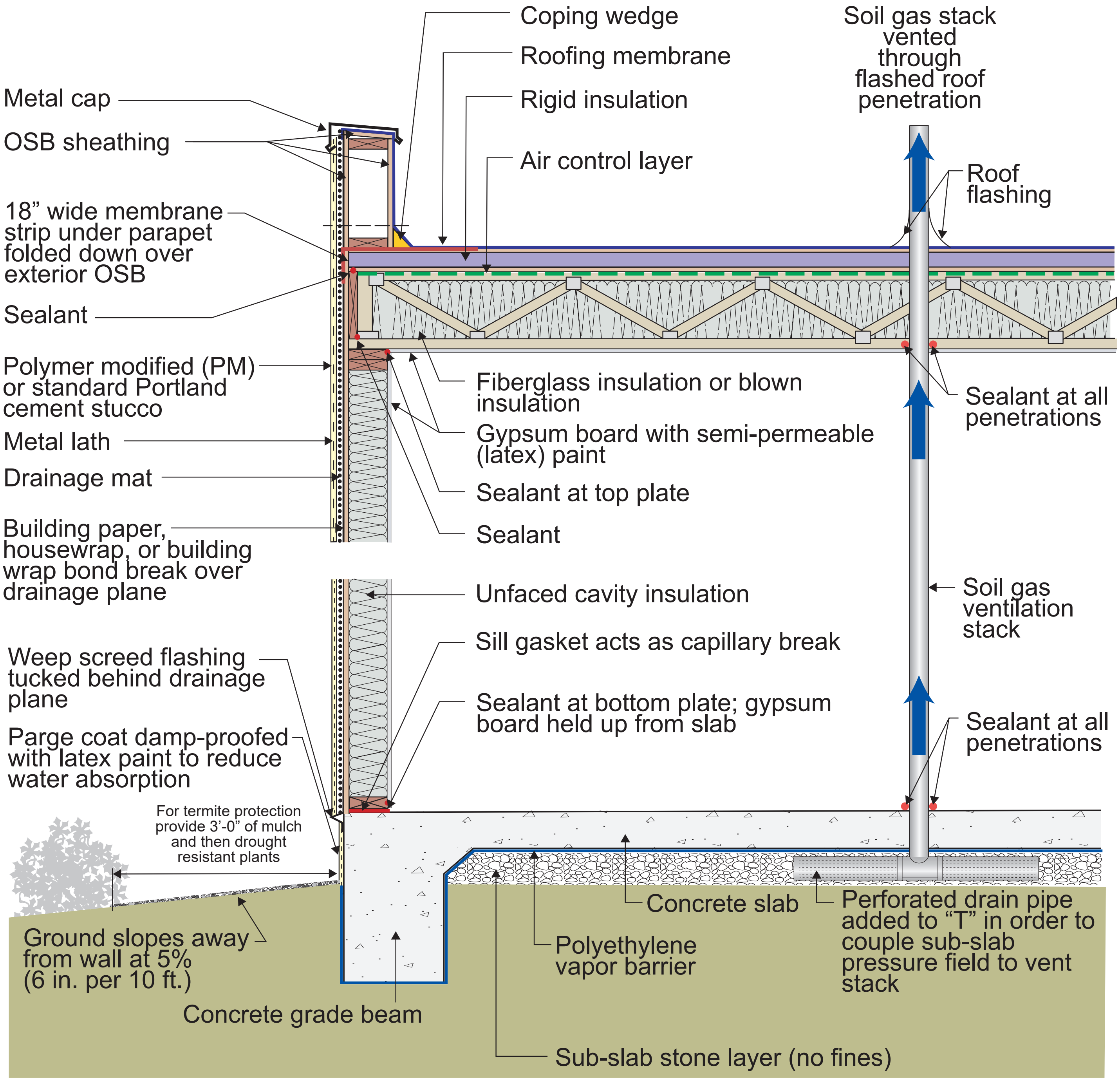

Figure 8.18: Tucson

CHAPTER 9

Climate Zones 3, 4, and 5

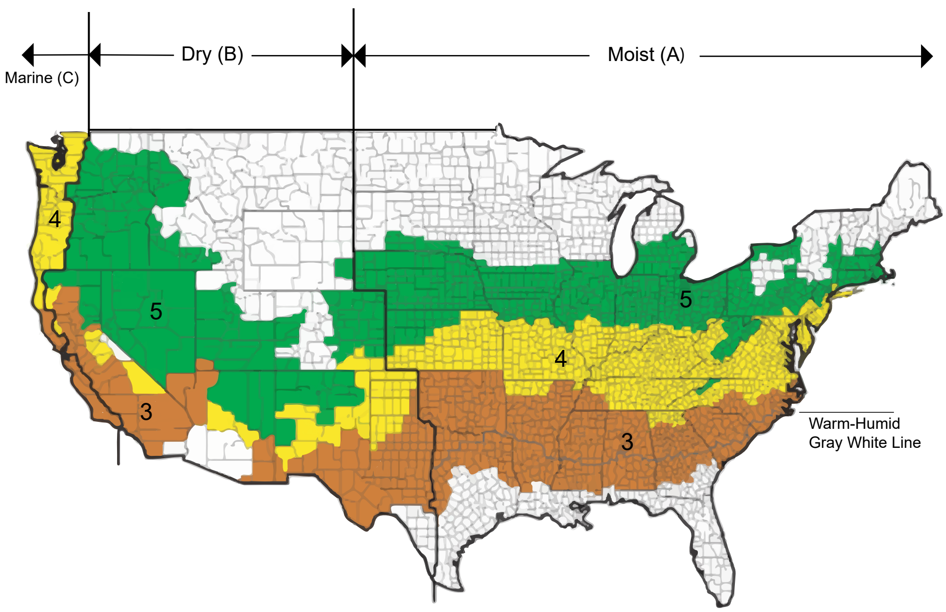

Figure 9.1: Climate Zones 3, 4, and 5.

The residential buildings constructed in these three zones (**Figure 9.1**) are constructed on each of the three typical foundation types: slab foundations, crawlspaces, and basements.

Where slab foundations are used they are insulated as are basement foundations.

Walls are typically wood frame – with both 2x4 and 2x6 framing.

Roof construction is predominately vented attics. Some unvented roof assemblies are being constructed, but they are not common.

Key Concerns and Control Strategies

The principal moisture concerns are rain penetration, groundwater, interstitial condensation (condensation within building assemblies), and interior mold and mildew linked to high interior levels of humidity.

Typically, in these climate zones, wetting from the interior during the heating season by air movement is a major concern. As such, building enclosures should be constructed in an airtight manner to control air leakage openings and to facilitate controlled ventilation, which provides for the dilution of interior pollutants and interior moisture by controlled air change.

Vapor diffusion from the interior is also a concern in these climate zones. Accordingly, vapor control layers coupled with control of condensing surfaces are strategies typically employed.

The presence of ground frost penetration concerns in this climate has led to the widespread use of basement foundations, with foundation footings located below ground frost penetration depth. Concrete and masonry foundations are common. Above-grade frame walls predominate.

Rain and Groundwater

Rain penetration and groundwater concerns are common to builders in all climates, and the methods of control in these climate zones are similar to those of other climates. Examples include overhanging roofs, draining claddings; appropriate placement of flashings, gutters, and downspouts that direct water away from foundations; and careful site grading and subgrade drainage.

Basement spaces are often conditioned and occupied. As such, concerns with groundwater penetration and infiltration of soil gas (including radon) are common.

Ice Damming

Heat loss at the perimeter edges of roof and attic assemblies during the heating months can lead to ice damming. This is caused by a lack of thermal insulation where exterior walls intersect these assemblies as well as air leakage up and out of exterior walls, coupled with insufficient or discontinuous soffit ventilation.

High Interior Humidity

The absence of a controlled ventilation system can lead to elevated levels of moisture within the conditioned space during the heating months as a result of a low air change rate. These elevated levels of interior moisture can lead to condensation on window surfaces and give rise to surface mold, as well as concealed condensation within walls and roof spaces.

Cold interior surfaces during the heating months arising from thermal bridges or wind blowing through insulations create high interior surface relative humidities and often lead to mold and mildew at these locations. Most common locations are where exterior walls intersect insulated ceilings, exterior corners, and uninsulated (or poorly insulated) window lintels or headers.

Humidity control within conditioned spaces is accomplished during heating periods by the dilution of interior moisture (air change) along with controlled mechanical ventilation and source control. During cooling periods, humidity is controlled by the dehumidification capabilities of air-conditioning systems and source control. Since latent cooling loads on air-conditioning systems can be higher than sensible cooling loads, proper sizing of air-conditioning systems with consideration of dehumidification capabilities is important. Oversizing of air-conditioning equipment can lead to high interior humidity problems due to a lack of dehumidification capability (oversized air-conditioning equipment will not operate as often and therefore will dehumidify less than properly sized equipment).

Mechanical System Concerns

Ductwork for forced-air heating and cooling systems should be installed only within conditioned spaces. Ductwork should not be installed in vented attics or vented crawl spaces. Leaky return ducts located in attics draw significant amounts of cold air into conditioned spaces during the heating months, increasing heating loads and drawing significant amounts of warm, moisture-laden air into the conditioned space from the attic during cooling periods, increasing cooling loads. Leaky return ducts located in vented crawl spaces draw significant amounts of soil gas, moisture, possibly pesticides, radon, and other pollutants into the conditioned spaces, often creating moisture problems, increasing heating and cooling loads, and risking occupant health and safety.

Leaky supply ducts located in attics or vented crawl spaces lead to the uncontrolled depressurization of the conditioned space, leading to excessive infiltration of cold air during heating periods, increasing heating loads, and potentially supplying sufficient interior moisture to attic and roof assemblies to create roof sheathing moisture and decay problems. During cooling periods, the same mechanism can lead to the infiltration of exterior warm moisture-laden air, increasing cooling loads.

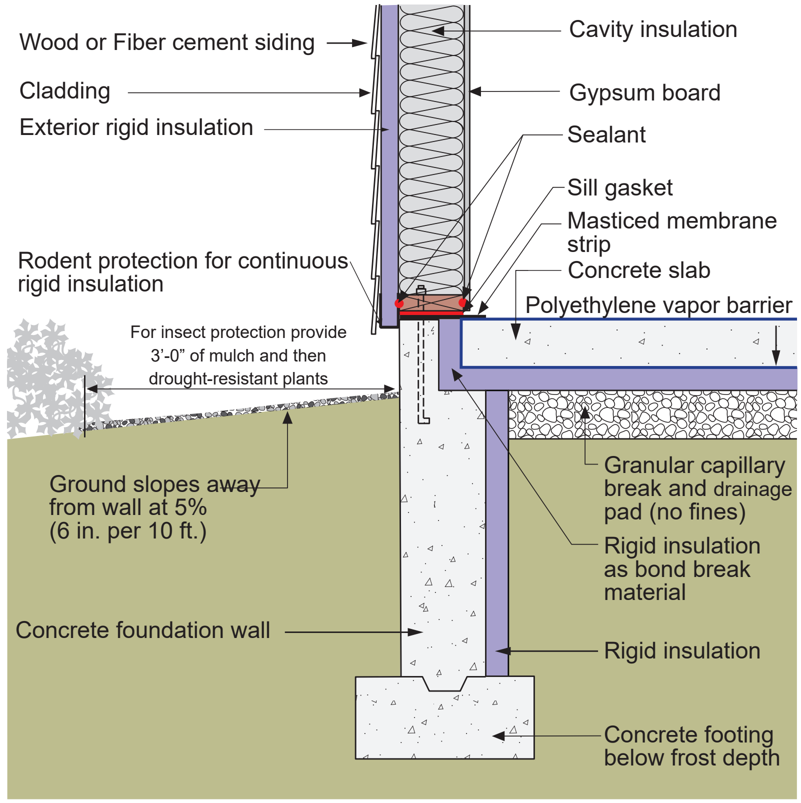

Figure 9.2: Stem Wall Foundation – Internally insulated.

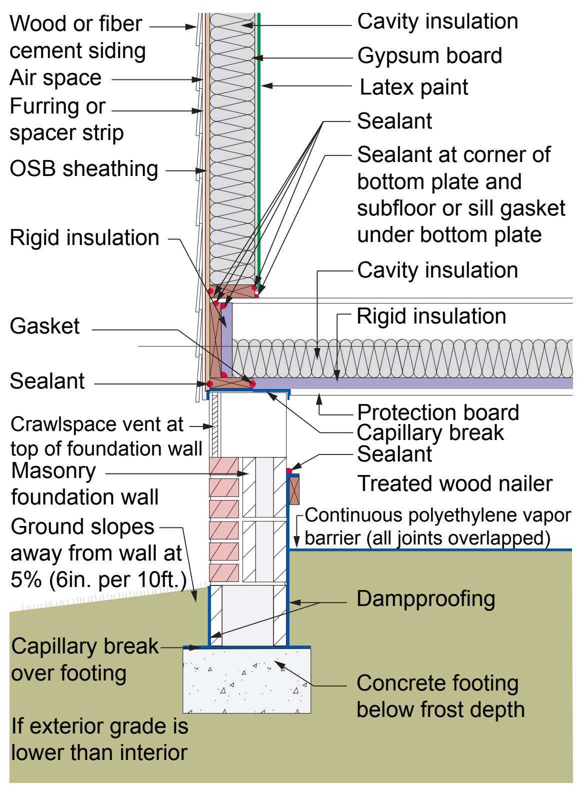

Figure 9.3: Crawl Space Foundation – Vented crawl space.

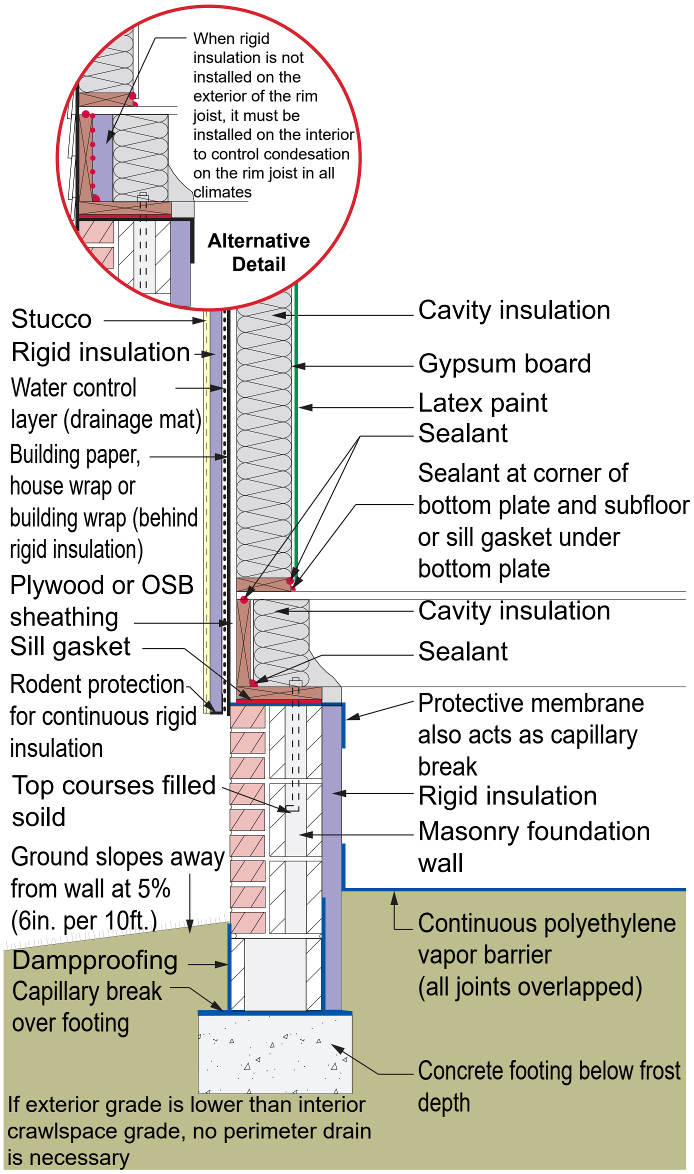

Figure 9.4: Crawl Space Foundation – Conditioned crawl space.

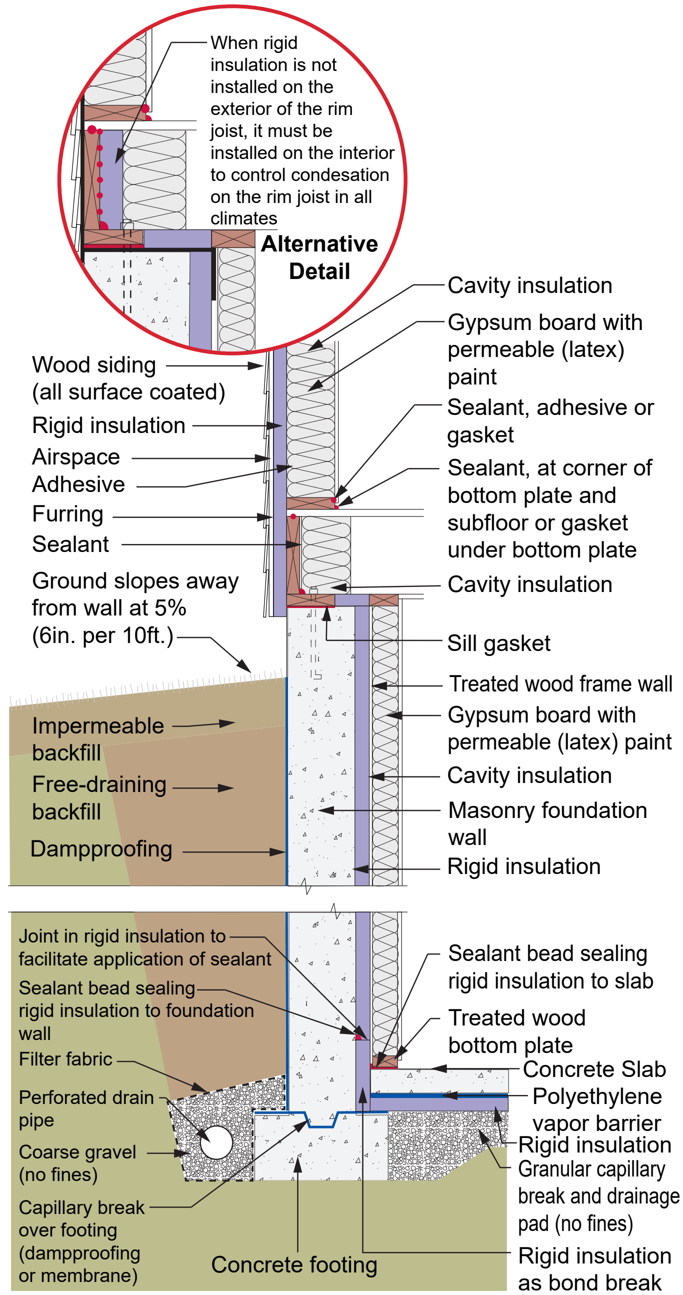

Figure 9.5: Basement Foundation – Internally insulated.

Combustion Appliances

Unvented combustion appliances such as gas stoves with standing pilot lights and room space heaters are significant sources of moisture as well as sources for other pollutants and should be avoided. Gas stoves and cook tops without standing pilot lights should be installed in conjunction with vented range hoods or some other vent provision.

Where combustion appliances are installed they should be uncoupled (not influenced by enclosure air pressures or supply air availability) from the conditioned space. In other words, sealed combustion, power-vented, induced draft, condensing, or pulse combustion devices should be used. Devices with traditional draft hoods should be avoided. Where fireplaces are installed, they should have their own supply of air from the exterior as well as tight-fitting glass doors. Wood stoves should also have their own supply of exterior air ducted directly to their firebox.

Foundations

Figure 9.2 is an effective means of providing a "dry" slab that is also insulated with rigid insulation where the insulation does not act as an insect entry point. A protective membrane strip is used to create a physical barrier to the entry of insects into the building enclosure. Fully adhered membranes are effective means of insect control. Ground treatment is also recommended.

Crawl spaces are typically are constructed as "vented" crawl spaces. **Figure 9.3** is an example of recommended vented crawl space construction. Note the continuous rigid insulation on the underside of the floor framing. This rigid insulation's primary function is to protect the floor assembly from moisture. The rigid insulation should be protected with protection board from fire, insects, and vermin. Note that the floor cavity insulation is located in direct contact with the continuous rigid insulation leaving and air space above the cavity insulation. The air space results in a more comfortable floor. It is key with this approach to prevent air entry into the perimeter of the floor framing.

Unvented crawl spaces should only be considered where flooding is not a concern. **Figure 9.4** illustrates an approach to constructing conditioned crawl spaces. Note the protection board on the rigid insulation protecting the rigid insulation from fire. Also note the fully adhered membrane barrier for insect control.

Basement foundations are principally insulated from the interior due to constructability issues, thermal bridging issues with brick veneer construction, insect control/ vermin issues, and cost issues.

Figure 9.5 and **Figure 9.6** are two means of constructing insulated basements.

Walls

A common approach to constructing wood-frame walls in Climate Zones 3,4, and 5 is illustrated in **Figure 9.7**. The plywood or OSB sheathing is covered by a housewrap water control layer. The key element of this wall is the gap between the cladding and the housewrap water control layer used to control hydrostatic pressure. The wall cavity insulation can be fiberglass, cellulose or mineral wool. **Figure 9.8** is identical to

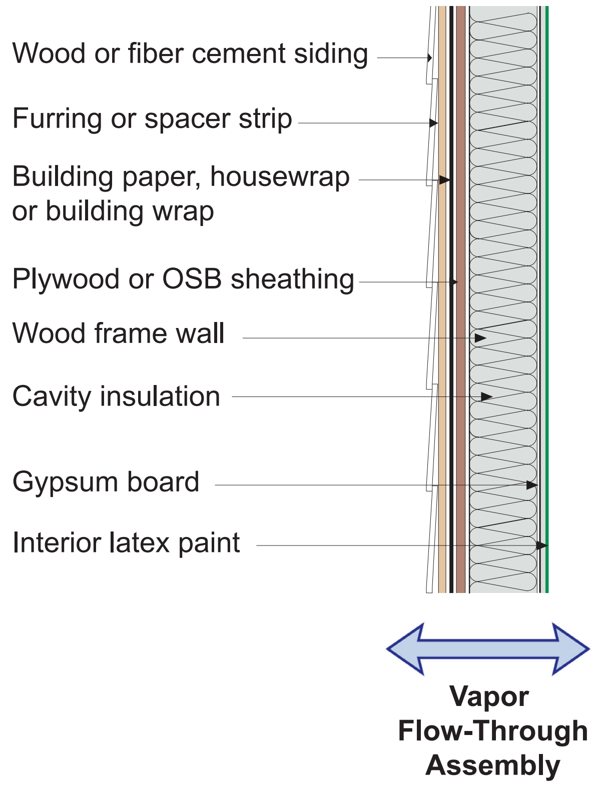

Figure 9.7: Wood Frame Wall – Vapor flow-through assembly.

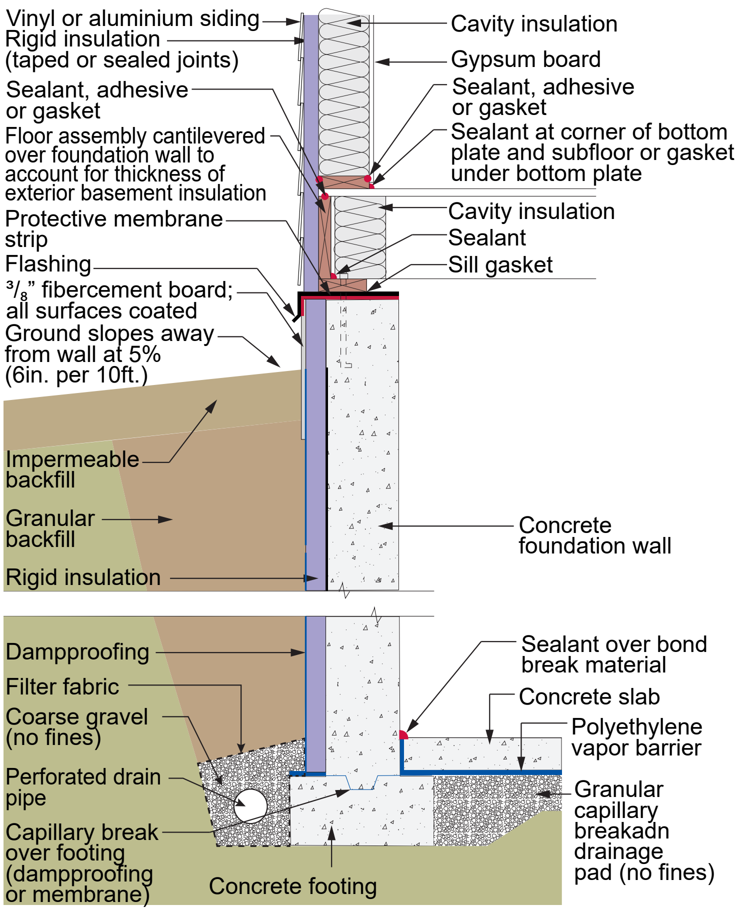

Figure 9.6: Basement Foundation – Externally insulated.

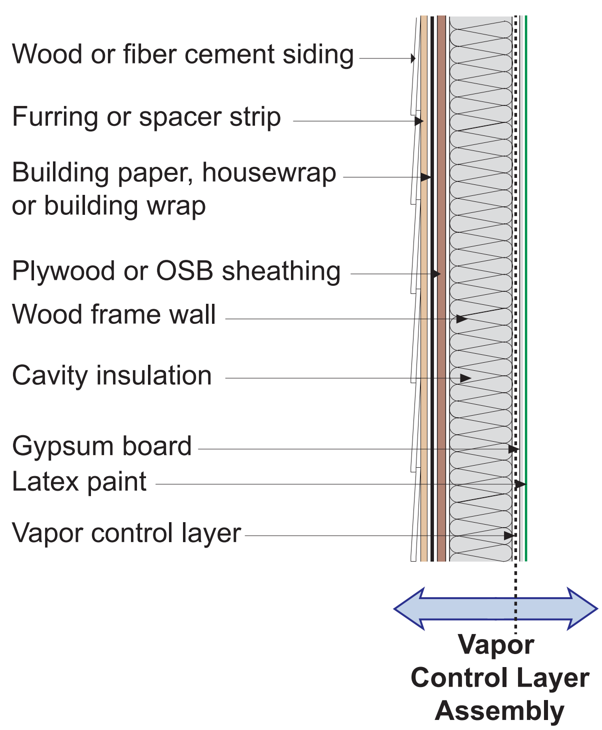

Figure 9.8: Wood Frame Wall – Vapor control layer assembly.

Figure 9.7 except for the use of an interior vapor control layer.

The use of continuous exterior rigid insulation is illustrated in **Figure 9.9**. In this wall assembly taped and sealed rigid insulation is used to provide water control. Again note the gap between the cladding and the sheathing to control hydrostatic pressure.

Figure 9.10 illustrates a wall completely sheathed with plywood or OSB and then in turn externally insulated with continuous rigid insulation. Note the use of a water control layer between the continuous rigid insulation and the plywood or OSB sheathing.

In **Figure 9.9** and **Figure 9.10** the thermal resistance of the exterior continuous rigid insulation is determined by climate as shown in **Table 3.1**.

Roofs

The most common approach to roof construction in these climate zones is a vented attic. **Figure 9.11** illustrates the recommended approach to constructing vented attics. Asphalt shingles are the most common type of roof covering on residential roofs.

Balanced attic ventilation (low-high) approaches are more effective than cross-ventilation approaches. Intake vents should be located in the lower section of the roof (typically in the soffit), and exhaust vents are located in the upper section of the roof (typically along the ridge).

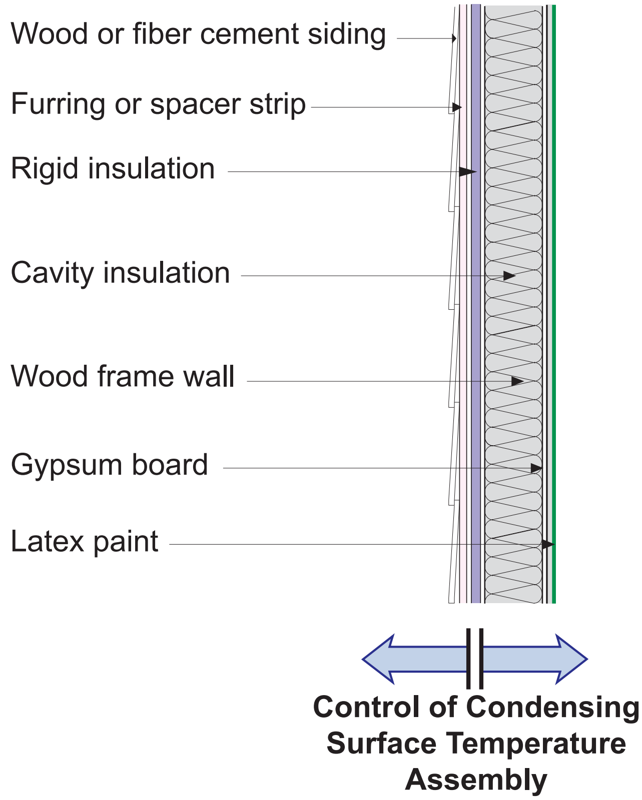

Figure 9.9: Wood Frame Wall – Control of condensing surface temperature assembly.

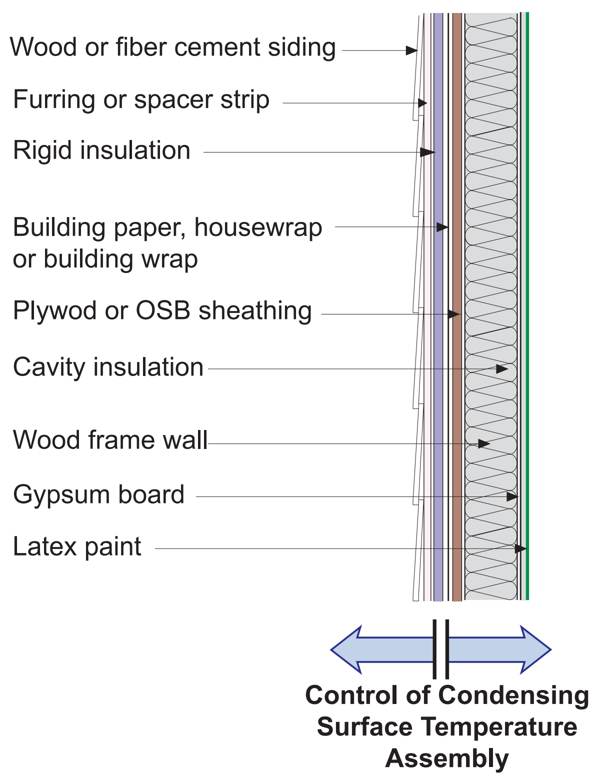

Figure 9.10: Wood Frame Wall – Control of condensing surface temperature assembly.

Case Studies

Two complete sections are presented as typical for Louisville (**Figure 9.12**) and Chicago (**Figure 9.13**).

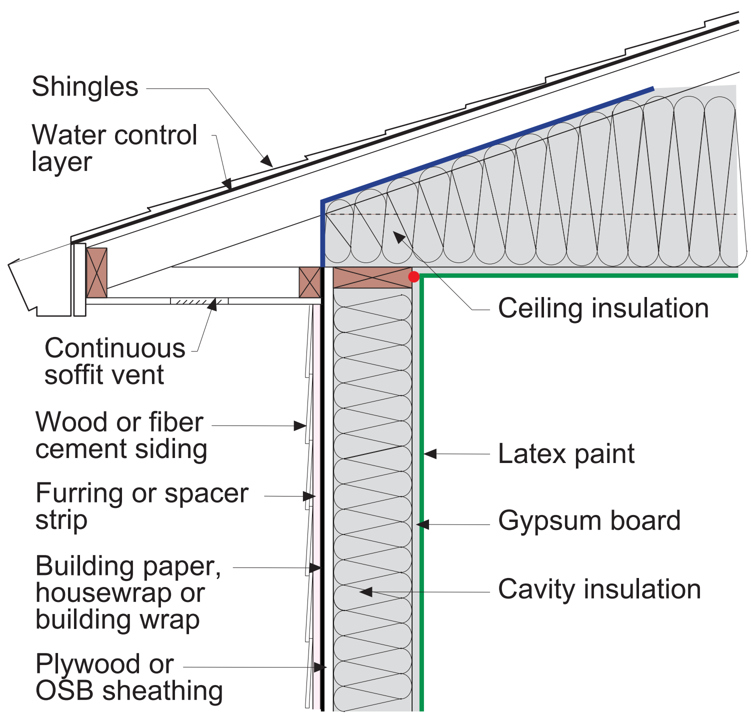

Figure 9.11: Vented Attic – Balanced attic ventilation.

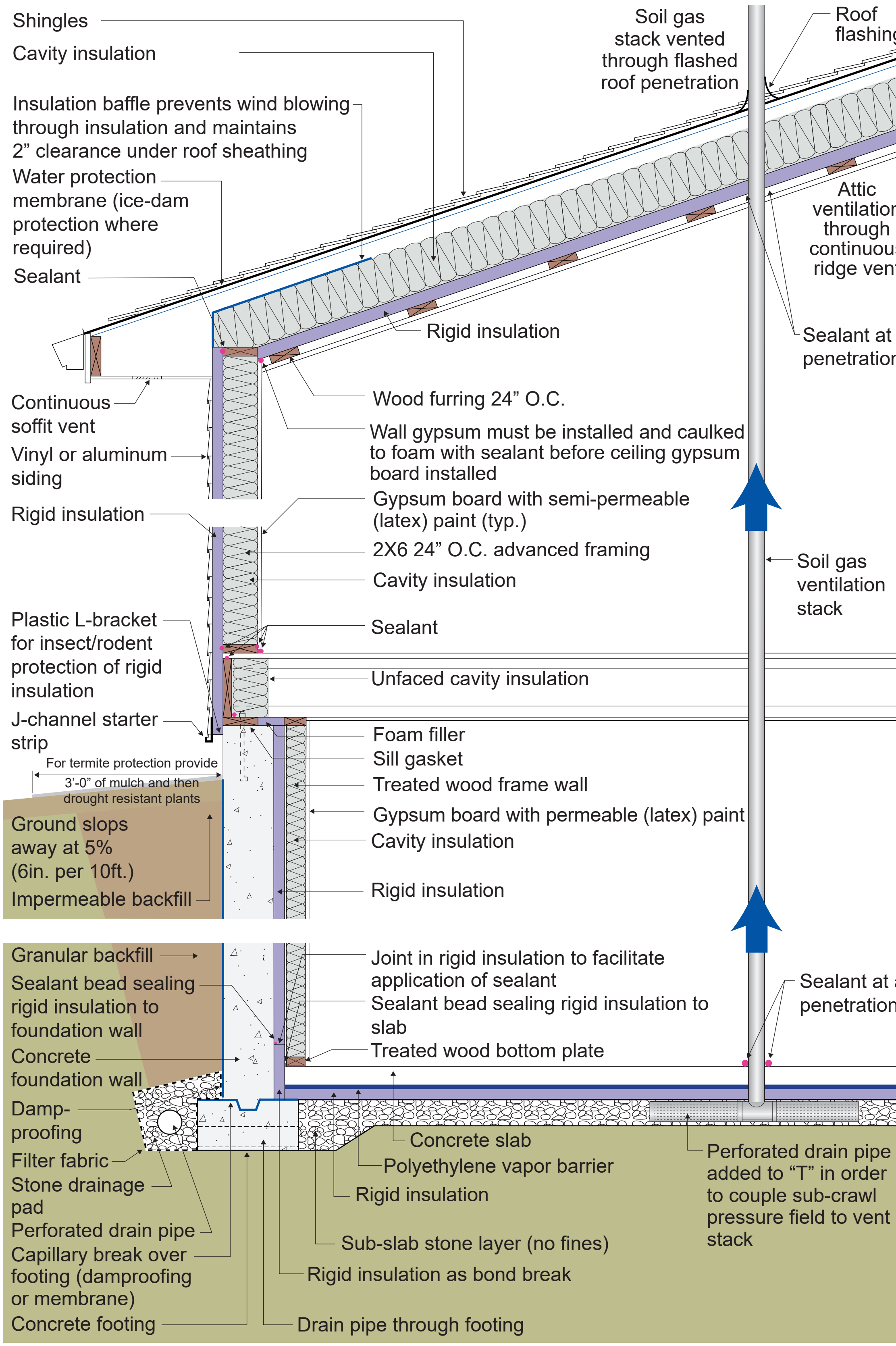

Figure 9.12: Louisville

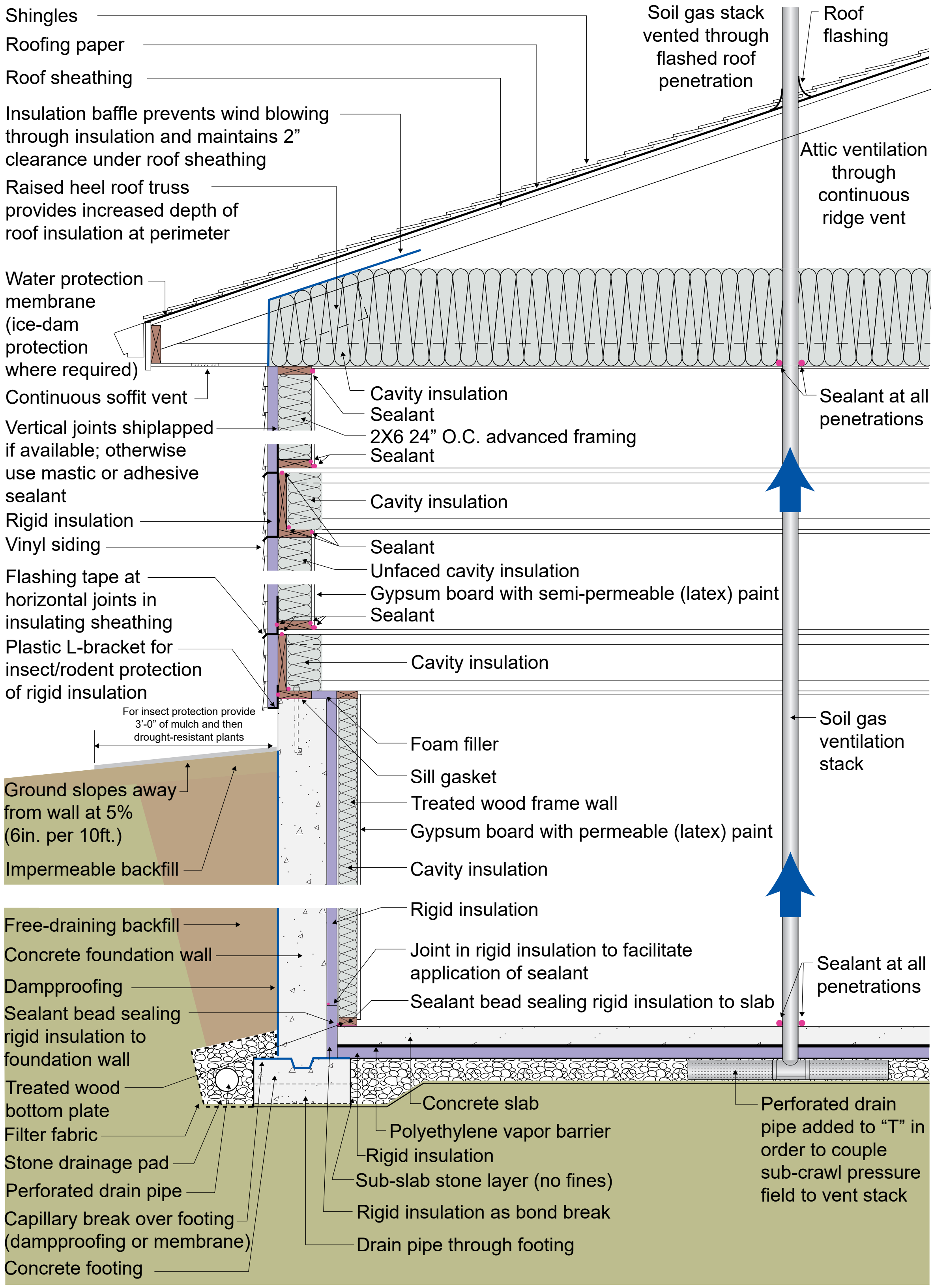

Figure 9.13: Chicago

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CHAPTER 10

Climate Zones 6, 7, and 8

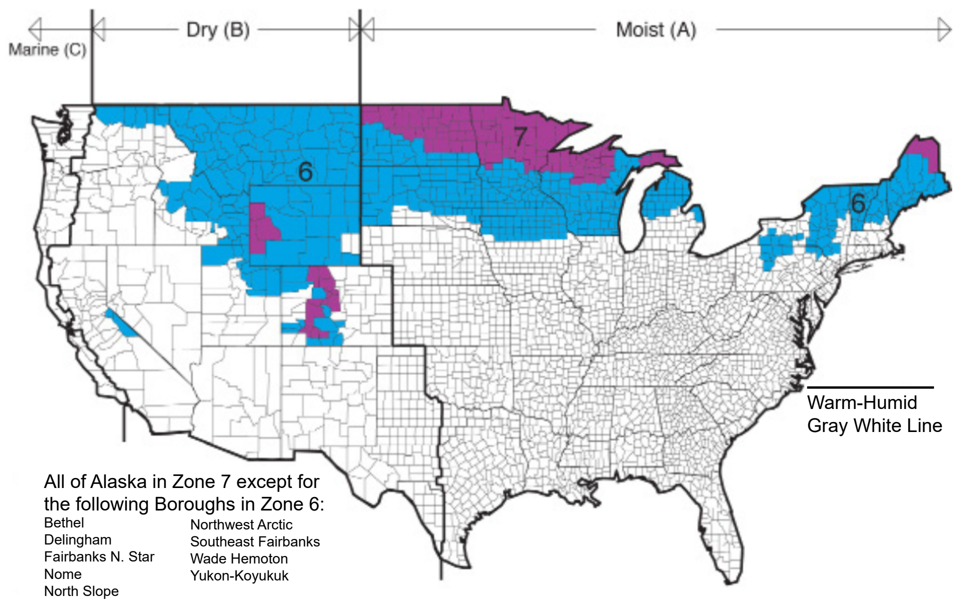

Figure 10.1: Climate Zones 6, 7, and 8.

The residential buildings constructed in these three zones (**Figure 10.1**) are constructed on each of the three typical foundation types: slab foundations, crawlspaces and basements.

Where slab foundations are used they are insulated as are basement foundations. Exterior rigid insulation is often avoided for insect control reasons and constructability.

Walls are typically wood-frame – predominately 2x6 framing.

Roof construction is predominately vented attics. Some unvented roof assemblies are being constructed, but they are not common.

Key Concerns and Control Strategies

The principal moisture concerns are rain penetration, groundwater, interstitial condensation (condensation within building assemblies), and interior mold and mildew linked to high interior levels of humidity.

Typically, in these climate zones, wetting from the interior during the heating season by air movement is a major concern. As such, building enclosures should be constructed in an airtight manner to control air leakage openings and to facilitate controlled ventilation, which provides for the dilution of interior pollutants and interior moisture by controlled air change.

Vapor diffusion from the interior is also a concern in these climate zones. Accordingly, vapor control layers coupled with control of condensing surfaces are strategies typically employed.

The presence of ground frost penetration concerns in this climate has led to the widespread use of basement foundations, with foundation footings located below ground frost penetration depth. Concrete and masonry foundations are common. Above-grade frame walls predominate.

Rain and Groundwater

Rain penetration and groundwater concerns are common to builders in all climates, and the methods of control in these climate zones are similar to those of other climates. Examples include draining claddings; appropriate placement of flashings, gutters, and downspouts that direct water away from foundations; and careful site grading and subgrade drainage.

Basement spaces are often conditioned and occupied. As such, concerns with groundwater penetration and infiltration of soil gas (including radon) are common.

Ice Damming

Heat loss at the perimeter edges of roof and attic assemblies during the heating months can lead to ice damming. This is caused by a lack of thermal insulation where exterior walls intersect these assemblies as well as air leakage up and out of exterior walls, coupled with insufficient or discontinuous soffit ventilation.

High Interior Humidity

The absence of a controlled ventilation system can lead to elevated levels of moisture within the conditioned space during the heating months as a result of a low air change rate. These elevated levels of interior moisture can lead to condensation on window surfaces and give rise to surface mold, as well as concealed condensation within walls and roof spaces.

Cold interior surfaces during the heating months arising from thermal bridges or wind blowing through insulations create high interior surface relative humidities and often lead to mold and mildew at these locations. Most common locations are where exterior walls intersect insulated ceilings, exterior corners, and uninsulated (or poorly insulated) window lintels or headers.

Mechanical System Concerns

Ductwork for forced-air heating and cooling systems should be installed only within conditioned spaces. Ductwork should not be installed in vented attics or vented crawl spaces. Leaky return ducts located in attics draw significant amounts of cold air into conditioned spaces during the heating months, increasing heating loads and drawing significant amounts of warm, moisture-laden air into the conditioned space from the attic during cooling periods, increasing cooling loads. Leaky return ducts located in vented crawl spaces draw significant amounts of soil gas, moisture, possibly pesticides, radon, and other pollutants into the conditioned spaces, often creating moisture problems, increasing heating and cooling loads, and risking occupant health and safety.

Leaky supply ducts located in attics or vented crawl spaces lead to the uncontrolled depressurization of the conditioned space, leading to excessive infiltration of cold air during heating periods, increasing heating loads and potentially supplying sufficient interior moisture to attic and roof assemblies to create roof sheathing moisture and decay problems. During cooling periods, the same mechanism can lead to the infiltration of exterior warm moisture-laden air, increasing cooling loads.

Combustion Appliances

Unvented combustion appliances such as gas stoves with standing pilot lights and room space heaters are significant sources of moisture as well as sources for other pollutants and should be avoided. Gas stoves and cook tops without standing pilot lights should be installed in conjunction with vented range hoods or some other vent provision.

Where combustion appliances are installed they should be uncoupled (not influenced by enclosure air pressures or supply air availability) from the conditioned space. In other words, sealed combustion, power-vented, induced draft, condensing, or pulse combustion devices should be used.

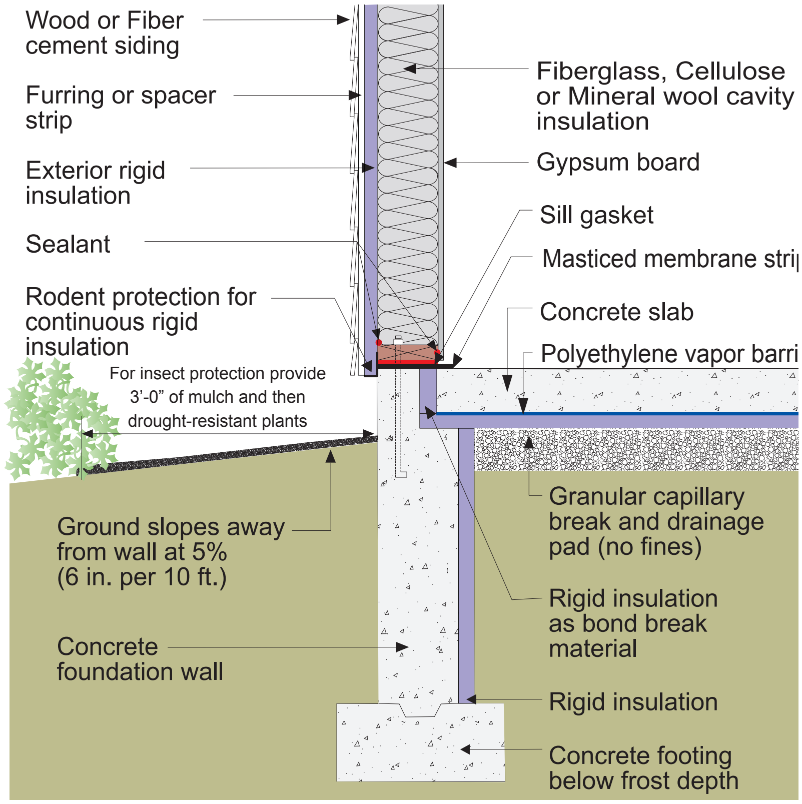

Figure 10.2: Stem Wall Foundation – Internally insulated.

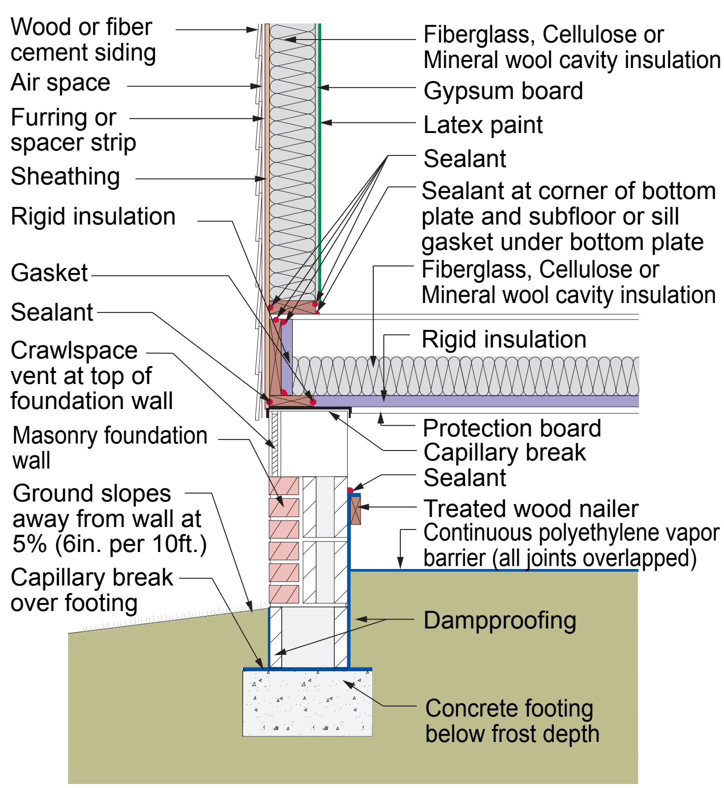

Figure 10.3: Crawl Space Foundation – Vented crawl space.

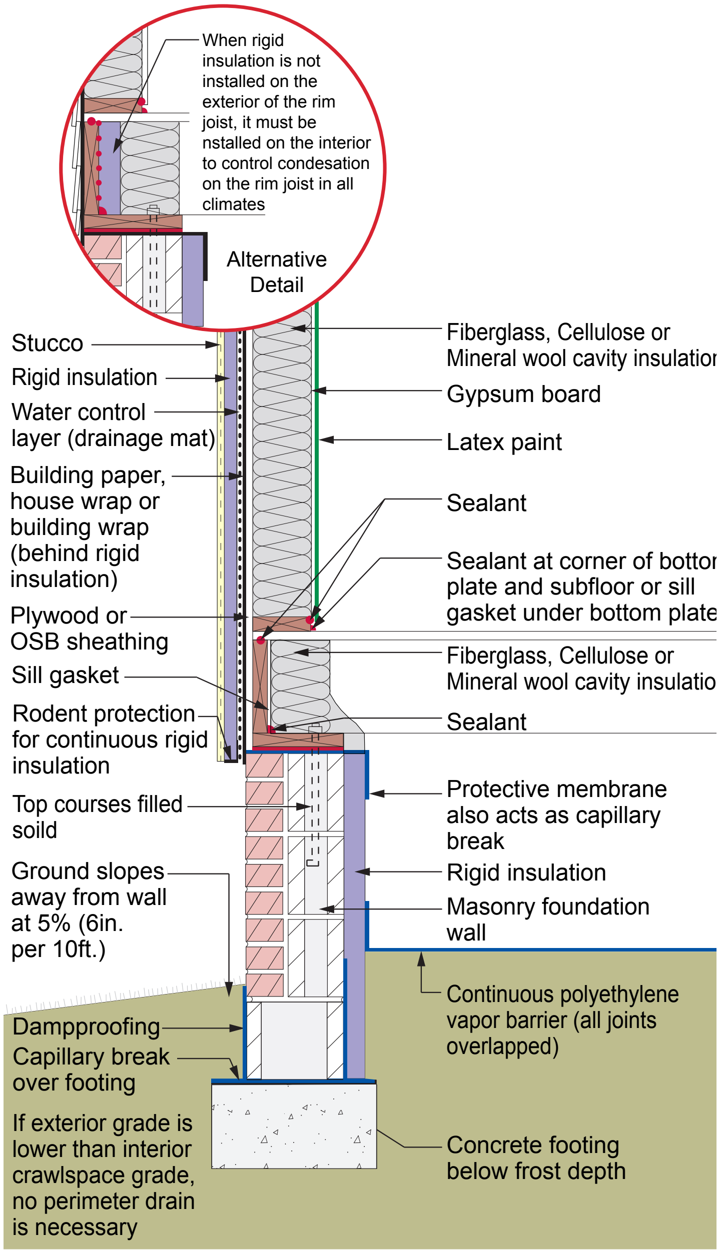

Figure 10.4: Crawl Space Foundation – Conditioned crawl space.

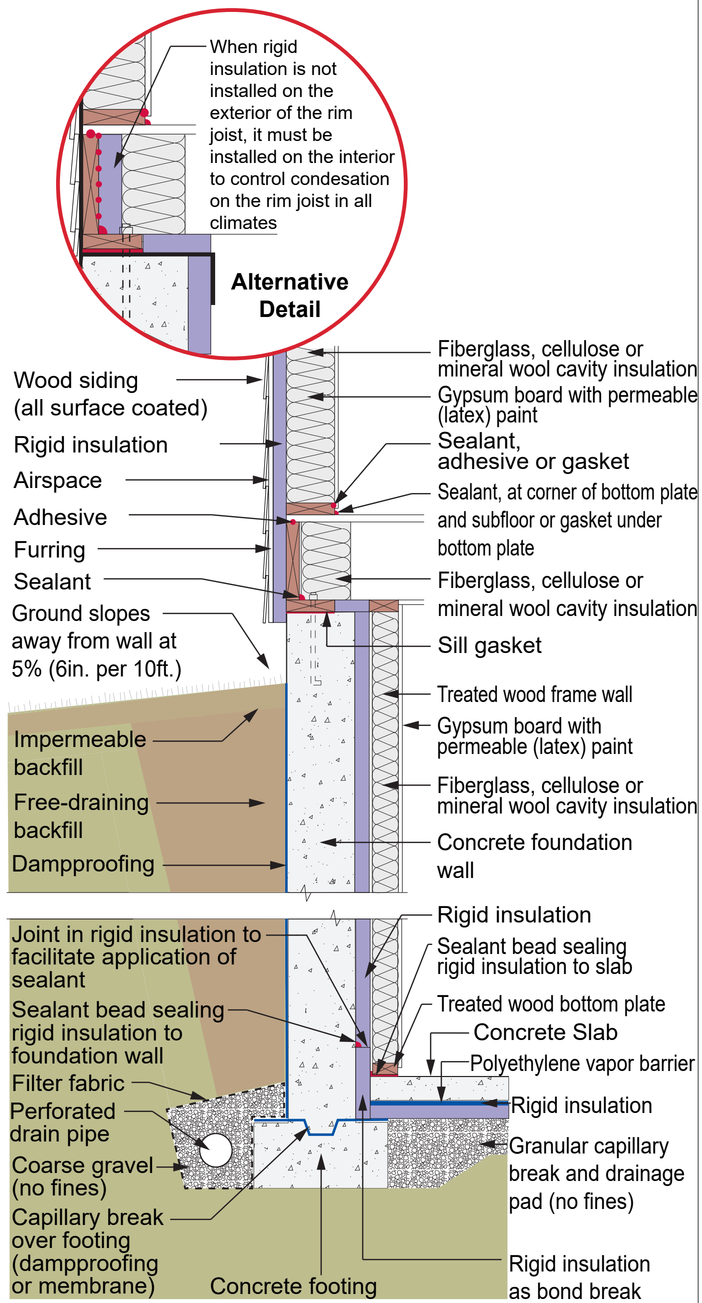

Figure 10.5: Basement Foundation – Internally insulated.

Devices with traditional draft hoods should be avoided. Where fireplaces are installed, they should have their own supply of air from the exterior as well as tight-fitting glass doors. Wood stoves should also have their own supply of exterior air ducted directly to their firebox.

Foundations

Figure 10.2 is an effective means of providing a "dry" slab that is also insulated with rigid insulation where the insulation does not act as an insect entry point. A protective membrane strip is used to create a physical barrier to the entry of insects into the building enclosure. Fully adhered membranes are effective means of insect control. Ground treatment is also recommended.

Crawl spaces are typically are constructed as "vented" crawl spaces. **Figure 10.3** is an example of recommended vented crawl space construction. Note the continuous rigid insulation on the underside of the floor framing. This rigid insulation's primary function is to protect the floor assembly from moisture. The rigid insulation should be protected with protection board from fire, insects and vermin. Note that the floor cavity insulation is located in direct contact with the continuous rigid insulation leaving and air space above the cavity insulation. The air space results in a more comfortable floor. It is key with this approach to prevent air entry into the perimeter of the floor framing.

Unvented crawl spaces should only be considered where flooding is not a concern. **Figure 10.4** illustrates an approach to constructing conditioned crawl spaces. Note the protection board on the rigid

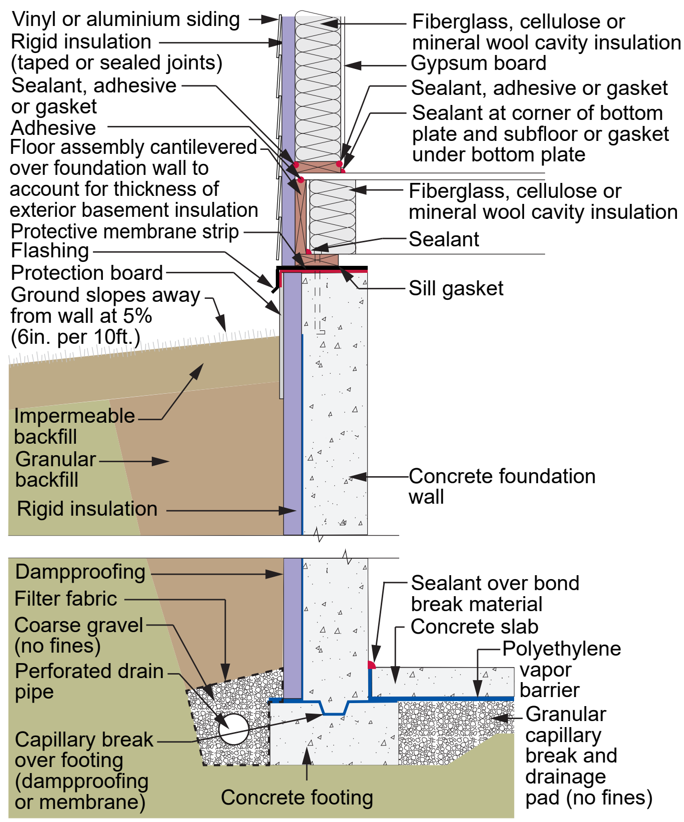

Figure 10.6: Basement Foundation – Externally insulated.

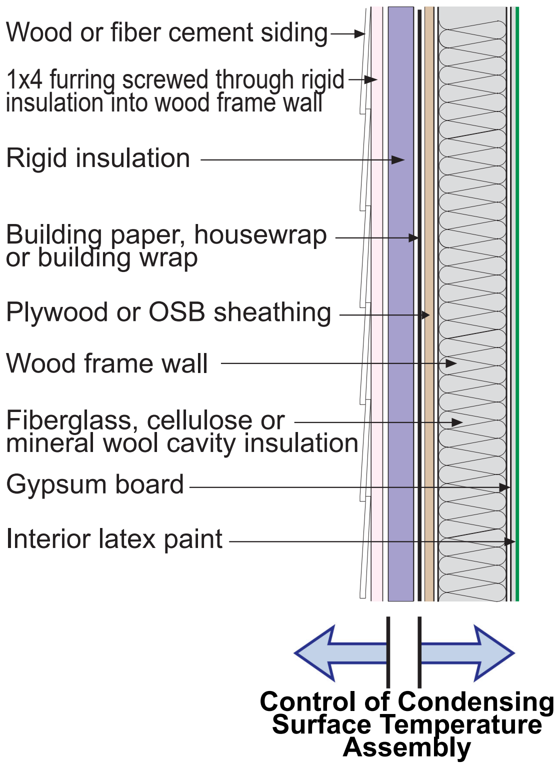

Figure 10.7: Wood Frame Wall – Control of condensing surface temperature assembly.

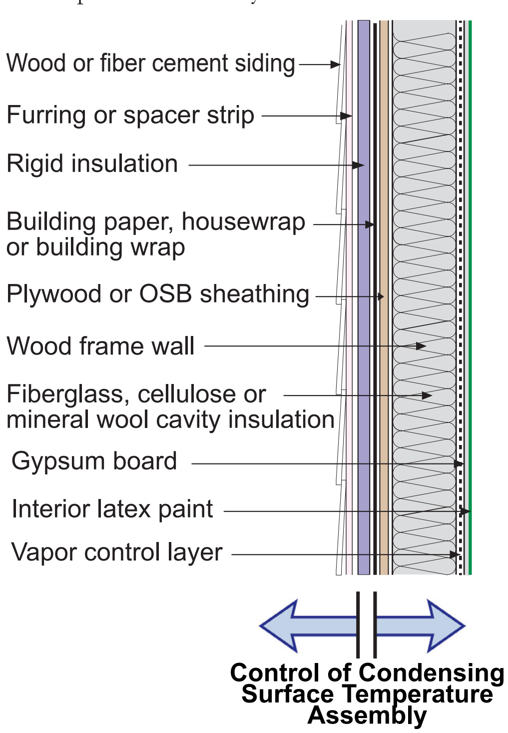

Figure 10.8: Wood Frame Wall – Control of condensing surface temperature coupled with vapor control layer assembly.

insulation protecting the rigid insulation from fire. Also note the fully adhered membrane barrier for insect control.

Basement foundations are principally insulated from the interior due to constructability issues, thermal bridging issues with brick veneer construction, insect control and vermin issues and cost issues.

Figure 10.5 and **Figure 10.6** are two means of constructing insulated basements.

Walls

A common approach to construct wood frame walls in Climate Zone 6, 7 and 8 is illustrated in **Figure 10.7**. The plywood or OSB sheathing is covered by a housewrap water control layer. The key element of this wall is the gap between the cladding and the rigid insulation used to control hydrostatic pressure. The wall cavity insulation can be fiberglass, cellulose or mineral wool. **Figure 10.8** is identical to **Figure 10.7** except for the use of an interior vapor control layer.

In **Figure 10.7** the thermal resistance of the exterior continuous rigid insulation is determined by climate as shown in **Table 3.1**.

Roofs

The most common approach to roof construction in these climate zones is a vented attic. **Figure 10.9** illustrates the recommended approach to constructing vented attics. Asphalt shingles are the most common type of roof covering on residential roofs.

Balanced attic ventilation approaches are more effective than cross-ventilation approaches. Intake vents should be located in the lower section of the roof (typically in the soffit), and exhaust vents are located in the upper section of the roof (typically along the ridge).

Note the use of a vapor control layer in **Figure 10.9**.

An unvented roofing assembly is illustrated in **Figure 10.10** The amount of rigid insulation to control condensation is specified in **Table 5.1**.

Unvented roofs constructed where the ground snow load is greater than 50 lb/ft^2 need a vented over-roof to control ice damming as illustrated in **Figure 10.10**.

Case Studies

One complete section is presented as typical for Minneapolis (**Figure 10.11**).

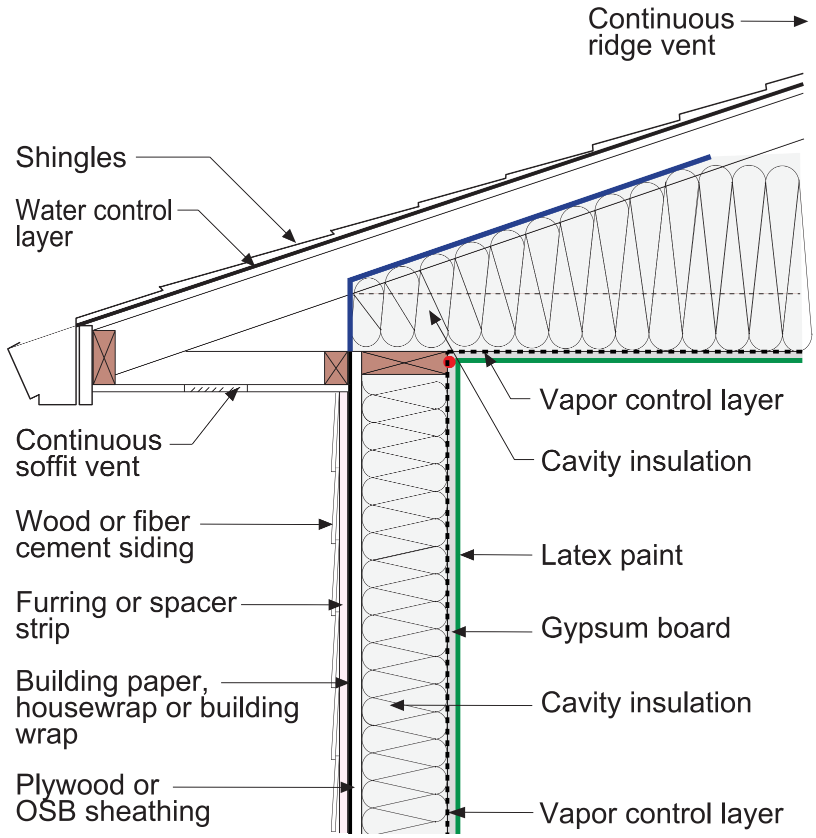

Figure 10.9: Vented Attic – Balanced attic ventilation.

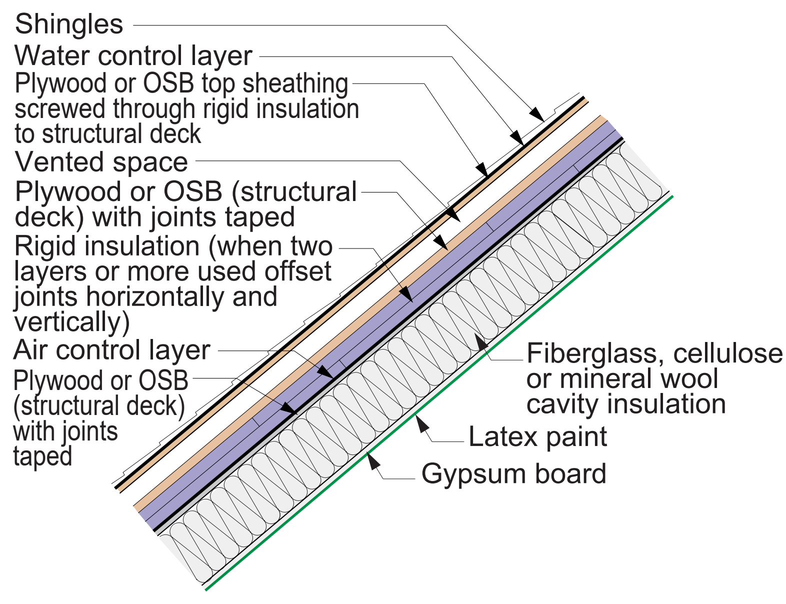

Figure 10.10: Vented Over Roof – Unvented attic with vented over roof.

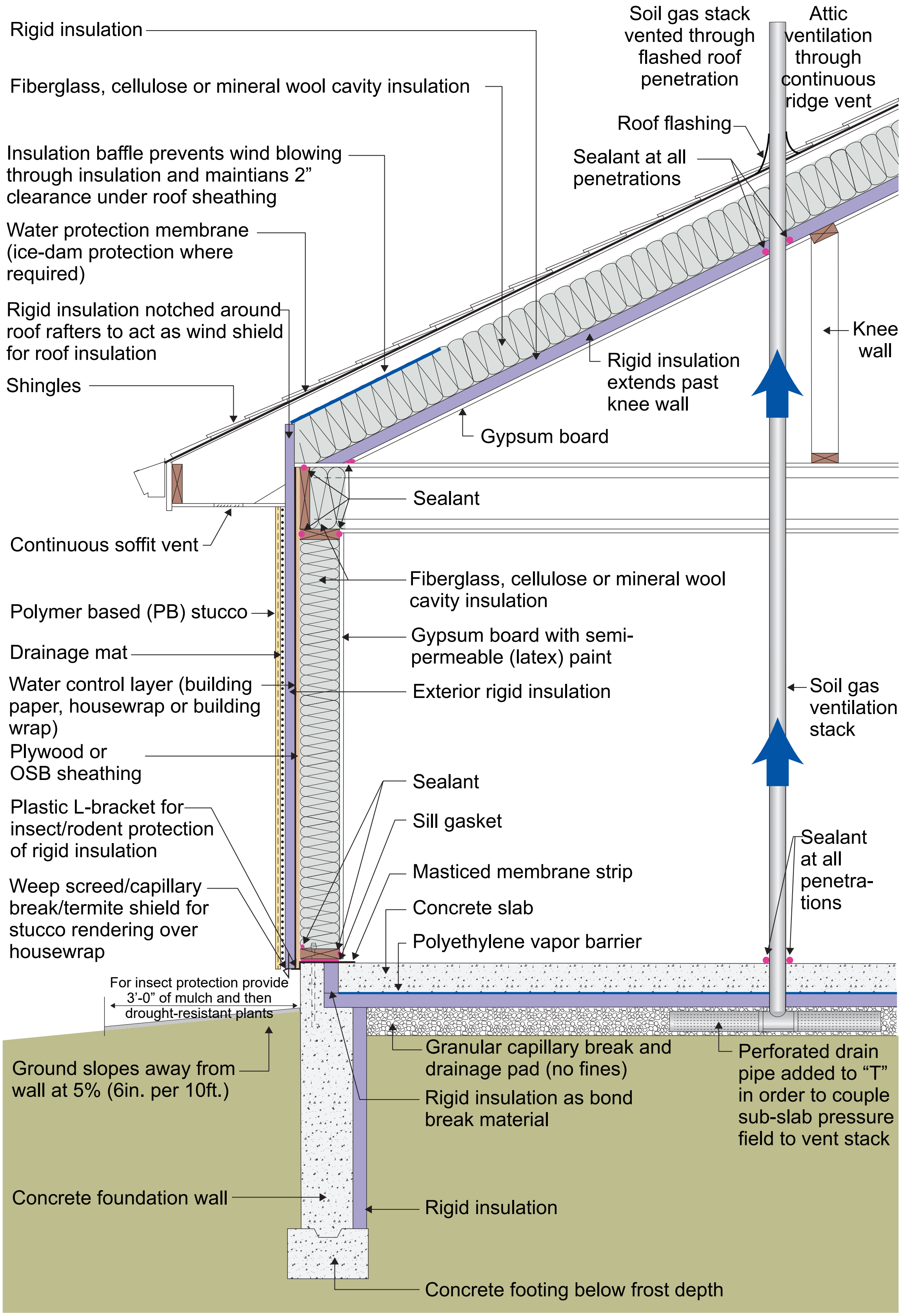

Figure 10.11: Minneapolis

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CHAPTER 11

Common Problems

Common Problems

- Windows and Continuous Insulation
- Ice Dams
- Wood Floors on Concrete
- Stucco Decay
- Cladding and Trim Deterioration
- Condensation on Attic Ductwork in Vented Attics and Elevated Interior Humidity in Hot Humid Climates

Windows and Continuous Insulation

The basic concept for dealing with window openings is straightforward:

- Connect the water control layer of the wall to the water control layer of the window.
- Connect the air control layer of the wall to the air control layer of the window.
- Connect the vapor control layer of the wall to the vapor control layer of the window.
- Connect the thermal control layer of the wall to the thermal control layer of the window.
- Install the window plumb, level and square.
- Don't let the wind suck or push the window out of the wall.

Complications arise with the location of the wall water control layer and air control layer. With continuous insulation, these layers can be the continuous insulation layer itself – or they can be behind the continuous insulation.

Historically, water control layers have been thin mechanically attached membranes such as tar paper, impregnated felt, coated paper, and polyolefin films. The best performance from a wind load and durability perspective is to install such films behind the continuous insulation layer and over structural sheathing. That way the film is supported on both sides - it is sandwiched typically between OSB/ plywood/gypsum structural sheathing on one side and the continuous insulation layer on the other. Neither sucking nor blowing cause flexing or billowing.

More recently the structural sheathing itself is being used a water control layer and air control layer with the continuous insulation

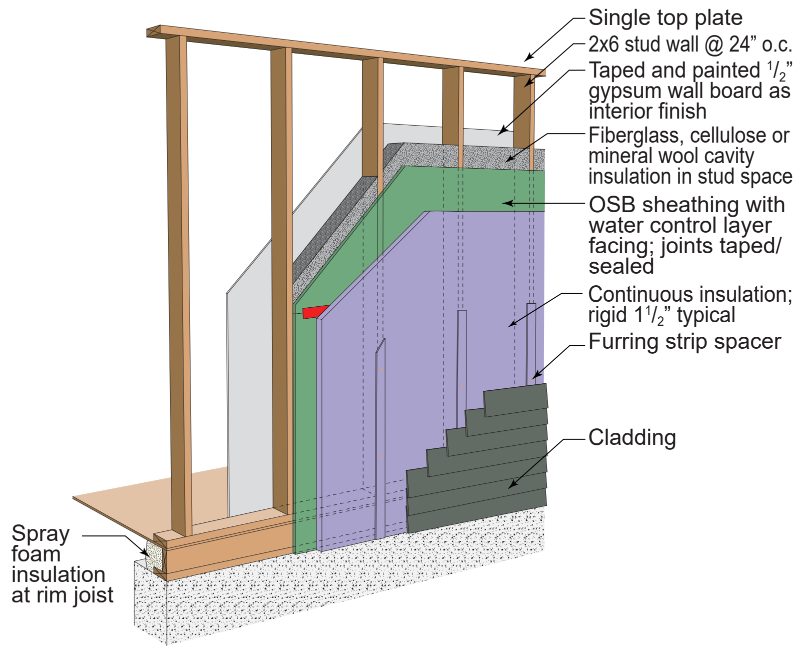

Figure 11.1: Structural Sheathing as the Water Control Layer and Air Control Layer – Continuous insulation is installed over the structural sheathing.

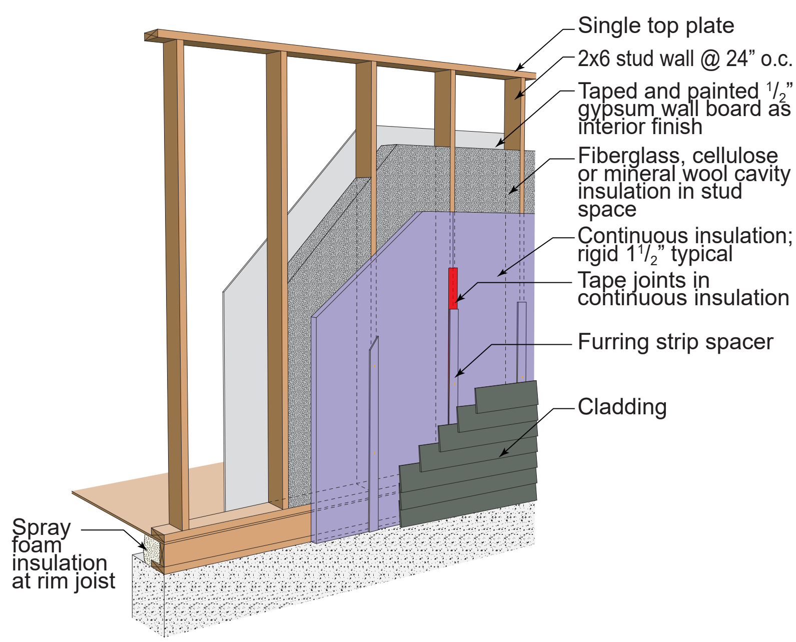

Figure 11.2: Continuous Insulation as the Water Control Layer and Air Control Layer - Include or exclude the structural sheathing based on structural considerations.

Figure 11.3: Window Installation Sequence For "Innies". The water control layer and air control layer is the sheathing behind the continuous insulation. Note that the water control of the flanged window lines up with the water control of the sheathing. Note that the pan flashing can be liquid applied or a formable membrane. Note that sealant is not necessary behind the window flanges. Note that the seams in the continuous insulation do not need to be sealed or taped.

being installed over the structural sheathing (**Figure 11.1**). It is also becoming common for the continuous insulation itself being used as the water control layer and air control layer (**Figure 11.2**).

Further complications arise from the location of the window. Are the windows going to be "inset" (aka "innies") or are they going to be outboard of the structure at the exterior face of the continuous insulation (aka "outies")? If the windows are "inset" and the water and air control layer is behind the continuous insulation installation of the windows is rather straightforward as the control layers "line up". If the windows are “outset” and the water and air control layer is the face of the continuous insulation installation of the windows is also rather straightforward – again, the control layers also “line up”. But if the windows are outset and the water and control layer is behind the continuous insulation installation of windows can become complicated.

The typical sequence of installation for windows that are “inset” with the water and air control layer behind the continuous insulation installation is presented in **Figure 11.3**. Note that the water control of the flanged window lines up with the water control of the sheathing. Note that the pan flashing can be liquid applied or a formable membrane. Note that sealant is not necessary behind the window flanges. Note that the seams in the continuous insulation do not need to be sealed or taped.

The continuous insulation does not have to be rigid with this approach, when the windows are “innies” with the water control layer and air control layer being the structural sheathing. The continuous insulation can be any type of continuous insulation - rigid or mineral fiber. Therefore, options include extruded polystyrene (XPS), expanded polystyrene (EPS), foil-faced polyisocyanurate, or mineral fiber insulation boards (**Figure 11.4**). The continuous insulation can be any thickness.

(**Figure 11.5** shows an “innie” window head detail, with the water control layer at the structural sheathing). The head trim flashing only covers the top of the trim itself – it only protects the top of the trim, This head flashing does not have to extend through the continuous insulation to the face of the structural sheathing/ water control and air control layer. Also see the isometric detail in **Figure 11.31c** for

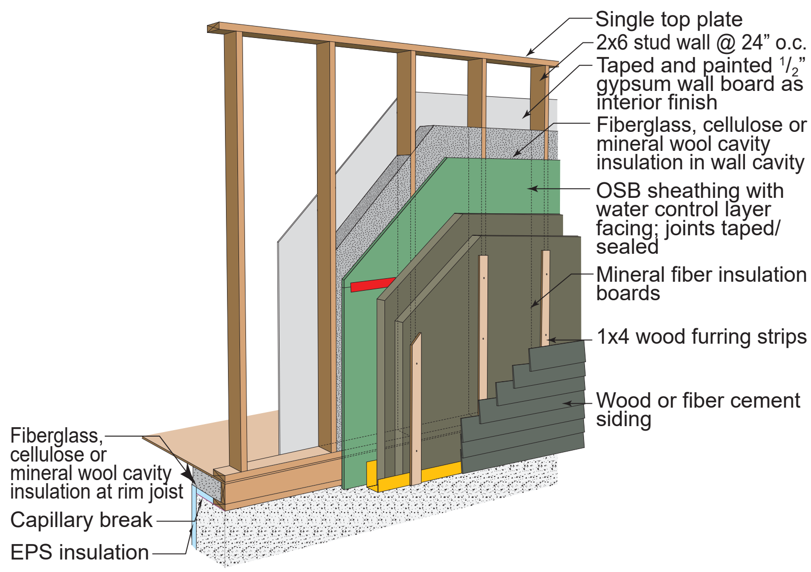

Figure 11.4: Mineral Fiber Insulation - With mineral fiber insulation the face of the mineral fiber insulation cannot be the water control layer and the air control layer. Structural sheathing is typically necessary with mineral fiber insulation. Typically the structural sheathing is turned into the water control layer and the air control layer.

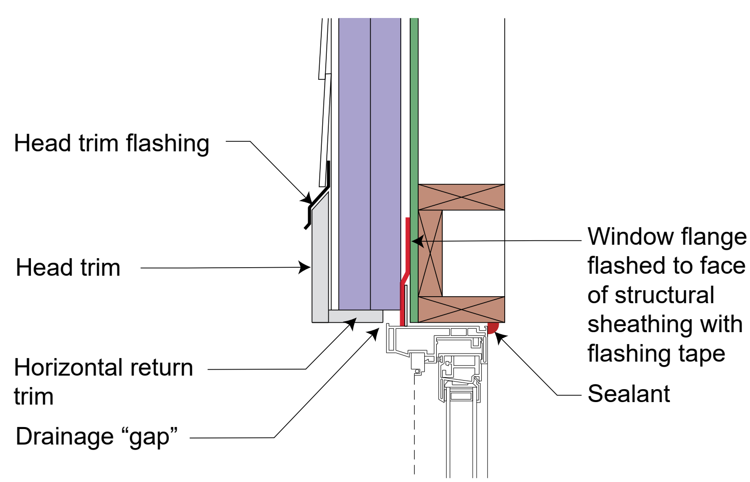

Figure 11.5: Window Head - The window head – the flange at the top of the window – is flashed to the face of the structural sheathing/water control layer and air control layer behind the continuous insulation. A gap is left at the inboard side of the horizontal return trim at the top of the window opening to let any penetrating rainwater run out between the window flange and the horizontal trim.

Figure 11.6: Window Installation Sequence For "Outies". The water and air control layer is the face of the continuous insulation. Note that the water control of the flanged window lines up with the water control of the face of the continuous insulation. Again note that the pan flashing can be liquid applied or a formable membrane. Again note that sealant is not necessary behind the window flanges. And finally note that there is no wood behind the window flange – the flange is seated directly over the continuous insulation. The window is attached through the flange and continuous insulation to the framing with long screws.

reference. The window head – the flange at the top of the window – is already flashed to the face of the structural sheathing/ water control and air control layer behind the continuous insulation. A gap is left at the inboard side of the horizontal return trim at the top of the window opening to let any penetrating rainwater run out between the window flange and the horizontal trim.

The typical sequence of installation for windows that are outset ("outies") with the face of the continuous insulation as the water and air control layer is presented in **Figure 11.6**. Note that the water control of the flanged window lines up with the water control of the face of the continuous insulation. Again note that the pan flashing can be liquid applied or a formable membrane. Again note that sealant is not necessary behind the window flanges. And finally note that there is no wood behind the window flange – it is unnecessar – the flange is seated directly over the continuous insulation. The window is attached through the flange and continuous insulation to the framing with long screws.

However with this approach the continuous insulation must be rigid. It cannot be mineral fiber insulation boards as the mineral wool cannot support the window. The continuous insulation in this approach is limited to extruded polystyrene (XPS), expanded polystyrene (EPS), or foil-faced polyisocyanurate. Additionally, the seams in the continuous insulation need to be sealed or taped. The thickness of the continuous insulation is limited to 1.5 inches for this window detail – also for structural reasons. For thicker layers of continuous insulation the opening needs to be lined with a structural box and the windows attached with straps (**Figure 11.7**). The structural box is typically plywood or OSB and it protrudes past the exterior face of the framing the thickness of the continuous insulation. Note that with the structural box the water control layer is wrapped into the box opening and the material is typically flashing tape. Also note that exterior cladding will need to be installed to 1x4 furring strips that are attached through the continuous insulation to the structural frame with long screws.

The typical sequence of installation for windows that are outset ("outies") with mineral fiber continuous insulation is used is presented in **Figure 11.8**. Note that with mineral fiber insulation the face of the mineral fiber insulation cannot be the water control layer and air control layer. The water control layer and air control layer need to be

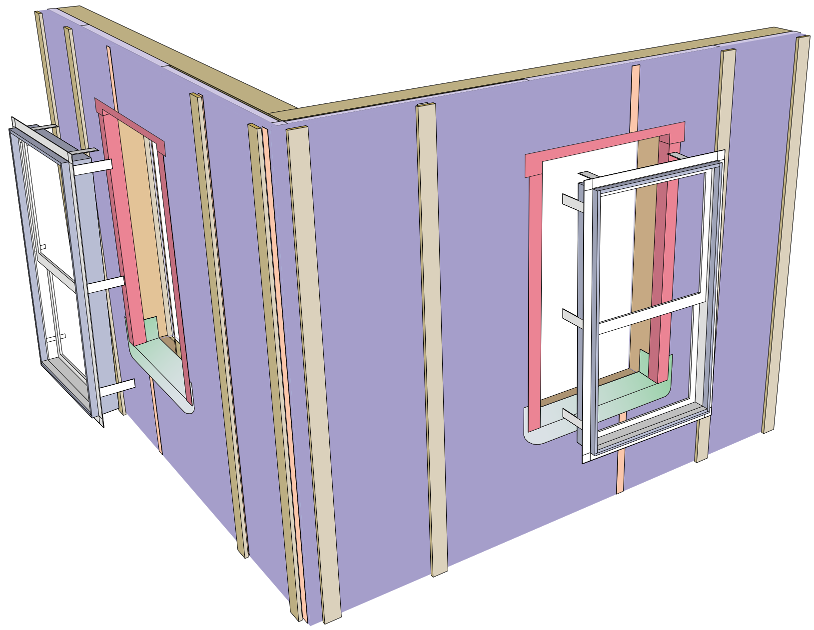

Figure 11.7: Structural Box - Note that with the structural box the water control layer is wrapped into the box opening and the material is typically flashing tape.

Figure 11.8: Window Installation Sequence For Mineral Fiber Installation (Stone Wool) - Note that liquid applied flashing is used to provide continuity with the water control layer on the face of the structural sheathing and the “picture framing” “structural extension”. The liquid applied flashing wraps into the frame opening and creates the “pan flashing” for the opening. The window installation now follows the same steps as for the “innie” approach.

behind the mineral fiber insulation.

The window opening is lined with wood framing that is the thickness of the mineral fiber insulation and this "structural extension" should be wide enough on its face to be able to integrate the window flange with the water control layer and air control layer at the face of the structural sheathing. This is typically 2x material. With 1-½ inch thick mineral fiber insulation the rough opening is "picture framed" with 2x2's. For thicker continuous mineral fiber insulation 2x4's or 2x6's are trimmed to the correct thickness for the "picture framing". Note that liquid applied flashing is used to provide continuity with the water control layer on the face of the structural sheathing and the "picture framing" "structural extension". The liquid-applied flashing wraps into the frame opening and creates the "pan flashing" for the opening. The window installation now follows the same steps as for the "innie" approach.

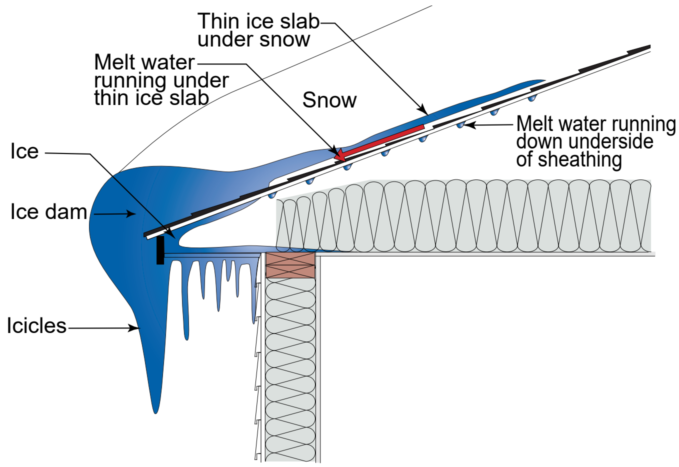

Figure 11.9: Melt Water – When the snow layer adjacent the roof deck melts the liquid water is wicked upward into the snow pack by capillarity away from the roof covering. As the liquid water migrates upwards it gets colder and freezes. As more snow melts and the liquid water phase exceeds the storage capacity of the snow it runs downward under the ice layer via gravity. At the roof edge and roof overhang the deck is much colder and the drainage gap freezes solid causing the water to back up.

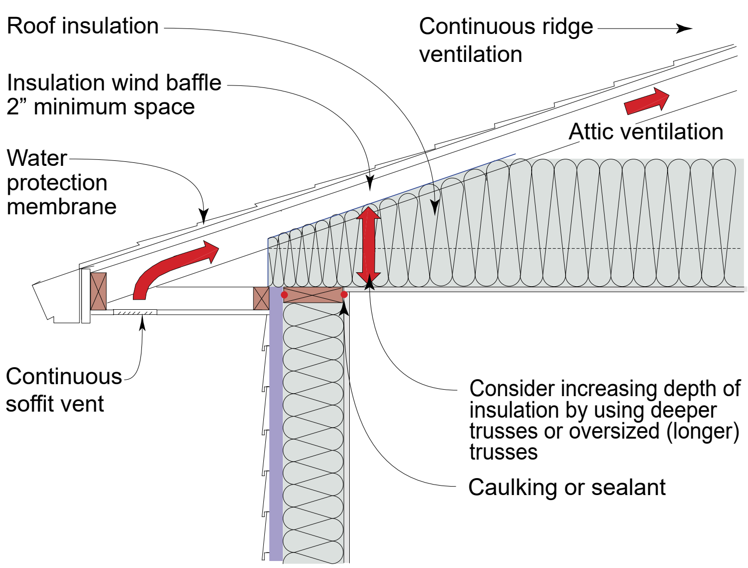

Figure 11.10: Classic Control Approach - Keep heat from the interior from getting to the roof deck and then remove any heat that gets there. First, construct an airtight "lid" or ceiling plane. Second, insulate the top of the lid with insulation. And then third, flush away any heat that gets to the roof deck by ventilating the underside of the roof deck with exterior air. Note the air seals at the top of the exterior wall. Exterior walls are like chimneys – you don't want to vent the tops of them into your roof. The minimum thermal resistance directly over the top of the top plate should be greater than the thermal resistance of the wall. Also, note that a 2 inch minimum airspace is recommended under the sheathing

Ice Dams

Ice dams occur when the outside temperature is below freezing, the roof deck temperature is above freezing, and there is snow on the roof. The warm roof deck melts the snow on top of the roof deck, and the melt water runs down to the edge of the roof where the water freezes leading to a buildup of ice and a back-up of water – hence the term "dam" (**Figure 11.9**).

The strategy to control ice dams is to keep the roof deck below freezing when the outside temperature is below freezing. The best approach – the classic approach - to accomplish this is the vented roof (**Figure 11.10**). Keep heat from the interior from getting to the roof deck and then remove any heat that gets to the roof deck using ventilation.

For this approach to work three requirements need to be met. First, an airtight "lid" or ceiling must be constructed. Second, the top of the lid must be insulated well. Third, heat that gets to the roof deck must be removed by ventilating the underside of the roof deck with exterior air.

The most common failure causing ice dams is not making the lid airtight allowing heated air to get into the attic. Even worse is to install heating systems in attics that leak air, conduct heat and radiate heat (**Figure 11.11**).

Although most roof deck assemblies are ventilated they are often not ventilated correctly. To control ice dams the entire underside of the roof deck should be "washed" with outside air. Every rafter or truss bay, not every third one, needs to be ventilated.

Ductwork and heating systems should be located inside – not in vented attics. One approach is to convert vented attics into conditioned attics by moving the air control layer and thermal control layer to the roof deck (**Figure 11.12**). This can be done by either insulating above the roof deck or insulating below the roof deck. Regardless of whether the insulation is above or below the roof deck, ventilation is still necessary to control ice dams. The best approach is to install a vented "over-roof" over an unvented "under-roof (**Figure 11.13**).

Snow has an R-value of R-1 to R-2 per inch depending on density (**Figure 6**). Snow on a roof acts as an insulating blanket that elevates the temperature of the roof deck. More snow, more ice damming simply because of the thermal resistance of the snow. A foot of snow on a roof yields a thermal resistance of between R-10 and R-20. Even if an airtight roof assembly is constructed with a great deal of insulation at some point the thermal resistance of the snow will be such that the roof deck will be above freezing when the outside temperature is below freezing. Unvented roofs should not be constructed where it snows a lot even with "super-insulated" roofs. Where the ground snow load exceeds 50 lbs/ft^2 all roofs should be vented – even "super-insulated" roofs – to control ice-damming.

Overhangs trap heated air (**Figure 11.14**). This is a real problem with dark claddings. The trapped heat melts the snow and an ice dam results. Overhangs in high snow load regions should be insulated to control ice damming caused by thermal plumes off claddings.

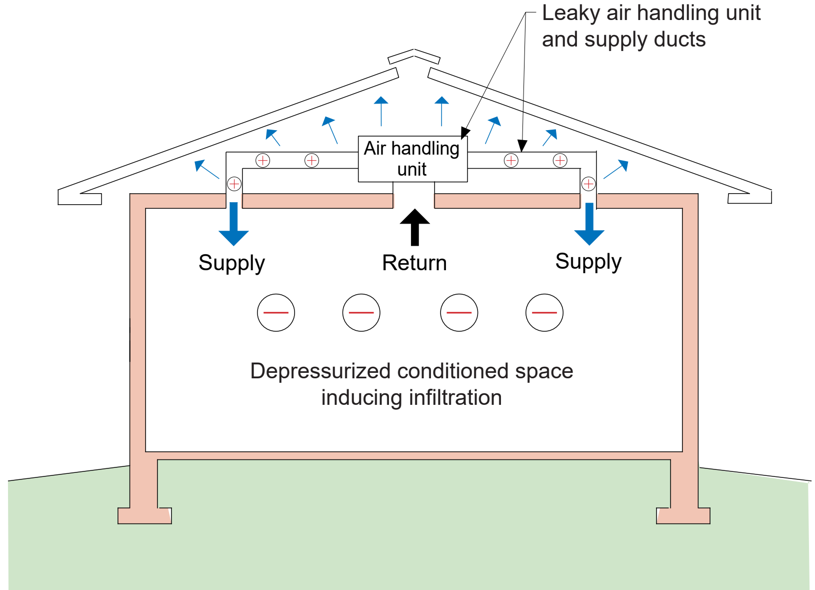

Figure 11.11: Ductwork in Attics - The air leakage out of the ducts and the conductive and radiative losses from the surfaces of the ducts results in ice damming.

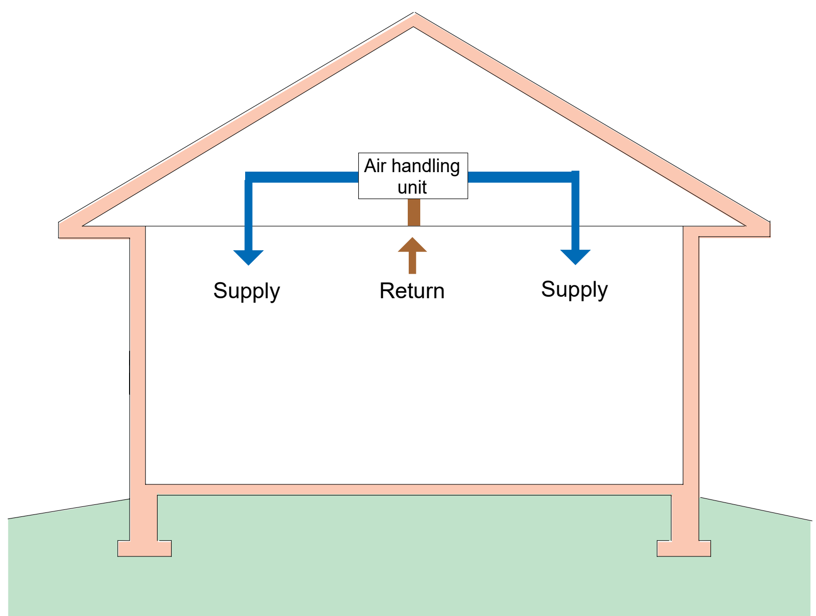

Figure 11.12: Conditioned Attic – Putting the ducts inside by moving the thermal boundary and pressure boundary to the roof deck. This can be done by insulating on the top of the deck or applying spray foam on the underside of the deck.

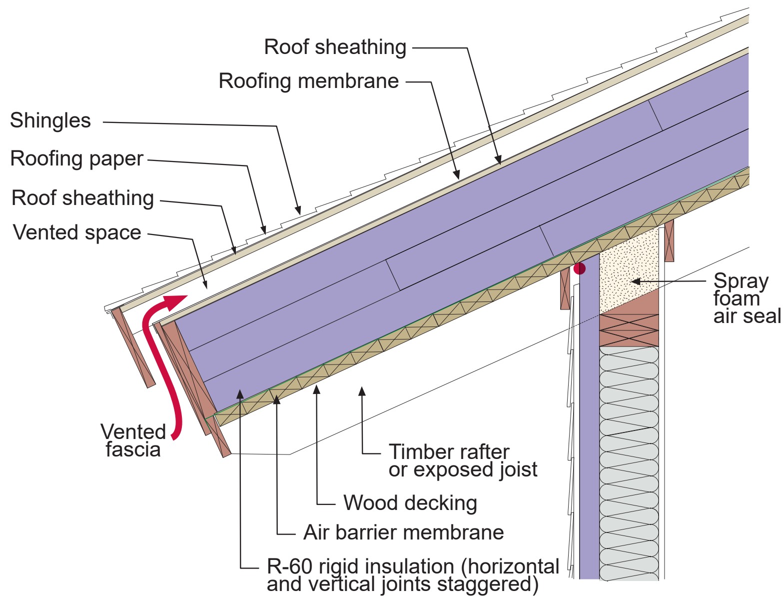

Figure 11.13: Compact Roof – Roof deck insulated on the topside. Note the air control layer. Note that the air intake for the vented "over-roof" is at the facia and that the over-hang is insulated compensating for cladding thermal plumes due to incident solar radiation.

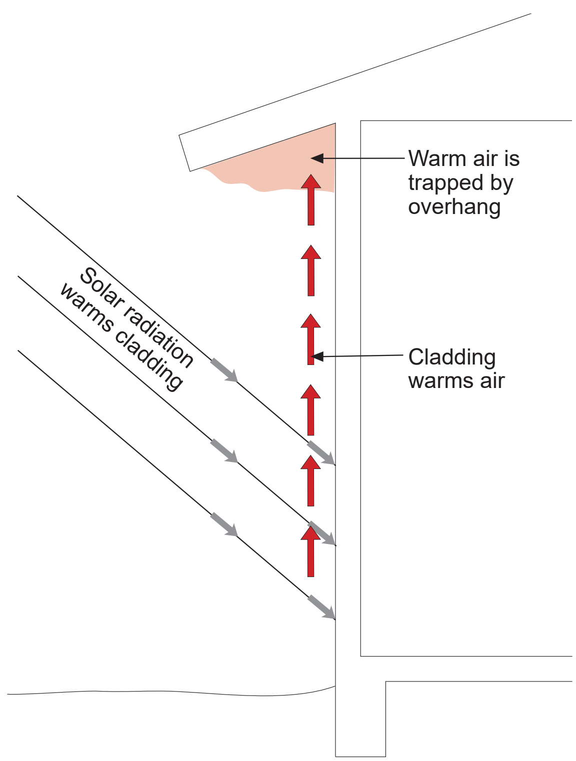

Figure 11.14: Cladding Thermal Plumes – Dark cladding, solar radiation and large over-hangs combine to create ice-dam heaven.

Wood Floors on Concrete

Concrete loves water. It would love to stay wet forever. The longer it stays wet the stronger it becomes. Wood hates water. Water makes wood move and decay. For wood and concrete get along either the wood must be separated from the concrete or the concrete must be dry enough not to cause issues with the wood. Installing wood floors over concrete often leads to problems.

Historically, concrete slabs on grade or basement concrete floors were covered with a continuous layer of bitumen to separate wood floors from the concrete (**Figure 11.15**). The bitumen would be both a vapor control layer (vapor barrier) and a capillary break. The bitumen was covered with felt paper. Sometimes it was installed in two layers. This was nothing more than a single-ply or double-ply built-up roof installed on a concrete slab. This was an inside roof.

Over the top of this felt-covered bitumen layer (or two bitumen layers) wood sleepers and wood plank flooring were installed. The backside of the wood flooring was typically machined so that it would not warp due to differential drying between the top and bottom surfaces during seasonal moisture content changes (**Figure 11.16a**, **11.16b**, **11.16c** and **11.16d**).

Over time the wood sleepers were replaced with plywood that was covered with a slip surface to keep the wood flooring from squeaking as it changed moisture content seasonally.

In the last half of the last century the continuous bitumen layer practice changed. The bitumen layer was no longer installed – only the layer of felt was installed. Felts

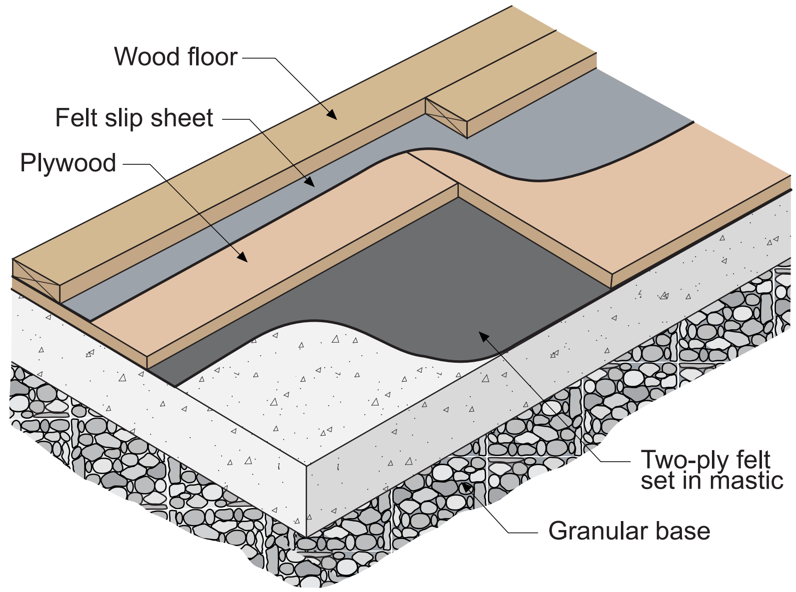

Figure 11.15: Historic Practice: A continuous layer of bitumen was installed over the top of the concrete surface. The bitumen would be both a vapor barrier and a capillary break. To keep it from getting over everything it was covered with felt paper. Sometimes installed in two layers.

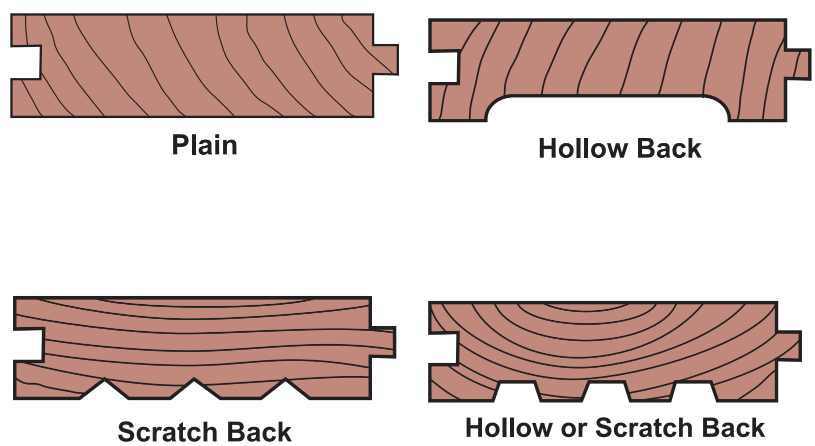

Figure 11.16a, Figure 11.16b, Figure 11.16c and Figure 11.16d: Wood Floor Profiles: The backside of wood flooring was machined so that it would not warp due to differential drying between the top and bottom surfaces during seasonal moisture content changes.

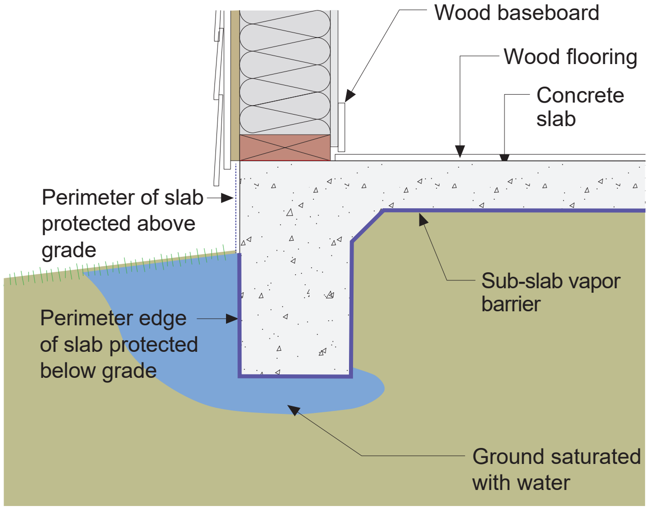

Figure 11.17: Monolithic Slab: A continuous polyethylene vapor barrier and capillary break needs to wrap the entire concrete surface that contacts the ground – especially the perimeter. It is also recommended to paint the exposed edge of the slab above grade to keep it from getting wet from "splash back" (rainwater hitting the ground and bouncing back up) and enthusiastic over irrigation by occupants. The paint should be "liquid water" closed and "vapor water" open – hygrophobic and vapor permeable – typical acrylic latex paint formulated for concrete substrates

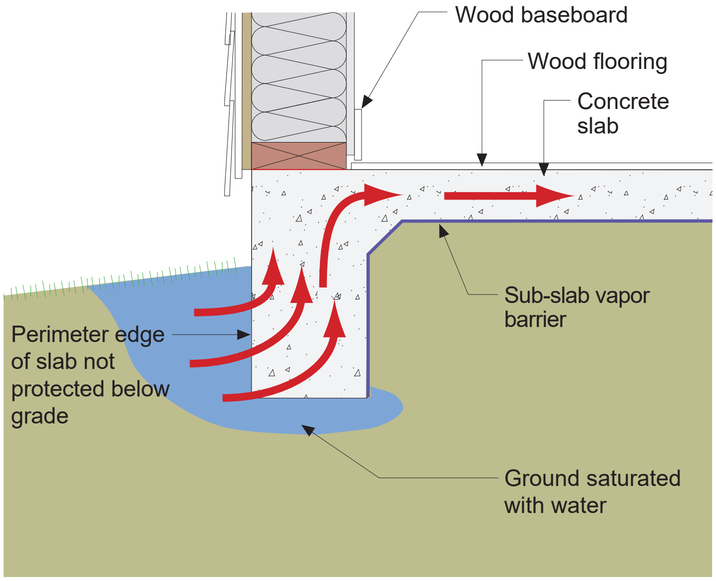

Figure 11.18: Capillary Wicking: Without the slab edge protection water can wick dozens of feet inward via capillarity.

during this period were typically impregnated with some bitumen. But impregnated felt is not a vapor barrier or a capillary break. The original intention of the felt was to be a cover sheet for the bitumen. It was never intended to be a replacement for the bitumen.

However, at approximately the same time it became common practice to install a sheet of plastic under the concrete to separate the concrete from the ground. If the concrete was allowed to dry before the wood flooring was installed problems were avoided – as long as the concrete did not get wet from the ground underneath or from the side.

It is not necessary to separate the wood flooring from the concrete as long as the concrete is separated from the ground and the concrete is allowed to dry before the wood flooring is installed.

With monolithic slabs a continuous polyethylene vapor barrier and capillary break should wrap the entire concrete surface that contacts the ground – especially the perimeter (**Figure 11.17**). A plastic "skirt" is typically attached to the perimeter form boards or running the plastic over the top of the form boards and trimming the plastic later after the form boards are stripped. Without the slab edge protection water can wick dozens of feet inward via capillarity (**Figure 11.18**) and flooring problems result such as discoloration, movement and decay.

The exposed edge of the slab above grade should be painted to keep it from getting wet from "splash back" (rainwater hitting the ground and bouncing back up) and over-irrigation of adjacent plantings by occupants. The paint should be "liquid water" closed and "vapor water" open – hygrophobic and vapor permeable – typical acrylic latex paint formulated for concrete substrates.

With stem wall foundations the edge of the slab is wrapped and slabs should be well elevated (**Figure 11.19**).

If the concrete is separated from the ground – both from underneath and from the sides and the concrete is allowed to dry – wood flooring can be directly installed on the concrete (**Figure 11.20**).

Unfortunately, with "wet" concrete mixes "drying" typically takes several months. In new construction such a time delay is typically not practical and it is increasingly common and necessary to install a top side fluid applied vapor barrier (**Figure 11.21**).

The smart way is a fluid applied vapor barrier (**Figure 7**). Epoxies work well. It is not recommended to install a sheet good vapor barrier such as polyethylene on the top side. If the vapor barrier layer is not completely fully adhered condensation will occur in air pockets. If these air pockets communicate with the interior mold and algae can grow, resulting in odors.

With insulated floor slabs the insulation should be placed under the plastic vapor barrier and over the top of a granular capillary break (**Figure 11.22**). Insulation should not be installed over the top of the plastic vapor barrier and under the slab. The insulation will get wet and likely remain wet. Insulation located under vapor barriers can dry into the granular layer. With under-slab insulation it is necessary to install a granular layer with no fines to act as a capillary break.

Wood moves with relative humidity changes as it is a hygroscopic material (**Figure 11.23**). In most places the interior winter

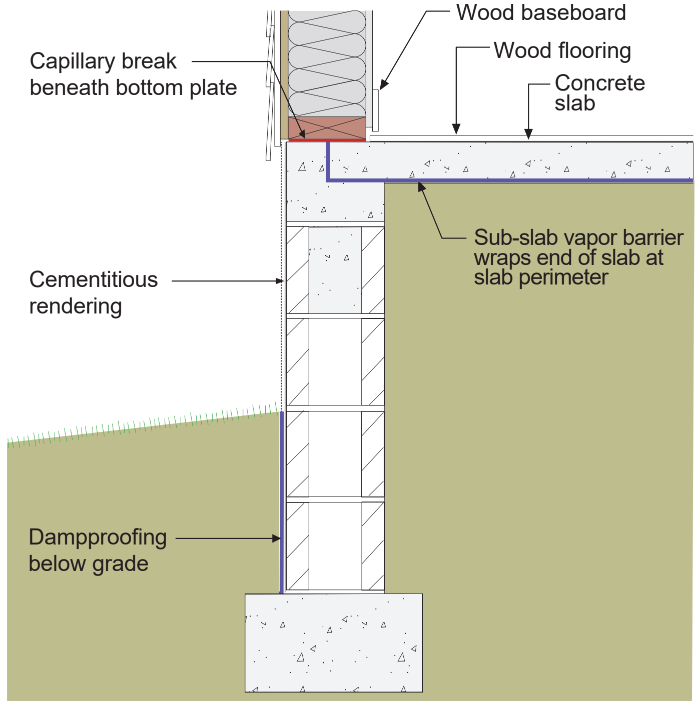

Figure 11.19: Stem Wall Foundation: It is a lot easier to handle a stem wall foundation where the edge of the slab is wrapped and the slab is well elevated.

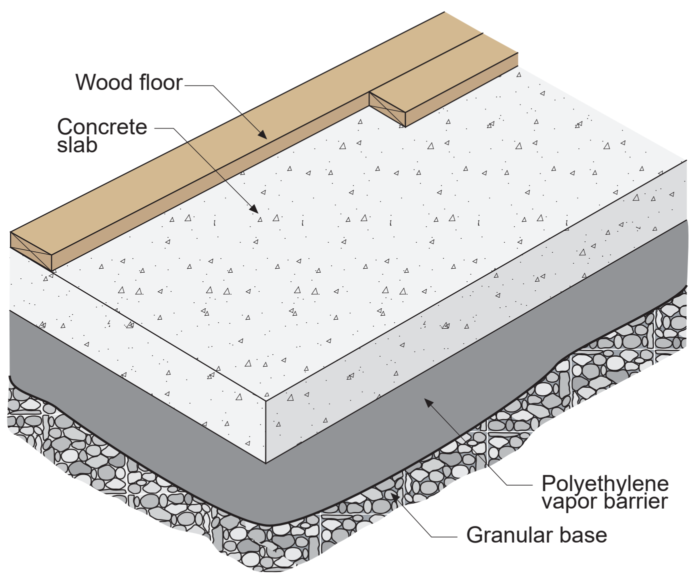

Figure 11.20: Separate the Concrete from the Ground: This needs to be done from underneath and from the sides. We also need dry concrete. We need low water-to-cement ratio concrete or we need to wait for the concrete to dry before we install flooring.

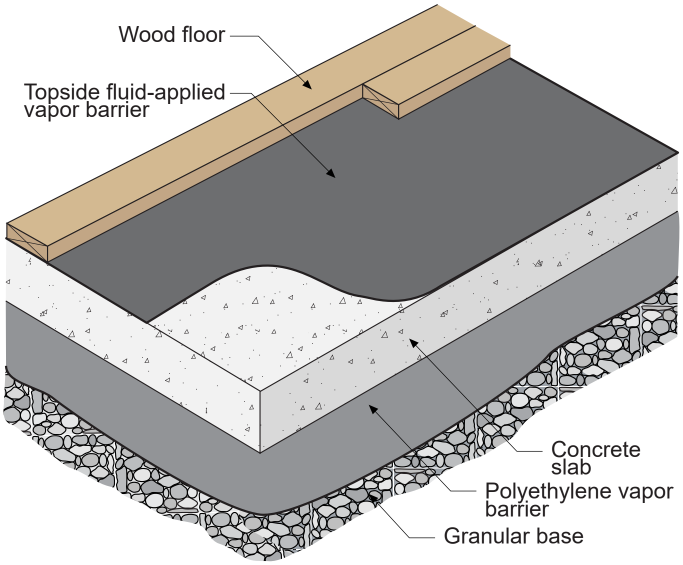

Figure 11.21: What if Your Slab is Wet?: A topside vapor barrier should be installed. A fluid applied vapor barrier such as epoxy work well.

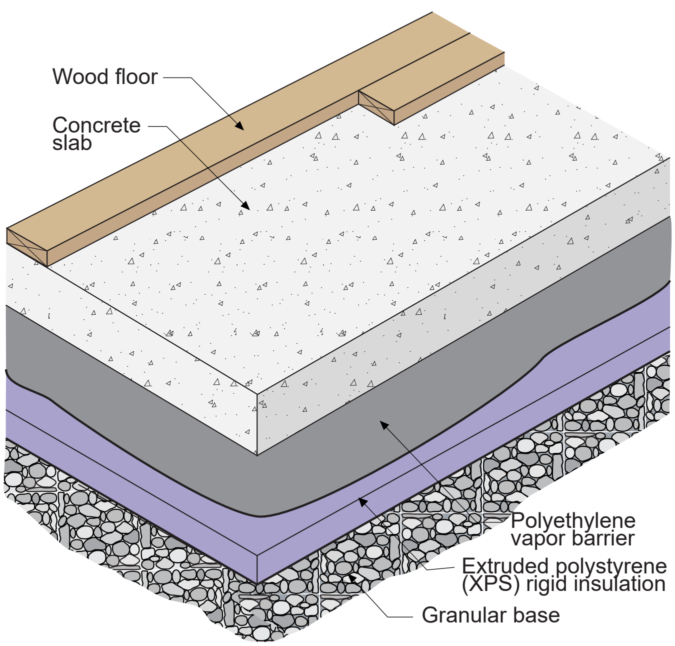

Figure 11.22: Insulating the Slab: Install the insulation under the plastic vapor barrier and over the top of a granular capillary break. Do not install the insulation over the top of the plastic vapor barrier and under the slab. The insulation will get wet. Installing insulation under the vapor barrier allows it to dry into the granular layer.

relative humidity is low (typically 30 percent) and high during the summer (typically 65 percent). As such the wood flooring will float between 6 percent moisture content by weight and 12 percent moisture content by weight - a 6 percent seasonal swing.

If wood flooring is installed at 6 percent it will buckle when it goes to 12 percent. If wood flooring is installed at 12 percent it will shrink and leave big gaps when it goes to 6 percent. Wood flooring should be conditioned to the mid-range moisture content it is likely to see during service. For most of the lower 48 states that would be 9 percent moisture content by weight.

Wood flooring manufacturers typically precondition the wood to 9 percent before shipping. Flooring manufacturers also prefer narrower planks as that results in more joints; they can accommodate more movement. Unfortunately, the aesthetic trend is towards wider planks. It is also necessary to leave gaps at the perimeter of rooms to accommodate movement.

How can wood movement be accommodated if the wood is not conditioned and wider planks are used? Floating floors can be installed – typically on a foam slip surface. The slip surface allows for movement and provides sound attenuation.

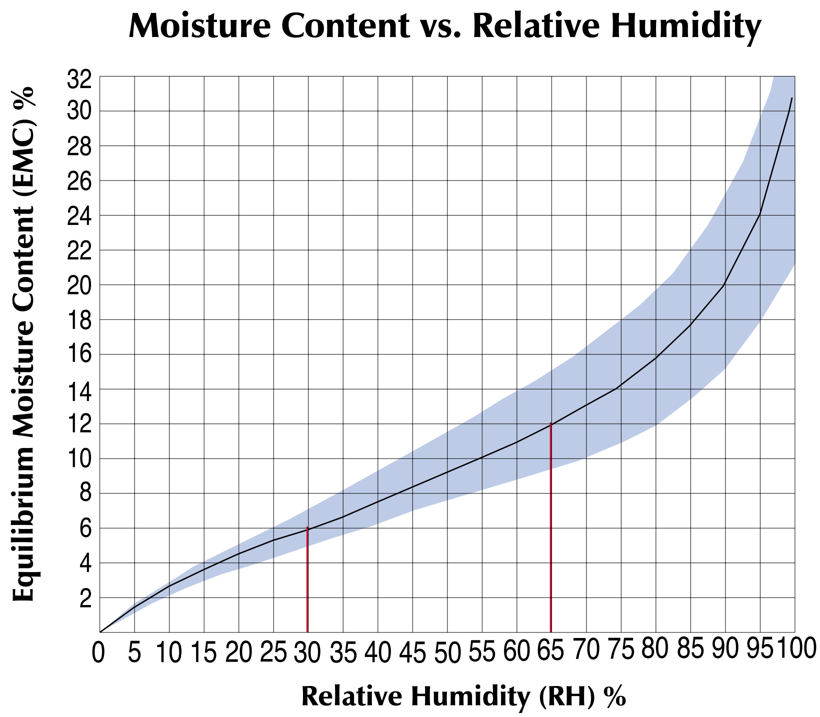

Figure 11.23: Conditioning the Wood Flooring: Wood expands and contracts with relative humidity changes as it is a hygroscopic material. In most places the interior winter relative humidity is low (typically 30 percent) and high during the summer (typically 65 percent). The wood flooring is going to float between 6 percent moisture content by weight and 12 percent moisture content by weight - a 6 percent seasonal swing. If wood flooring is installed at 6 percent it will buckle when it goes to 12 percent. If wood flooring is installed at 12 percent it will shrink and leave big gaps when it goes to 6 percent. Condition wood to the mid-range moisture content it is likely to see during service. For most of the lower 48 states that is 9 percent moisture content by weight.

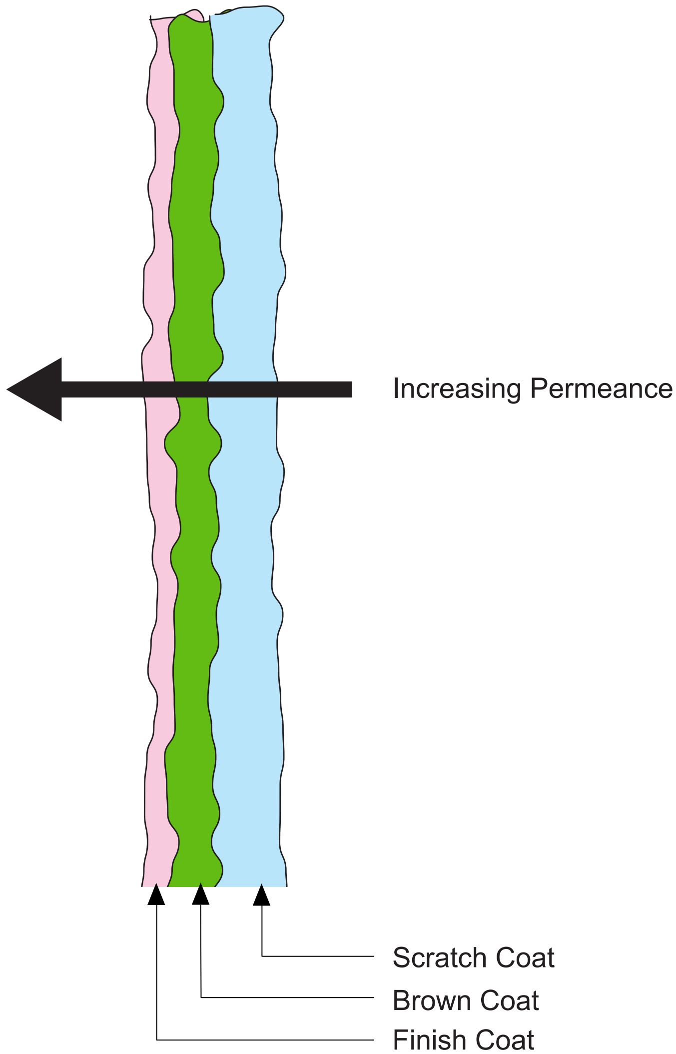

Figure 11.24: Traditional Stucco - Each successive layer to the exterior was more vapor open than the layer it covered.

Stucco Decay

Over several millennia stucco has evolved from a lime-based system to lime-Portland cement-based to Portland cement-based and finally to polymer modified. Each step has resulted in stronger systems. However, each step has resulted in lower vapor permeance.

Traditional lime based stucco Greater than 20 perms
Lime-Portland cement based stucco 5 to 10 perms
Portland cement based stucco 1 to 5 perms
Polymer modified stucco Less than 1 perm

This has resulted in a reduced ability of stucco system to dry.

Traditional lime based stucco was three layers: scratch coat, brown coat and finish coat (**Figure 11.24**). Each successive layer to the exterior was more vapor open than the layer it covered.

Stucco historically had good compressive strength but not very good tensile strength. As stucco formulations evolved compressive strength has increased as has tensile strength. To that end additives such as cow dung, egg whites, pigs blood, and finally polymers modified traditional stucco systems.

Traditional lime based stuccos had larger voids within their layers allowing vapor transmission. The additives reduced void volume, thereby reducing vapor transmission.

Additionally, many modern stucco assemblies do not always follow the traditional permeance rules laid out in **Figure 11.24**. Sometimes the finish coat and brown coat are less permeable than the scratch coat depending on what is added and how much.

Historically, stucco was applied directly over brick and stone. If stucco assemblies passed water there were no moisture sensitive substrates to decay. And the walls were not insulated resulting in energy exchange facilitating drying.

As stucco began to be installed over wood sheathed walls, as long as drying occurred assemblies performed well. Additionally, stucco was installed over traditional building paper to reduce water entry.

Three things changed: we stopped using real wood…we insulated significantly… and we stopped installing the stucco over traditional building paper.

Stucco substrates evolved from woven branches ("waddle and daub") to board sheathing. Then from board sheathing to plywood. Then finally from plywood to oriented strand board (OSB). The strength of the substrate increased as well as constructability. But with this evolution, permeance was reduced and therefore drying. The ability of penetrating water to be redistributed also was reduced while the moisture sensitivity of substrate increased.

At the same time insulation levels were increased thereby reducing the ability of the assemblies to dry when they got wet. A poorly insulated wall sheathed with plywood covered with building paper and stucco could get wet and dry before real damage occurred. A well-insulated wall sheathed

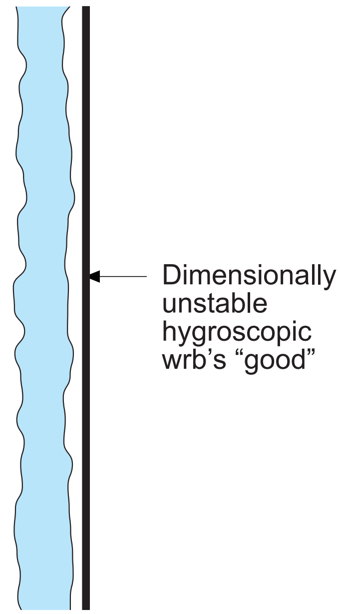

Figure 11.25: Dimensionally Unstable Building Paper - When building papers (aka "water resistive barriers" WRBs) were hygroscopic they expanded and contracted and stucco did not bond effectively to them.

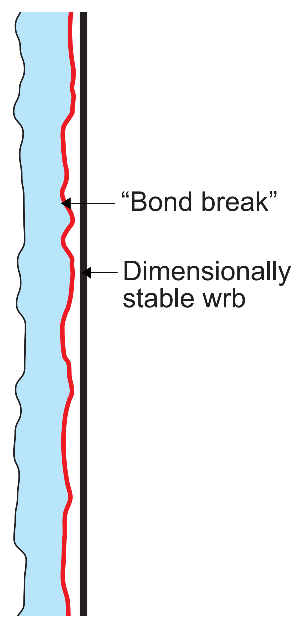

Figure 11.26: Bond Break - It became clear that there were issues with building papers and the first intervention was to use two layers – an outer layer that would act as a bond break and an inner layer that was the "true" water control layer.

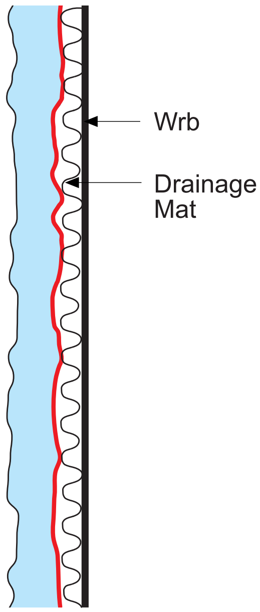

Figure 11.27: Drainage and Drying Gap - The assemblies needed enhanced drainage and enhanced drying. One of the more effective means of accomplishing both is to provide a drainage matt between the bond break and the water control layer.

with OSB covered with modern building papers and Portland cement based-stucco could not.

Additionally, building papers evolved – they became dimensionally stable. When building papers were hygroscopic they expanded and contracted and stucco did not bond to them effectively (**Figure 11.25**). Manufacturers of building papers began to make them more hydrophobic and dimensionally stable. This had unforeseen consequences. Stucco began to bond to building paper. When stucco bonds to building paper the building paper loses water repellency and its' ability to drain. Modern "plastic" building papers are even more dimensionally stable so the stucco bond is even more robust and the material even more sensitive to loss of water repellency.

Low permeance stucco, high thermal resistance wall assemblies, OSB sheathing, and dimensionally stable building papers result in stucco damage.

As it became clear that there were issues with building paper, the first intervention was to use two layers – an outer layer that would act as a bond break and an inner layer that was the "true" water control layer (**Figure 11.26**).

The stucco assemblies needed enhanced drainage and enhanced drying. One of the most effective means of accomplishing both is to provide a drainage gap between the bond break and the water control layer (**Figure 11.27**).

To avoid stucco failure over wood based sheathings a minimum 3/8 inch air space should be provided behind stucco installed over OSB sheathing.

Cladding and Trim Deterioration

Claddings and trim are stressed by rain and sun and go through huge temperature swings – the principal "damage functions" of water, heat, and ultra violet radiation.

Providing surface finishes and preventing underlying damage to wood, engineered wood, fiber cement, and other composite claddings and trim have become more difficult due to the changed the energy balance and changed underlying materials and layers.

Highly insulated wall assemblies constructed with modern sheathings such as oriented strand board (OSB) and foam plastic such as extruded polystyrene (XPS) and foil-faced polyisocyanurates, modern building wraps, fluid-applied coatings, and fully adhered membranes perform significantly differently than poorly insulated wall assemblies constructed from traditional materials.

The recommended solution to addressing the issues associated with claddings and trim is twofold: coat all six sides of claddings and trim and then back ventilate claddings and trim.

Back ventilation of claddings and trim results in an airspace that provides a benefit in rainwater entry as it controls hydrostatic pressure along with providing another benefit in enhancing outward drying of the wall assemblies themselves compensating for the change in energy balance.

Water traditionally entered wood siding assemblies and trim via capillarity (**Figure 11.28**). The water can't readily evaporate outward through the siding and paint film. The principal drying is inward. The moisture

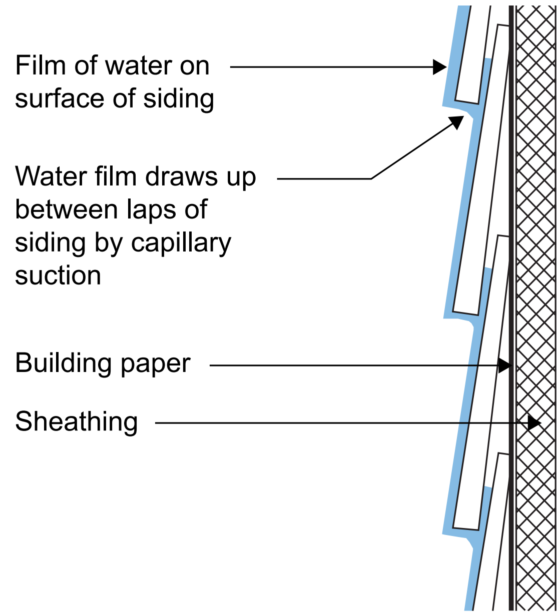

Figure 11.28: Capillary Rise In Siding – Water is pulled upwards between the laps of siding by capillarity.

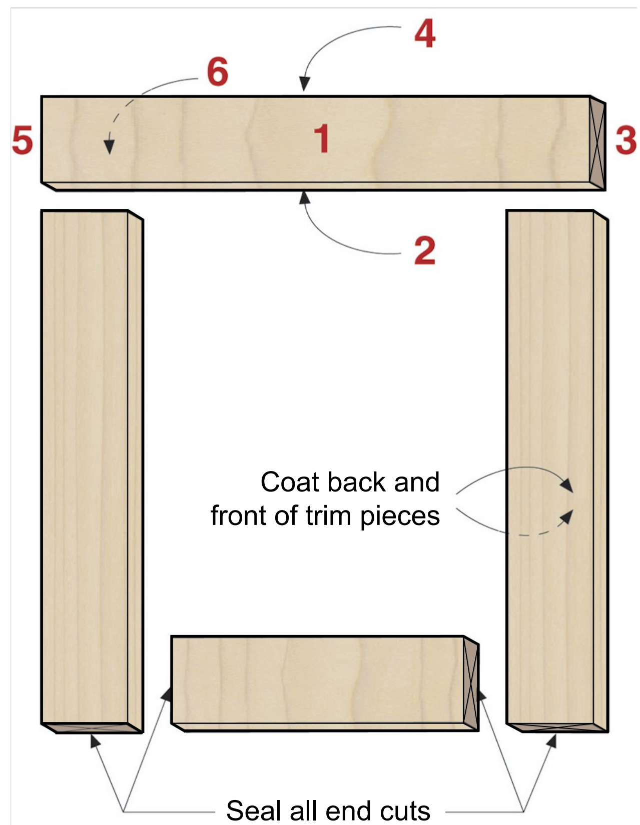

Figure 11.29: Trim Details - Seal or coat all six surfaces of materials to limit water absorption. Back ventilate trim materials so that absorbed water can evaporate and be vented to the exterior.

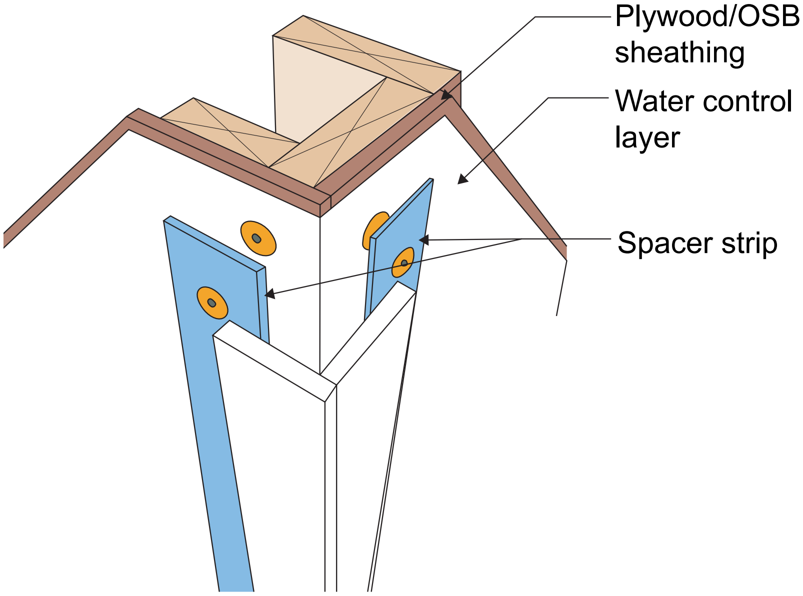

Figure 11.30: Air Gap – OSB and plastic housewrap. The spacer strips are ¼ inch to 3/8 inch strips of foam or sill gasket material.

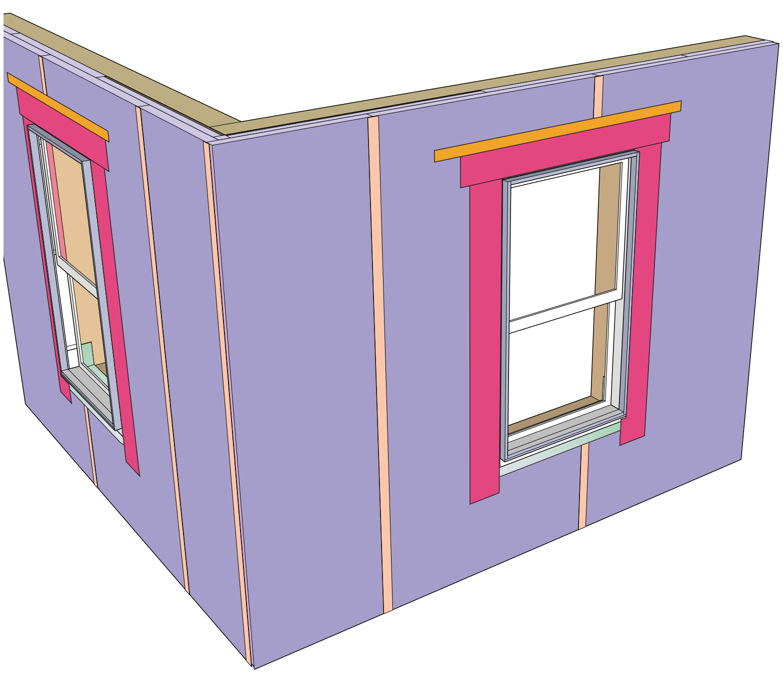

Figure 11.31a: Continuous Exterior Insulation – Water control layer is the exterior face of the insulation. Note the taped joints.

content in the wood siding and trim cycles due to incident solar radiation and heat loss from the building. The moisture content cycling causes expansion and contraction in the wood, creating stress in the paint film, resulting in failure.

Traditional walls had board sheathing and felt paper and could absorb inwardly driven moisture. When the board sheathing is replaced with OSB and a modern plastic housewrap the moisture remains more concentrated at the back side of the siding and trim at the housewrap/OSB interface. This increases the stress on the paint film as the moisture cycling increases in both frequency and amplitude – and the paint fails.

Insulation reduces heat loss and increases the dwell time for moisture at the overlaps of wood siding and at joints between trim and siding. The colder the siding, the higher the relative humidity at the surfaces. Wood moisture content is directly related to relative humidity. The higher the relative humidity the higher the moisture content.

The "classic" means of addressing this issue is to reduce the capillary absorption at the overlaps and joints by "back priming" or "back coating" the back surfaces of the siding. Over time coating of the back surfaces of siding was extended to the cut ends of siding and trim. Wood is anisotropic and it absorbs water differently based on the grain/fiber direction. Cut ends absorb more water than the face of siding and trim. Painting of cut ends became necessary to control decay of wood and wood-based claddings as it reduced water absorption.

Trim elements tended to be the "weak link" in cladding assemblies as they had the most joints-hence the most cut ends and exposed fibers. Where they butted into other elements or components or other trim pieces capillary absorption tended to be enhanced. Sealing or painting cut ends, back coating, and adding an air gap to act as a capillary break became necessary. The approach evolved into coating "all six surfaces" (**Figure 11.29**) coupled with air gaps between intersecting components such as decks and roofs.

Coating all six surfaces dramatically increased performance of coating systems as it reduced water absorption. But the approach did not address the reduced ability of the assemblies to redistribute moisture inwards. The old felt papers provided a reservoir to take inward-driven moisture as did plywood and board sheathings. As they were replaced with plastic building wraps, OSB, and foam plastic such as extruded polystyrene (XPS) and foil faced polyisocyanurates inward moisture redistribution was not possible. In hot humid climates this is significant due to the inward drive due to solar radiation. It is not possible to drive moisture out of the back side of cladding into a layer of plastic or aluminum foil. An air gap is necessary to uncouple the cladding and the trim from the rest of the wall assembly. The recommended gap for wood and engineered wood-based claddings and trim along with fiber cement cladding and trim components is ¼ inch to 3/8 inch.

It is common for wood trim and engineered wood claddings, fiber cement, and composites to come coated on all six sides or protected on all six sides. However, not all trim and claddings are installed over air gaps. As previously stressed the gap is necessary in high-performance assemblies.

Figure 11.30 illustrates providing an air gap with structural sheathing and continuous insulation less than 1.5 inches thick. The spacer strips are ¼ inch to 3/8 inch strips of foam or sill gasket material.

For thicker layers of continuous insulation furring strips of 1x4 wood and long wood screws are typically used. The screws should be epoxy coated steel. **Figure 11.31** illustrates the steps to install back vented trim and siding on a high-performance wall with multiple layers of continuous insulation.

The air gap should be open both at the bottom and top of the wall. The top of the wall can be vented into the soffit assembly. The bottom of the wall needs to be screened to control insect entry. Because the cladding and trim on one side of the air gap and the building wraps and sheathings on the other side of the air gap are significantly drier insects tend to stay away.

The most effective way to reduce "stress" on claddings and trim is to coat or protect all six sides and to back ventilate. This works for all cladding and trim materials: wood, engineered wood, fiber cement, and composites. Reduce water absorption and uncouple the materials with an air gap from the rest of the assembly. This works in all climates.

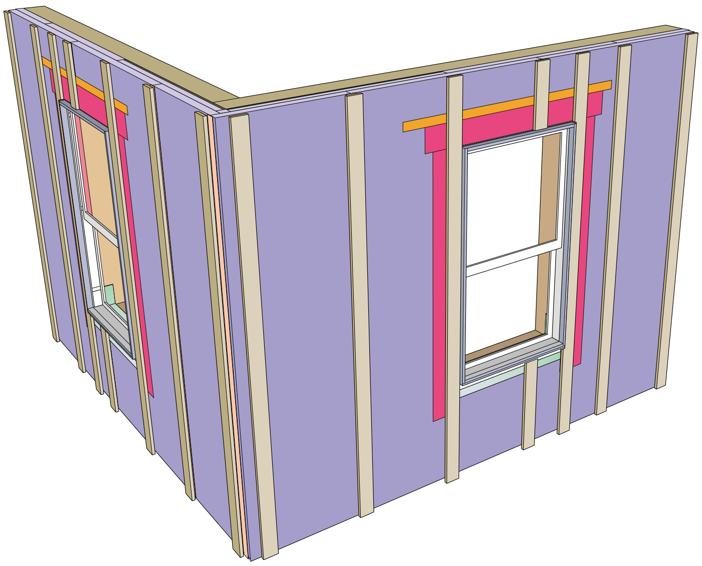

Figure 11.31b: Furring Strip Spacers – Note the corner geometry of the wood furring. The furring is gaped laterally at the corner.

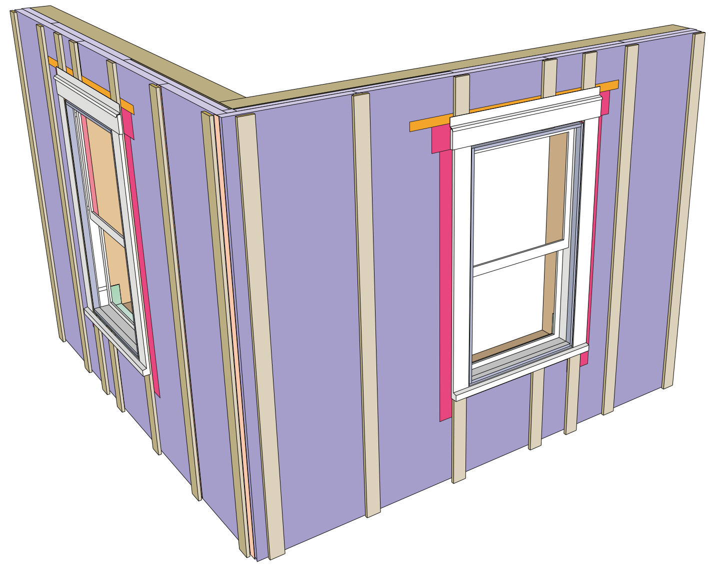

Figure 11.31c: Window Trim Installed – Note that the flashing above the horizontal trim at the top of the window is installed to protect the trim - not to protect the window unit.

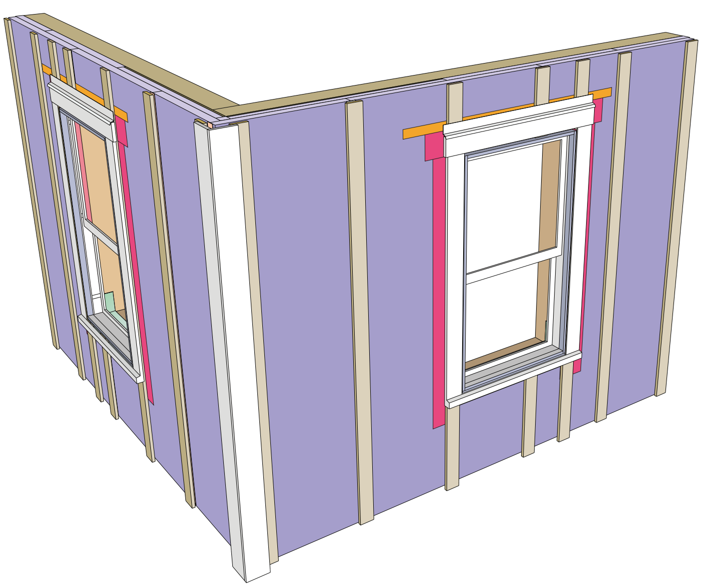

Figure 11.31d: Corner Trim Installed – The two corner trim pieces are attached "to themselves" and then the "L-shaped" trim assembly is attached to the gapped wood furring at the corner.

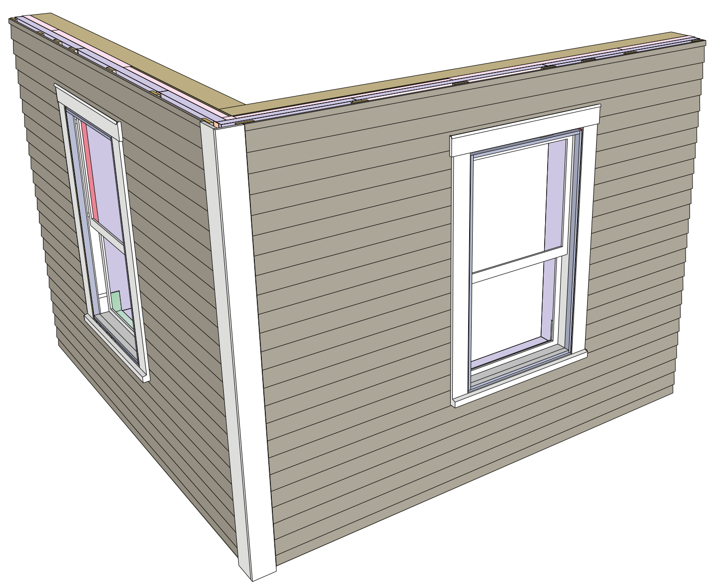

Figure 11.31e: Cladding Installed – Sealed on all six sides over an air gap.

Condensation on Attic Ductwork in Vented Attics and Elevated Interior Humidity in Hot Humid Climates

The function of venting attics in mixed climates and cold climates is primarily to control the accumulation of moisture. The venting of attics in these climates serves to remove moisture from the attic. In hot humid climates before the advent of air-conditioning venting attics served to provide a cooling benefit by promoting air circulation in the house below the attic. Air from the house would exit the top of the house enter the attic and be removed from the attic by thermal buoyancy and wind. Air leaving the house would be replaced with outside air through open windows.

With the introduction of air-conditioning and thermal insulation in the ceiling house ventilation was no longer practical. Some reduction of air-conditioning load occurred by venting attics with outside air when attic ceiling insulation levels were low. Once attic ceiling insulation levels were increased the venting of attics to reduce air conditioning loads became negligible.

In well-insulated attics the dominant mode of heat transfer is radiation, not convection and conduction. A well ventilated attic has almost no impact on radiant transfer of heat between the underside of the roof deck and the top of the insulation. As such, there is no energy benefit to vent an attic in a hot humid climate…but there is a large moisture penalty due to the moisture being brought into the attic by venting the attic.

Installing ductwork and air handlers in vented attics in hot humid climates typically results in sweating of the ductwork and air handlers. Air-`conditioners are machines that make air cold – and the cold air is then distributed by ductwork – making the ductwork cold. Cold air handlers and cold ducts in vented attics in hot humid climates sweat.

Ductwork and air handlers in vented attics in hot humid climates have always sweated. However, there is significantly more sweating now. Attic surfaces are colder due installing radiant barriers and building codes changed regarding the sizing of air-conditioners.

Radiant barriers made the attics colder particularly the ductwork and the air handler. Colder ductwork and colder air handlers increased sweating of ductwork and air handlers. Additionally, the run times of the air-conditioners, the duty cycles increased. The ductwork and air handlers stayed colder longer therefore more condensation occurred on ductwork and air handler surfaces.

With short duty cycles and not much sweating the condensate would have time to evaporate between run times. Repeated sweating followed by repeated drying was not much of an issue.

Radiant barriers are typical in south Texas but not so typical in south Florida. They are not much of a thermal benefit in south Florida given the preponderance of tile roofs. Tile roofs address solar radiation better than asphalt shingle roofs. The tile roof dominance of south Florida results in effective "cool roof" technology…there is not much of an improvement when a radiant barrier is added to a tile roof.

Historically oversizing of air conditioners was common. It did not matter much because the latent-to-sensible cooling ratio was small. The air-conditioners did not have to have long run times to control interior humidities. That changed when sensible loads were reduced due to windows with low SHGC ratings, compact fluorescent and LED lighting, higher levels of insulation, more efficient appliances, and radiant barriers.

Air-conditioners are dehumidifiers, but they only dehumidify when they are running. The approach to sizing and equipment selection is changing due to the reduction in sensible load. Single-speed single-stage air conditioning systems sized "correctly" are no longer able to control interior relative humidity.

Even with multi-speed multi-stage air-conditioners interior relative humidity cannot be controlled if too much ventilation air is introduced. Supplemental dehumidification becomes necessary.

The issues are no longer limited to attics. The radiant barriers and increased attic insulation makes interior closet ceilings colder resulting in mold. When the colder closets are coupled with higher levels of ventilation air supplemental dehumidification is necessary-or you have to provide closet ventilation or both.

Air handlers should not be located in vented attics – they should be located within conditioned spaces. Ductwork in attics should be insulated to a minimum of R-8.

Additionally, closet ventilation should be provided by installing a small return air duct in all closets located under vented attic ceilings.

The part load humidity issue should also be addressed. Multi-speed and multi-stage air-conditioning systems are recommended. It is likely that supplemental dehumidification will be necessary if mechanical ventilation is provided at a rate higher than the required ventilation rate specified in the model building codes.

Glossary

Absorption
Process whereby a porous material extracts one or more substances from an atmosphere, a mixture of gases, or a mixture of liquids.

Adhesion
Property that describes a material's ability to bond to a surface physio-chemically or chemically.

Adsorption
(1)Process in which fluid molecules are concentrated on a surface by chemical or physical forces or both; (2) surface adherence of a material in extracting one or more substances present in an atmosphere or mixture of gases and liquids, unaccompanied by physical or chemical change.

Air Control Layer (also referred to as Air Barrier Layer)
Air control layers control airflow between a conditioned space and an unconditioned space or between units in multi-family and apartment construction.

Air Control Layer System (also referred to as Air Barrier System)
The air control layer system is the primary air enclosure boundary that separates indoor (conditioned) air and outdoor (unconditioned) air. In multi-unit/townhouse/apartment construction the air barrier system also separates the conditioned air between a given unit its adjacent units, and common areas such as corridors and stair walls. Air control layer systems also typically define the location of the air pressure boundary of the building enclosure. In multi-unit/townhouse/apartment construction the air control layer system is also the fire barrier and smoke barrier in inter-unit separations. In such assemblies the air control layer system must also meet the specific fire resistance rating requirement for the given separation.

Air control layer systems typically are assembled from materials (such as gypsum board, sealant, etc.) incorporated in assemblies (such as walls, roofs, etc.) that are interconnected to create enclosures. Each of these three elements has measurable resistance to airflow. The maximum air permeances for the three components are listed as follows:

- Material 0.02 l/(s·m2)@75 Pa
- Assembly 0.20 l/(s·m2)@75 Pa
- Enclosure 2.00l/(s·m2)@75 Pa

Materials and assemblies that meet these performance requirements are said to be air control layer materials and air control layer assemblies. Air control layer materials incorporated in air control layer assemblies that in turn are interconnected to create enclosures are called air control layer systems. Note sometimes assemblies can meet the assembly requirements without using materials that meet the material requirement. And sometimes enclosures can meet the enclosure requirements without meeting either the material or assembly requirements. Materials are tested according to ASTM E 2178 or E 283. Assemblies are tested according to ASTM E 2357. Enclosures are tested according to ASTM E 779 or CAN/CGSB – 149.

Air-Impermeable Material
An air impermeable material is an air control layer material (also referred to as an air barrier). An air-impermeable material has an air permeance equal to of less than 0.02 l/s-m2 at 75 Pa pressure differential when tested according to ASTM E 2178 or E 283.

Air Leakage
Uncontrolled and/or unintended airflow through a building enclosure or between units of occupancy. Leakage from indoors to outdoors is often referred to as exfiltration and leakage from outdoors to indoors as infiltration.

Air-Permeable Material
An air-permeable material has an air permeance greater than 0.02 $l/s \cdot m^2$ at 75 Pa pressure differential when tested according to ASTM E 2178 or E 283.

Building Envelope/ Building Enclosure
The system or assembly of components that provides environmental separation between the conditioned space and the exterior environment. Note: the envelope/enclosure is a special type of environmental separator. Environmental separators also exist within buildings as dividers between spaces with different environmental conditions.

Condensation
The change of state from vapor to liquid.

Conditioned Space
The part of the building that is designed to be thermally conditioned for the comfort of occupants or for other occupancies or for other reasons.

Corrosion
The deterioration of metal by chemical or electrochemical reaction resulting from exposure to weathering, moisture, chemicals or other agents or media.

Dehumidification
Removal of water vapor from air.

Diffusion
The movement of individual molecules through a material.

Dry
(1)To develop the ultimate properties of a wet state material solely by evaporation of volatile ingredients. (2)Free from significant moisture; not wet.

Efflorescence
The depositing of water-soluble salts left on the visible surface of masonry or concrete as the water evaporates.

Hygroscopic
Materials that interact with water vapor by adsorbing water vapor as a function of the relative humidity of the adjacent air.

Indoor Air
Air in a conditioned space.

Mass/Storage Assemblies
A rainwater control strategy that typically stores and redistributes penetrating rainwater in water resistant building materials until it can be released to the either the exterior or interior in the vapor form in a controlled manner that does not damage interior or exterior finishes. Mass/storage assemblies are often used with water resistant materials such as masonry, concrete, multi-wythe brick and stone.

Mechanical Ventilation
Controlled, purposeful introduction of outdoor air to the conditioned space.

Mold
A type of fungus that is different from plants, animals and bacteria. Molds are decomposers of dead organic material such as leaves, wood and plants. Molds sometimes can infect living plants and animals. The spores and hair-like bodies of individual mold colonies are too small to see without a microscope. When a lot of mold is growing on a surface, it often appears black or green. The color of mold is influenced by the nutrient source and the age of the colony. Mold growing on fabric is called mildew.

Outdoor Air
Air outside the building.

Perfect Barrier Assemblies
A rainwater and groundwater control strategy that typically relies on the exterior cladding or exterior surface to act as the water control layer. Perfect barrier assemblies are not commonly used in residential construction above grade except in roofing. Above grade "perfect barriers" can be constructed from materials that are defined as waterproof such as glass, steel, dense concrete or roof membranes. Below grade "perfect barriers" can be constructed from sheet waterproofing. Examples of perfect barrier assemblies are precast panel walls, glass curtain walls, insulated metal panel system, roof membranes and foundation waterproofing membranes.

Pressure Boundary
The primary air enclosure boundary separating conditioned air and unconditioned air. Typically defined by the air control layer system (also referred to as the air barrier system).

Screen Assemblies
A rainwater control strategy that accepts some water will penetrate the exterior cladding. Screen assemblies have multiple lines of defense for rainwater entry. In addition to the exterior cladding, screen assemblies layer building materials shingle fashion inward of the exterior cladding to direct rainwater that penetrates the cladding back to the exterior. The inward layer is called the water control layer. A space or air gap between the water control layer and other materials promotes drainage, ventilation and moisture redistribution.

Thermal Control Layer (also referred to as the Thermal Barrier)
The component (or components) that is (or are) designed and installed in an assembly to control the transfer of thermal energy (heat). Typically these are comprised of insulation products, radiant barriers, or trapped gaps filled with air or other gases. One quantitative measure of a thermal control layer's resistance to heat flow is the R-value. R-values are limited in that they only deal with conduction, one of three modes of heat flow (the other two being convection and radiation) and that their range of applicability is typically limited to materials not assemblies.

Vapor Barrier
A Class I vapor control layer.

Vapor Control Layer
The component (or components) that is (or are) designed and installed in an assembly to control the movement of water by vapor diffusion.

Vapor Control Layer Class
The measure of a material or assembly's ability to limit the amount of water that passes through the material or assembly by vapor diffusion. The test procedure for determining vapor barrier class is ASTM E-96 Test Method A (the desiccant or dry cup method).

Class I Vapor Control Layer: Materials that have a permeance of 0.1 perm or less.

Class II Vapor Control Layer:	Materials that have a permeance of 1.0 perm or less and greater than 0.1 perm
Class III Vapor Control Layer:	Materials that have a permeance of 10 perms or less and greater than 1.0 perm

Vapor Permeable
A material with vapor permeance greater than 10.0 perms

Water Control Layer
A sheet, spray or trowel-applied membrane or material layer that controls the passage of liquid water. Water control layers are interconnected with flashings, window and door openings, windows and doors, and other penetrations of the building enclosure.

Weep Hole
An opening in a wall or window assembly to permit the escape of liquid water from within the assembly. Weep holes can also act as vents to allow air to pass through the cladding.

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About the Author

JOSEPH LSTIBUREK, B.A.Sc., M.Eng., Ph.D., P.Eng., is the founding principal of Building Science Corporation and an ASHRAE Fellow. He is a building scientist who investigates building failures. Dr. Lstiburek received an undergraduate degree in Mechanical Engineering from the University of Toronto, a masters degree in Civil Engineering from the University of Toronto and a doctorate in Building Science Engineering from the University of Toronto. He has been a licensed Professional Engineer since 1982.

The Wall Street Journal referred to him as "the dean of North American building science." Fast Company magazine called him "the Sherlock Holmes of construction". He is internationally recognized and his work has influenced building codes and standards in every climate zone.

He is a recipient of the Carl Cash Award from ASTM, a "Becky" from the Ontario Building Envelope Committee (OBEC) and the EEBA Legacy Award all for lifetime contributions to building science. He has also been inducted into the Building Performance Industry Hall of Fame and has received the NESEA Professional Leadership Award for "changing the way we think about building science and how we perform our work".

Dr. Lstiburek is an acclaimed educator who has taught thousands of professionals over the past four decades and has written countless papers. He has a joy for telling tall tales to his proteges and audiences.