Photo 1 (left): Icky crawlspace. Note the condensation on the underside of the fiberglass batt insulation and the rot at the exposed portions of the crawlspace floor joists. Photo 2 (right): Ventilation opening. Crawlspace has plenty of cross ventilation and good drainage.

New Light in Crawlspaces

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

Crawlspaces stink, they rot, and are just plain icky. *Photo 1* shows the modern crawlspace, which is a forest of water droplets on the underside of fiberglass batt insulation. The exposed wood floor joists are rotting. This vented crawlspace has a continuous plastic sheet ground cover and excellent drainage (*Photo 2*). Everything in this crawlspace was done "correctly." It has code-specified ventilation, a continuous impermeable ground cover, excellent drainage, but still we have a mess. What caused this mess? The floor insulation.

Think of the good old days, before WWII, crawlspaces were uninsulated. They were ventilated, they didn't have ground covers, and they didn't have problems. Why? The floor framing was usually always warmer than the ground (*Figure 1*), even in air-conditioned buildings. This was a big deal as the temperature of the floor framing was above the dew-point temperature of the exterior air used for ventilation. The old floor finishes tended breathe. They were relatively vapor open. No one had heard of vinyl flooring yet.

The ground in crawlspaces is cold,* much colder than the outside air during the summer.

In an irony not appreciated except by building science geeks, ventilation air in the summer in most parts of North America brings moisture into crawlspaces and deposits this moisture on surfaces below the ventilation air dew point. In the good old days, this was the ground or the ground cover, which is at the same temperature as the ground. It was not the floor framing. And, who cared if the ground or the ground cover was wet as long as the wood framing was not. Hardly any ventilation air change occurs in crawlspaces. The typical ventilation air change rate in a crawlspace is approximately 1 air change per hour (ach).† In determining crawlspace surface temperatures we can pretty much ignore the ventilation air change.‡ We can't ignore the ventilation air in the moisture balance but we can in the energy balance. Crawlspace surface temperatures are dominated by radiation and conduction, not by convection (*Figure 2*). And, as pointed out, old crawlspace floor framing was not only warmer than the ground but also warmer than the ventilation air dew point.

That all changes when we install insulation in crawlspace floor framing. The most common insulation installed in this location are fiberglass batts. When fiberglass batts are installed between floor joists the exposed bottom edges of the floor joists become much colder (*Figure 3*). The surface temperature of the underside of the fiberglass batt insulation is also much colder than the floor sheathing, within one or two degrees of the ground temperature. The energy picture within the crawlspace is radiation dominated. The floor assembly surfaces are, in essence, radiation coupled to the ground. The exposed surface of the fiberglass batt insulation is below the dew-point temperature of the air in the crawlspace as is the exposed portion of the wood floor joists. Condensation forms on both the surface of the insulation and the surface of the exposed wood (*Photo 1*).

Now, let's look at the wood floor joist moisture content. Wood is hygroscopic. It "sees" relative humidity, not vapor pressure. We need a psychrometric chart and a sorption curve for wood (see *Page 70*). The temperature of the wood floor joist is 75°F

*A reasonable rule-of-thumb to estimate crawlspace ground surface temperatures is to use the average annual ambient air temperature for that location.

†This comes from using radon gas as a "tracer gas"—thank you EPA. Your radon studies provided useful information, at least in this regard.

‡This is another one of those engineering approximations that drives energy weenies crazy.

Advertisement formerly in this space.

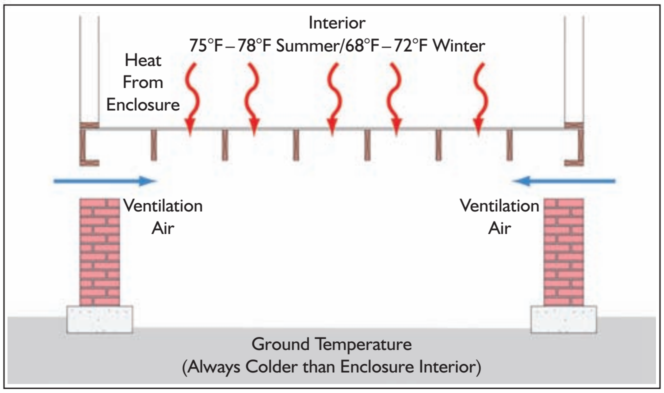


Figure 1: Old crawlspaces. Old uninsulated and ventilated crawlspaces had warm floor assembly surfaces due to heat flow downward from occupied space above.

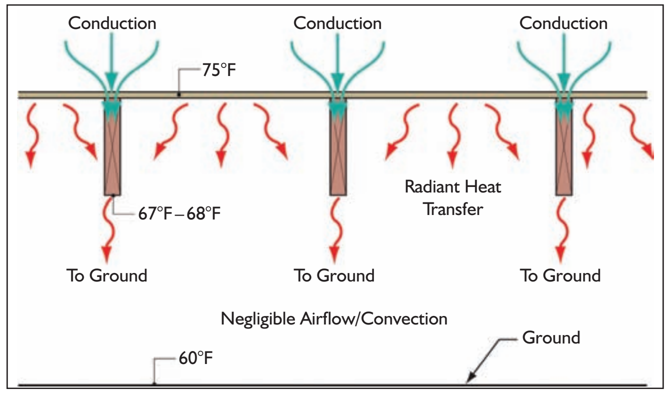


Figure 2: Old crawlspace temperatures. Surface temperatures are dominated by radiation and conduction, not by convection. Old crawlspace floor framing was not only warmer than the ground but also warmer than the ventilation air dew point.

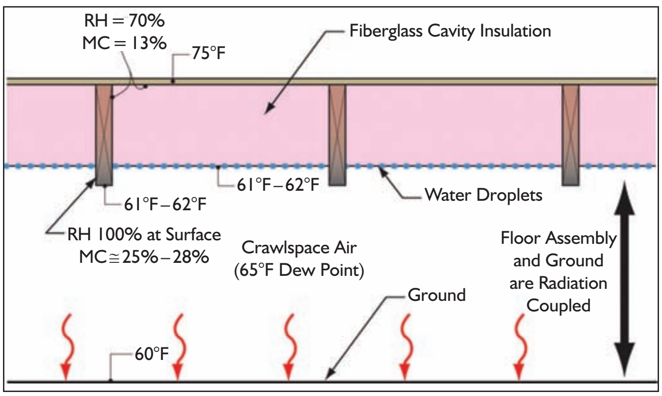


Figure 3: Insulated crawlspace temperatures. The surface temperature of the underside of the fiberglass batt insulation is colder than the floor sheathing—within one or two degrees of the ground temperature. The exposed surface of the fiberglass batt insulation is below the dew-point temperature of the air in the crawlspace as is the exposed portion of the wood floor joists. Condensation forms on the surface of the insulation and the surface of the exposed wood.

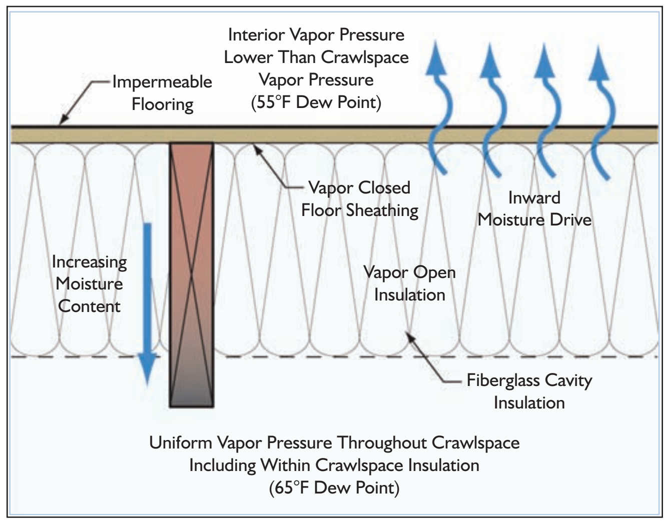


Figure 4: Moisture dynamics. The wood moisture content increases as we move down the floor joist. At the same time, the vapor drive is upward. The entire shaded area "sees" the same vapor pressure (dew point) due to the vapor openness of the fiberglass insulation. The entire vapor resistance is at the floor sheathing and flooring. If only the floor could breathe as it did in the old days when we had wood floors and not vinyl.

(24°C) at the top (i.e., interior temperature). We need to figure out the crawlspace conditions. The air in the crawlspace comes from the outside, who knew? Let's pretend this particular crawlspace is in Washington, D.C. The average dew point of the exterior air during the summer in Washington, D.C., is 65°F (18°C). Let's bring this air into the crawlspace. Therefore, the dew point of the air in the crawlspace is 65°F (18°C). Remember that the top of the floor joist is 75°F (24°C). The floor joist sees the dew point of the air in the crawlspace (we can ignore the vapor permeance characteristics of the fiberglass batt insulation since it is so vapor open. Simply pretend we have air, rather than insulation here. However, not just any air, air with a huge temperature drop—"insulating air"), but because the floor joist is 75°F (24°C) at this location, the relative humidity is 70%, yielding a wood equilibrium moisture content of 13%. The floor joist is "dry" at the top and "wet" at the bottom. Why wet at the bottom? The surface of the wood is cold, below the dew point of the air in the crawlspace. Therefore, condensation forms on the wood. At fiber saturation, the moisture content of wood is 28% (*Figure 3*).

The wood floor joist moisture content increases downward as the wood becomes progressively colder (*Figure 4*). Another way of saying this is the warmer the wood, the drier the wood. If we were to wrap the floor joists completely with insulation, we would warm the wood, lowering the relative humidity the wood "sees," which lowers the moisture content. This is a neat strategy that I will refer to later. How low do we need to lower the moisture content of the wood? Below 19% to never see rot or below 16% to never see mold. We could do this a couple of ways. One way is to use spray foam insulation (*Figure 5*).

Before we go there, we need to check out something else. Although the wood moisture content increases as we go

Advertisement formerly in this space.

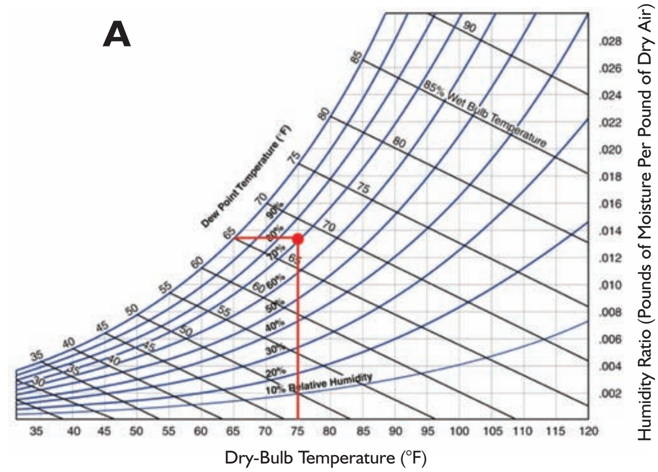
Psychrometric Chart & Wood Sorption Curve

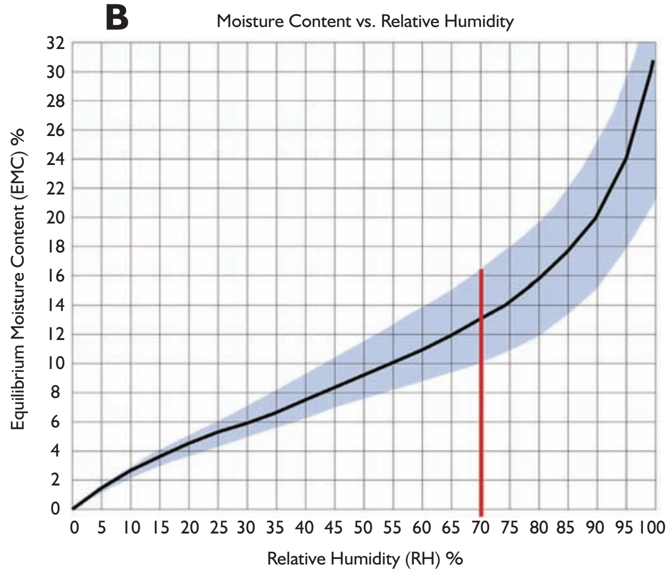
We know the dew-point temperature of the air in the crawlspace is 65°F (18°C). We also know the temperature at the top of the floor joist is 75°F (24°C). We need to get the relative humidity at the surface of the wood at this location, so that we can use the wood sorption curve to determine moisture content. The psychrometric chart's magic gives us the relative humidity.

First, we make the simple engineering assumption that we can ignore the vapor permeance (or vapor resistance) of the fiberglass batt insulation. That leads to the second assumption that the vapor pressure in the crawlspace is uniform. Both are reasonable assumptions within the range of accuracy we are dealing with (within 10% to 20% and obtained within seconds, rather than hours using mind numbing numerical simulations based on questionable boundary conditions that are not much more accurate than 10% to 20%).

With the constant vapor pressure assumption, we can trace a horizontal line from the 65°F (18°C) dew-point state-point on the saturation curve to where it crosses the vertical 75°F (24°C) dry-bulb temperature line. Presto! We get the relative humidity at the surface of the wood, which is 70% (*Figure A*).

We take this wonderful piece of information to the wood sorption curve and get a moisture content of 13% (*Figure B*). However, look at the error bar (the shading on the curve). Neat, eh! Wood is somewhat unpredictable—a characteristic I identify with—so although I say in the neighboring column that the wood moisture content is 13%, it could be anywhere between 10% and 16%. Or, 13% ± 3%. Keep those computer simulations and give me a psych chart, a sorption curve, and a beer, and I will beat you to the answer every time. Of course, the 30 years of being beat up by the old masters also helps (thank you Dr. Onysko, Prof. Timusk, Mr. Gatley, and Mr. Handegord).





downward, the vapor drive is upward. Huh? This wood stuff is weird. I just explained wood moisture content. It's time to look at vapor diffusion.

The interior is dry (dew point of 55°F [13°C]), and the crawlspace is wet (dew point of 65°F [18°C]). The moisture flow by vapor diffusion is from the crawlspace up through the floor into the building, at least during summer. The vapor drive is upward, even though the wood in the floor joist becomes wetter as we go downward. The inward drive is "felt" completely at the floor sheathing and floor finish. We can ignore the vapor open fiberglass batt cavity insulation. No vapor resistance here. We can't ignore the vapor resistance of the floor sheathing and the floor finish.

If we were do something foolish like install vinyl flooring (0.1 to 0.5 perms) over OSB floor sheathing (1.0 perms) in an assembly such as that described in *Figure 4*, we would get a result that looks like *Photo 3*. Notice the pink spots on the vinyl flooring. It reminds you of the pink spots on vinyl wall-covering.§ Come to think of it, haven't we just constructed a wall with vinyl wall-covering and laid it down? Same principle, same problem. The floor does not "breathe." We have a vapor barrier on the wrong side of the assembly.

We can fix this problem by having a vapor permeable floor assembly. Plywood sheathing (it is way more permeable than OSB) and carpet do the trick. Works, but it is kind of limiting. Oh, yeah, you also can't put furniture on the floor if the furniture is impermeable, so you have to hold it up to ventilate under it (same for cabinetry). You have to ventilate it as well. But, what if I don't

§The pink color comes from digestive enzymes exuded from mold that react with the plasticizers in the vinyl. The mold comes from the substrate being wet because of the impermeability of the vinyl. No vinyl no problem.

Advertisement formerly in this space.

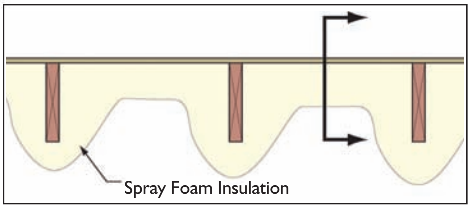
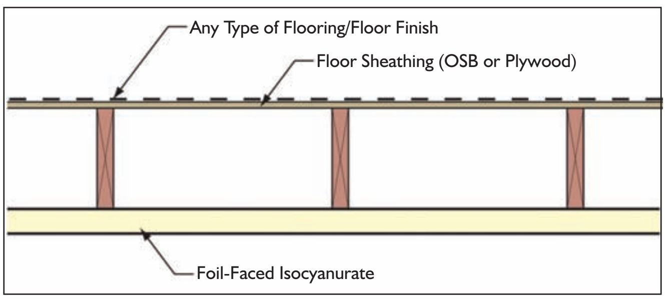


Figure 5:* Warming the wood. *Wrapping the floor framing in foam insulation lowers the equilibrium moisture content of the wood. Warm wood is dry wood. Warm wood is happy wood. One not so minor issue is that changing the temperature only gets you so far. The vapor drive upwards still needs to be addressed. The section line is the location of the cross-sections in* Figure 8*, which addresses the not so minor vapor drive issue.

Photo 3:* Vinyl flooring. *Pink spots are due to moisture problems arising from the impermeability of the vinyl flooring and ventilated and insulated crawlspace underneath.

Photo 4:* Conditioned crawlspace. *This is the way all crawlspaces should look—dry, warm, part of the house, not part of the outside or part of the ground. Insulated on the perimeter, not in the floor. Beautiful.



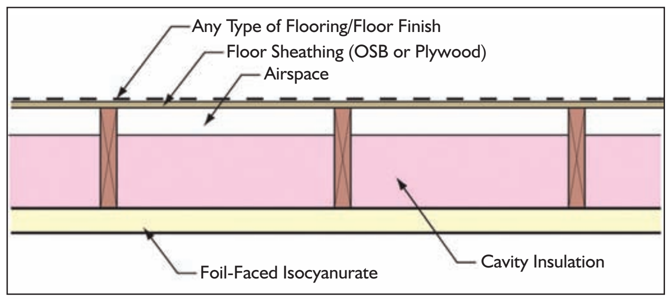


Figure 6 (left):* Vapor barrier. *Installing impermeable rigid insulation keeps the wood framing warm and provides a low perm layer that addresses the upward vapor drive. How impermeable? It's less than 0.1 perms. Foil-faced rigid insulations are the ticket here. This approach allows any type of flooring to be used above. Even better is exposing the shiny side of the foil facing (face it down into the crawlspace) which almost eliminates radiative coupling and means that the surface of the insulation approaches the temperature of the ventilation air, reducing condensation.* Figure 7 (right): Cavity insulation with vapor barrier. *Adding impermeable foil-faced insulating sheathing over fiberglass cavity insulation is a hybrid approach that uses the best qualities of both materials. Note that the optimum location for the airspace is above the cavity insulation. Are you folks at the EPA ENERGY STAR® program paying attention? This makes for warmer floors. This is the same detail that should be used under bedrooms over garages.

want plywood, carpet and ventilated furniture and cabinetry?

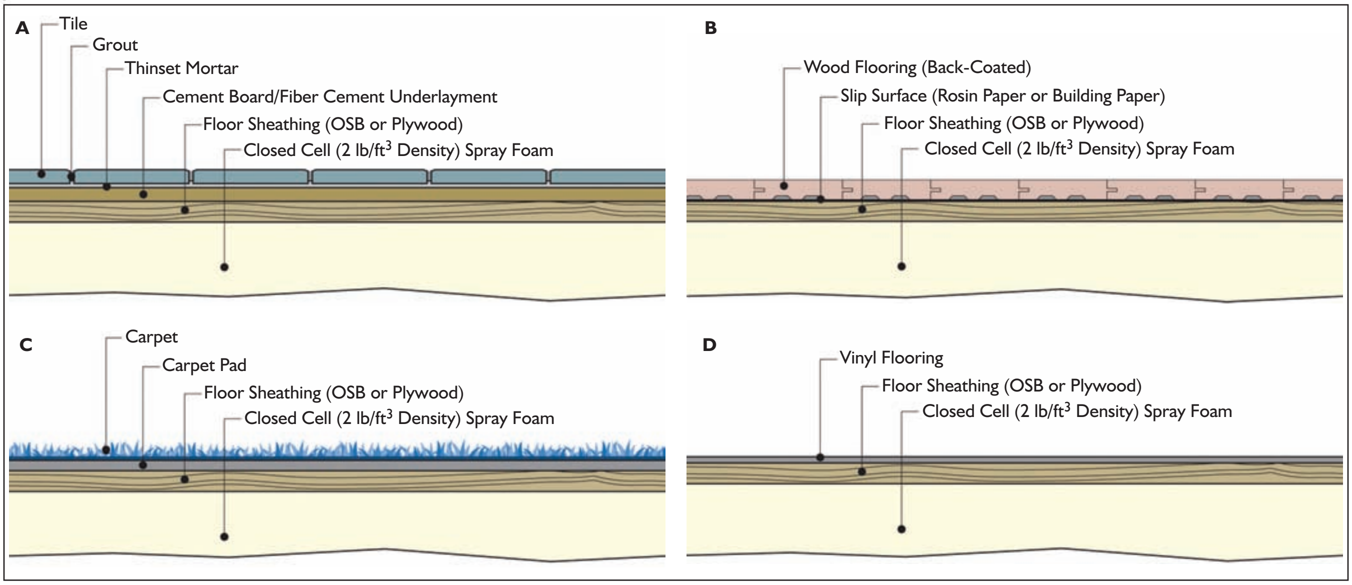
The easy answer is to construct a conditioned crawlspace (*Photo 4*). Construct it as a mini-basement. Then, you can have any floor finish and save energy and money. But, I know you folks. You are stubborn and insist on the vented crawlspace. Hey, maybe you need to use one because you are in a flood zone. It could be you actually have a legitimate reason to construct a vented crawlspace. So, how should the floor assembly look?

Check out *Figures 6* and *7*. Both show foil-faced rigid insulation under the floor framing. The wood is warm and, therefore, dry. The foil facing on the rigid insulation handles the vapor drive. The foil facing is an exceptional vapor barrier (< 0.1 perm). Beautiful. It gets better. If you expose the shiny side (face it down into the crawlspace) of the foil facing, it almost eliminates radiative coupling and means that the surface of the insulation approaches the temperature of the ventilation air, reducing condensation. Why don't we see lots of this? Well, I forgot to mention that the rigid insulation needs to be airtight. That requires tiny people with good workmanship to seal the seams with foil tape that must stick in miserable environmental conditions forever. Having said that, a poor job using the approaches described in *Figures 6* and *7* is better than what we typically get with *Photo 1* and *Figure 3*.

All of this leads us back to *Figure 5* and spray foam. Lots of folks are looking at this option due to the lack of tiny people with good workmanship.[‖] The spray foam clearly handles warming the wood. Any foam will work for the wood warming: low density, high density, whatever. Remember that just warming the wood lowers its equilibrium moisture content. Where it becomes difficult is with the vapor drive across the floor sheathing and the floor finish. Unless you stick to carpet, and ventilated furniture and ventilated cabinetry you must use high-density foam (at least 2 lb/ft^3 [32 kg/m^3]) due to its lower perm value. The foam needs to be at least 3 in. (76 mm) thick or thicker (gives you less than 1 perm at this thickness). *Figure 8* shows a few configurations that pretty much work everywhere. One limitation, *Figure 8d*, with vinyl flooring, probably does not work in mixed humid and hot humid climates. I included it because it

[‖]They all have gone on to fame and fortune in reality TV cable shows.

Advertisement formerly in this space.



***Figures 8a–d:** Spray foam configurations. Use closed cell 2 1b/ft^3 density spray foam. Avoid vinyl flooring except in dry and cold climates.*

does seem to work in dry places and in cold places. I think you should just say no to vinyl, which makes things much easier. If you really like vinyl, go with *Figures 6* or *7* or, even better, *Photo 4* (the conditioned crawlspace or minibasement).

At the end of the day, remember that the best crawlspace of all is filled with concrete and called a slab or dug out and called a basement.

Joseph W. Lstiburek, Ph.D., P.Eng., is a principal of Building Science Corporation, in Somerville, Mass. Visit www.buildingscience.com.

Advertisement formerly in this space.