ASHRAE 90.1 and Cold-Weather Condensation

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Abstract

To comply with the energy code, designers often utilize the Prescriptive Building Envelope Option described in ASHRAE 90.1 when determining the minimum amount of insulation required within a wall assembly. In cold climates, the minimum R-value requirement for framed wall assemblies allows designers to utilize a split-insulation arrangement to meet code requirements. However, these designs often carry an elevated risk of condensation that is not explained in the text of the standard and may lead a designer to unknowingly promote detrimental insulation combinations with regard to convective condensation.

A design tool has been developed based on psychometrics and ASHRAE 90.1 requirements that illustrates the ratio of continuous insulation to total insulation. The design tool currently assumes a high leakage rate; therefore, values along the pass-fail line may be overly conservative. In order to incorporate a more realistic air leakage rate and develop a more defined pass-fail criteria, our research uses software tools such as WUFI® to study the requirements offered by 90.1 to evaluate the hygrothermal performance of insulation combinations for framed wall assemblies based on the simplified exfiltration model. Hygrothermal engineering principles and the results will be presented with future publication of the design tool for the design industry.

Speakers

Dave Finley

DAVE FINLEY is involved in a wide range of structural and architectural investigations with Wiss, Janney, Elstner Associates, Inc. (WJE). His building enclosure experience includes water infiltration testing of windows, curtainwalls, masonry façades, and plaza and below-grade waterproofing, as well as condensation and air leakage testing of glazed fenestrations and masonry façades. Finley is well versed in performing hygrothermal analyses using steady and transient state techniques. Additionally, he is capable of analyzing window and wall systems for two-dimensional thermal conduction.

Manfred Kehrer

MANFRED KEHRER has been involved in researching, testing, and analysis of exterior enclosure and concrete systems. He has helped develop WJE's hygrothermal laboratory and computational fluid dynamics initiative for analysis of building enclosures. Prior to joining WJE, he worked for more than 20 years at Fraunhofer IBP, Germany, in the area of hygrothermics. Kehrer was a senior building scientist at the Oak Ridge National Laboratory (ORNL), where he was in charge of a variety of types of research in building science. Since 2011, Kehrer has been the Official WUFI® Collaboration Partner for USA/Canada.

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INTRODUCTION

To maximize the efficacy and performance of building enclosure walls, the four major building enclosure control layers (i.e., liquid water, air, water vapor, and thermal) should be designed and installed with continuity. The position of these control layers within a wall assembly can also significantly affect the hygrothermal performance (i.e., movement of heat and moisture) of an exterior wall. For buildings located in Climate Zones 4 and higher (*Figure 1*), insulation, which is the primary thermal control layer, should be ideally located outboard of the other control layers. However, to comply with energy code requirements, designers often utilize the Prescriptive Building Enclosure Option described in ASHRAE 90.1-2013 or the minimum R-values required by the 2015 International Energy Conservation Code (IECC) to determine the minimum amount and location of thermal insulation required in an opaque wall assembly.

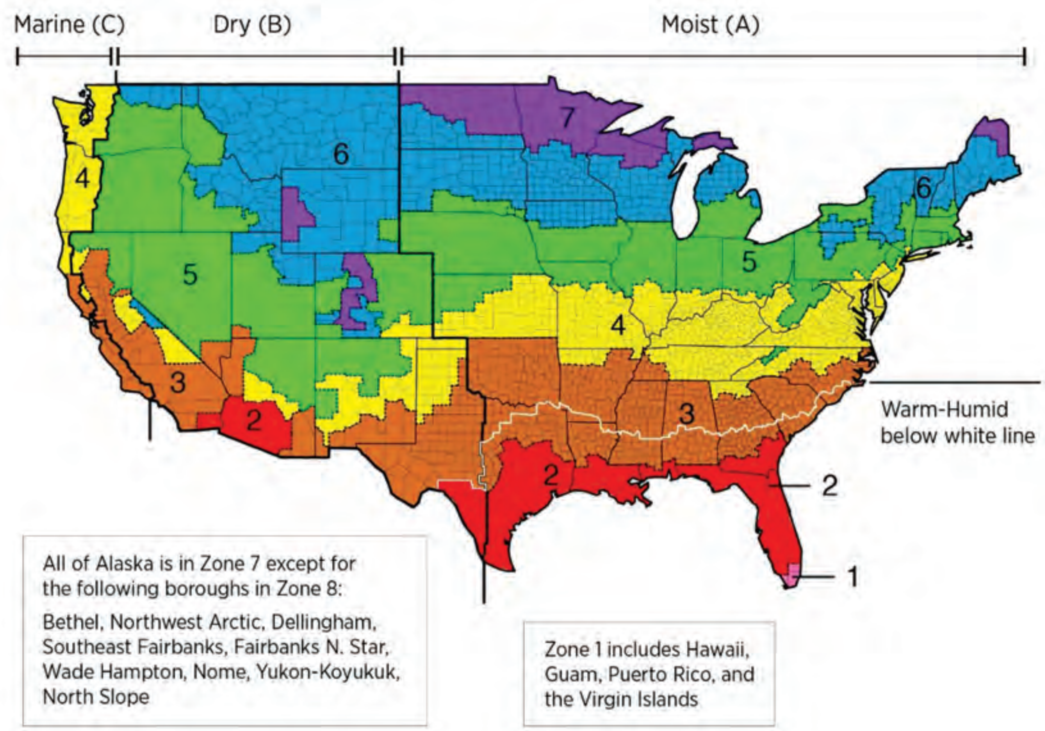

Figure 1 – Climate Zone map from International Energy Conservation Code.

The minimum R-value requirement in these zones for both steel-framed and wood-framed opaque wall assemblies allows designers to utilize a split-insulation arrangement to meet the minimum thermal requirement (*Table 1*). Split insulation designs utilize a certain amount of thermal resistance via continuous insulation outboard of the sheathing, where the air and water control layers are typically located, in addition to within the stud cavity inboard of the sheathing. The relative amount of continuous insulation outboard of the sheathing is expressed as an insulation ratio (*Equation 1*).

In certain circumstances, split insulation designs can be at risk of elevated relative humidity (RH) within the stud space or even at the first condensing surface—usually the interior side of the exterior sheathing. This risk is not explained in the text of the standard or the energy code and may lead a designer to unknowingly utilize split insulation assemblies without understanding their influence on the hygrothermal performance of the wall assembly. To compound the issues of split insulation assemblies, the introduction and placement of a vapor retarder within the wall system as mandated by code in some climate zones and local jurisdictions can result in trapped moisture and increased potential for condensation or microbial growth.

Careful analysis of the movement of heat and moisture through a wall assembly must be made when a portion of the thermal control is located inboard of the air, water, and water vapor control layers. The research project summarized in this document strives to use a hygrothermal software tool, such as WUFI®, to study the hygrothermal performance of the minimum R-value and distribution of wall insulation outlined in ASHRAE 90.1 and the IECC. Specifically, the moisture accumulation risk was evaluated for split-insulation wall assemblies for steel-stud-framed walls, as well as the remaining enclosure control layers, which are not fully prescribed by ASHRAE, but may be codified in the International Building Code (IBC) and by local municipalities.

Climate Zones	
1-2	3-8
R-5ci + R-13	R-7.5ci + R-13

Table 1 – 2015 IECC minimum R-values for metal stud framing.

EFFECTS OF INSULATION

The introduction of insulation in any exterior wall system reduces the heat flow through the wall assembly; as such, the

$$IR = \frac{R_{ci}}{R_{ci} + R_{batt}}$$

Equation 1 – The insulation ratio (IR) is equal to the continuous insulation, R_{ci}, divided by the sum of the continuous insulation and discontinuous cavity (often batt) insulation, R_{batt}.

$$P_{ws} = 1000e^{\left(52.58 - \frac{6790.5}{T} - 5.028 \ln T\right)}$$

Equation 2 – P_{ws} is the saturation vapor pressure, and T is temperature in Kelvin. Note that the saturation pressure will drop exponentially relative to temperature.

$$RH = \frac{P_w}{P_{ws}}$$

Equation 3 – P_w is the vapor pressure, and P_{ws} is the saturation vapor pressure.

surface temperatures of materials outboard of the insulation are reduced in cold weather. In addition to this temperature drop caused by the insulation, a subsequent and greater reduction in the saturation vapor pressure occurs, as shown in *Equation 2*, and can cause the development of condensation.

Saturation vapor pressure is the maximum pressure of water vapor, or absolute humidity that can exist within the air. RH is the ratio of actual water vapor in the air to the maximum amount of water vapor at saturation (*Equation 3*). Therefore, the RH of saturated air (i.e., actual vapor pressure equal to the saturation vapor pressure) is 100 percent.

Because of the relationship between the significant drop in saturation vapor pressure associated with thermal gradients via insulation, increased RH, as well as the inherent reduction in surface temperatures outboard of the insulation layer, are expected. As such, it is important and ideal to place the thermal control entirely outboard of the other building enclosure control layers in cold climates. However, when the thermal control layer is split and sandwiches some of the other control layers, it is imperative to control or reduce the vapor and air transport into and through the inboard insulation layer to avoid condensation development or increased surface RH that can promote microbial growth.

Condensation can occur on surfaces when the surface temperature drops below the dew point temperature of the ambient air, which occurs when the vapor pressure reaches the saturation vapor pressure, or an RH of 100 percent (*Equation 4*).

For interstitial spaces, such as within a wall system, the necessary moisture (vapor) for condensation or elevated surface RH typically comes from two sources: vapor diffusion and air leakage. Both of these mechanisms should be considered when evaluating the anticipated hygrothermal performance of a proposed exterior wall assembly.

DIFFUSIVE CONDENSATION

Diffusive condensation occurs when moisture migrates from air with a higher vapor pressure to air with a lower vapor pressure. Diffusion is a much slower method of transferring moisture than airflow. As a result, it is typically a less significant contributor to moisture migration associated with condensation problems than is airflow. However, the placement of vapor retarders within an exterior wall assembly with respect to the location of the insulation nonetheless warrants careful consideration.

As previously discussed, insulation causes a significant change in the thermal gradient and a corresponding drop in saturation vapor pressure. If the predicted vapor pressure at any point across the moisture-sensitive portion of the wall assembly exceeds the saturation vapor pressure, condensation would be predicted to occur to satisfy equilibrium (*Figure 2a*). It should be noted that the rate of condensation development is typically extremely low. For example, the rate of condensate deposition in *Figure 2a* is about a 0.32 ounces per square foot per day, assuming that the interior and exterior temperatures and RH remain constant.

As such, vapor retarders (in cases where needed), should be generally placed on the warm side of all insulation, inboard of the inherent drop in saturation vapor pressure, to locally reduce vapor pressure (*Figure 2b*). When the insulation is not the outermost control layer, the vapor retarder is typically placed inboard of the insulation to alleviate potential wintertime diffusive condensation. The IBC requires a Class I (e.g., polyethylene or foil sheet) or II (e.g., kraft paper) vapor retarder for Climate Zones 5 through 8 and Marine 4.

The use of vapor retarders with absorptive reservoir claddings (e.g., brick masonry, concrete, and stucco) in certain climates can result in summertime diffusive condensation on the outboard face of the vapor retarder, as it is then located on the cold side of the insulation (*Figure 3*). The typical deposition rate of condensate during summertime conditions is even lower than the typical rate expected during winter conditions.

In addition to ambient-temperature-induced diffusion, solar radiation can play a role in increasing the rate of moisture transfer through diffusion. After a significant rainfall that wets masonry or other absorptive cladding, solar radiation will heat the cladding material, promoting drying through evaporation. As this water evaporates from the cladding into the air space or inboard materials, it greatly increases the moisture content of the air or adjacent material. The higher the vapor pressure

$$T_{dp} = \frac{B\left[\ln\frac{RH}{100}\right] + \frac{A \cdot T_i}{B + T_i}}{A - \ln\frac{RH}{100} - \frac{A \cdot T_i}{B + T_i}}$$

Equation 4 – T_{dp} is the dew point temperature in Celsius, T_i is the interior temperature in Celsius, and constants A and B are 17.62 and 243.12, respectively.

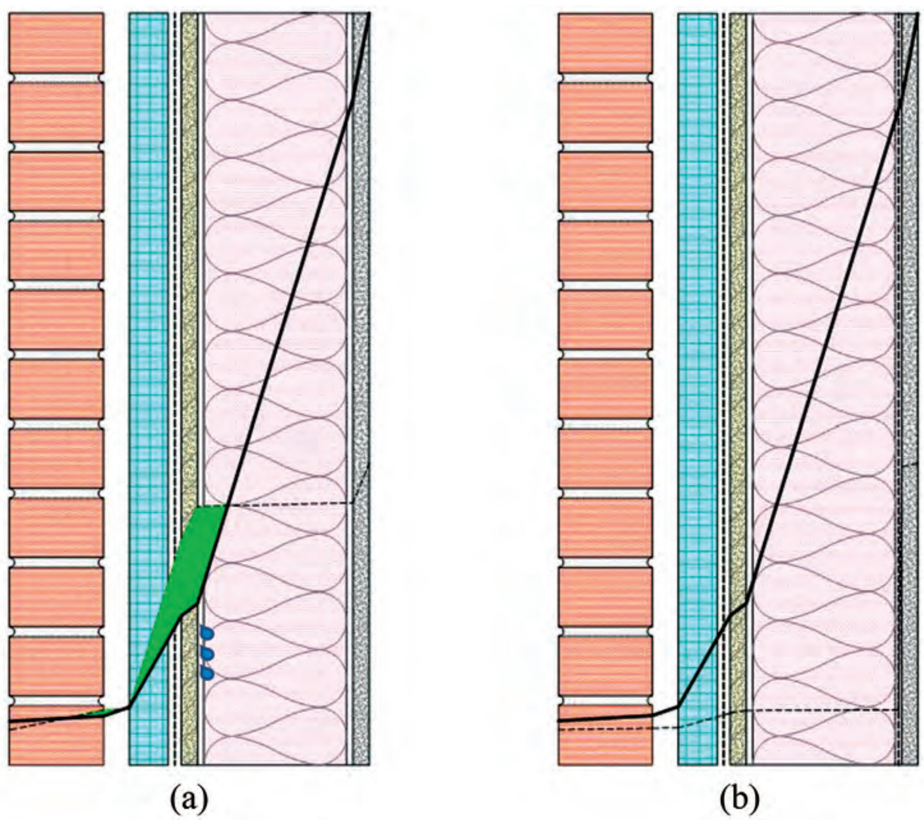

Figure 2 – Predicted vapor pressure profile of a typical split-insulation system during winter conditions. The dashed line represents the predicted vapor pressure, and the solid line represents the saturation vapor pressure. The green shaded region (left) indicates the area where the predicted vapor pressure exceeds the saturation pressure or where the predicted RH exceeds 100 percent. The right graphic shows the pressure profiles for the same assembly but with a vapor retarder added between the studs and drywall.

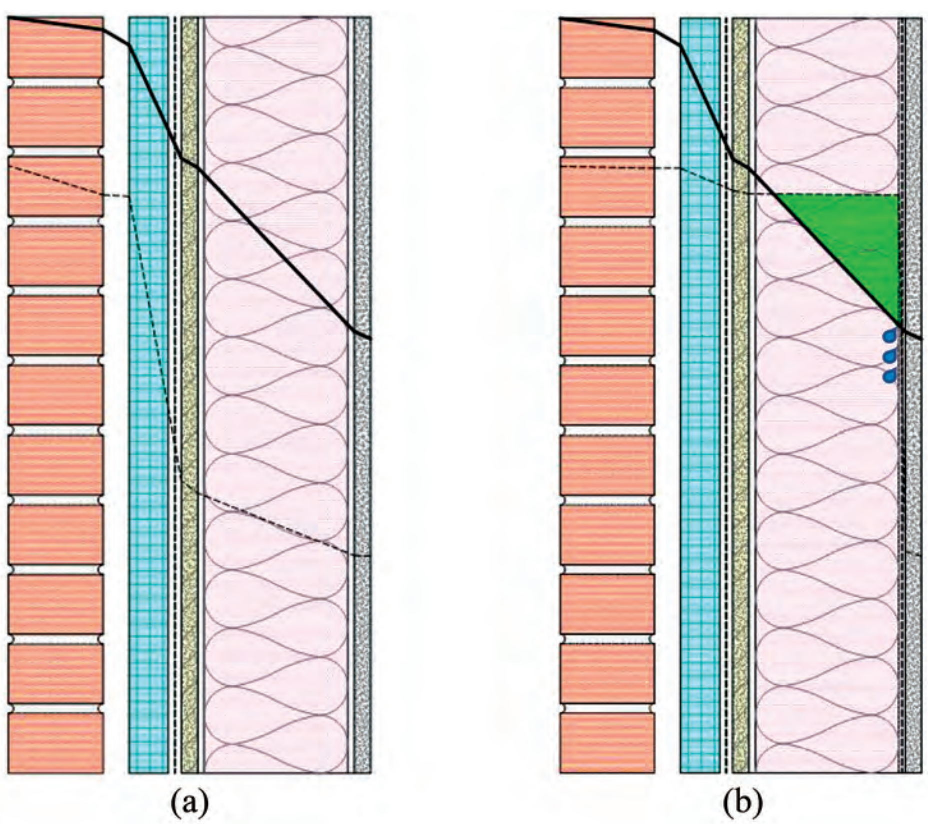

Figure 3 – Predicted vapor pressure profile of a typical split-insulation system during summer conditions. The dashed line represents the predicted vapor pressure, and the solid line represents the saturation vapor pressure. The green shaded region (right) indicates the area where the predicted vapor pressure exceeds the saturation pressure or where the predicted RH exceeds 100 percent. The left graphic shows the pressure profile for the same assembly but without the vapor retarder.

differential (i.e., higher moisture content differential of the air), the greater the rate of vapor diffusion. Condensation occurring due to solar radiation and/or summer conditions can wet the interface between the vapor retarder and the batt insulation, leading to the development of microbial growth if organic materials are present, such as dust particulates within the batt or paper facers.

In order to reduce the effect of solar-radiation-induced vapor diffusion, introducing a ventilated cavity behind reservoir claddings can significantly alleviate these vapor pressures. It should be noted that Class III vapor retarders (e.g., latex or enamel paints) are permitted in Climate Zones 5 through 8 and Marine 4 with ventilated claddings or insulated sheathings.

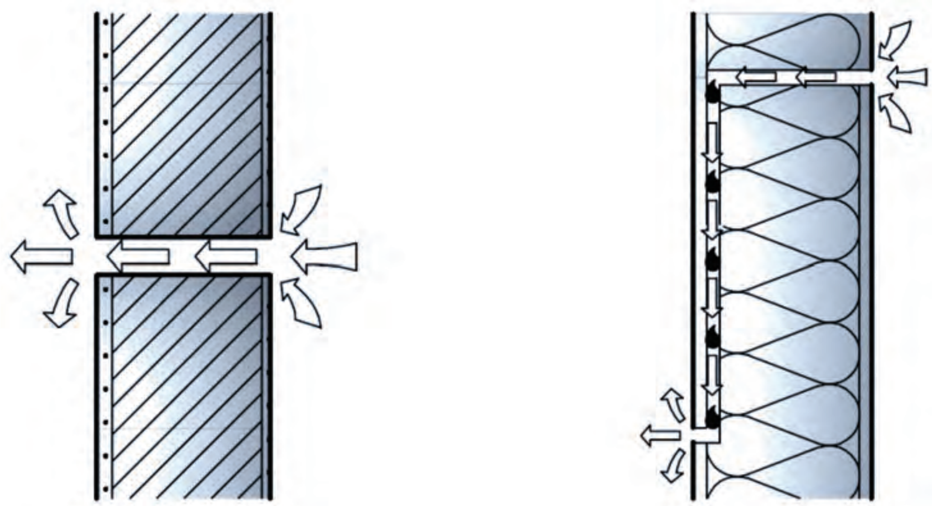

Figure 4 – Diagram showing direct air flow paths (left) and circuitous air flow paths (right) from* Modelling the Effect of Air Leakage in Hygrothermal Envelope Simulation *by Hartwig Künzel.

$$IR_{required} = \frac{T_{dp} - T_o}{T_i - T_o}$$

Equation 5 – The required minimum IR to maintain the surface temperature of the sheathing at the dewpoint temperature (T_{dp}), where T_i and T_o are the interior and exterior temperatures, respectively.

CONVECTIVE CONDENSATION

As airflow through discontinuities can carry moisture into a wall assembly at a rate orders of magnitude higher than can diffusion through materials, air infiltration or exfiltration is often the primary source of moisture transfer associated with condensation within a wall assembly. Depending on the direction of air flow, ambient air temperatures, and RH of the air and wall system materials, airflow may cause either wetting via condensation or drying through evaporation of the assembly's materials. Airflow occurs when there is an air pressure differential resulting from wind, mechanical pressurization, stack effect, etc., across an assembly and travels from a higher to a lower air pressure.

For example, warm and humid interior air that is able to flow into the exterior wall assembly due to a pressure differential can condense on surfaces of wall components that are below the dew point of the exfiltrating interior air. With air-permeable batt insulation within the stud cavity, it can be expected that some exfiltrating interior air will be able to reach the inboard face of the exterior sheathing, which may have a surface temperature below the dew point temperature to promote condensation. Paths for this type of air flow include discontinuities within the interior gypsum wallboard, commonly found around electrical outlets and other penetrations and along terminal edges at interfaces with floors, ceilings, and fenestration.

In general, there are two primary air leakage paths: direct and circuitous. Direct paths, like the one shown on the left in *Figure 4*, are typical of a through-wall connection or penetration, where the air flows directly from the inside to the outside or vice-versa. In this case, the air usually carries enough thermal energy to warm up or cool down the component surfaces along the flow path. This typically keeps the surface temperature of the contacted elements within the flow path above the dew point, which means that there will be no condensation along the path. Depending on climatic conditions, liquid condensation or ice may develop on the outboard surface. The primary concern with direct leakage paths is typically thermal shorts ("energy leaks") within the building enclosure.

Conversely, circuitous flow patterns, as shown on the right in *Figure 4*, do not sufficiently warm or cool the greater area of the traversed surfaces, resulting in the potential for moisture-laden air to contact surfaces that are below the dew point temperature of the air. This type of air leakage path can result in the deposition of significant amounts of condensate within the wall system. In order to prevent direct and circuitous air paths, all materials, components, and assemblies should be integrated to provide a continuous air control layer. Even with a "continuous" air control layer, construction practices and general operation and service of the building will allow some air leakage, likely increasing during the service life of the building.

To accommodate reasonably expected imperfections in the air control layer while limiting the development of convective condensation on the inboard face of the exterior sheathing, designers utilizing the split-insulation approach can empirically determine the minimum ratio of continuous insulation to total insulation necessary to maintain the inboard surface temperature of the exterior sheathing above the interior dew point. *Equation 5* is the simplified method of calculating this ratio considering only the effects of thermal conduction on exterior temperatures. Thermal radiation (e.g., solar heat gain, clear-sky cooling), internal thermal convection, and wind washing are disregarded by this formula.

Tabulation of calculated minimum IRs for typical interior and exterior climatic conditions are presented in *Table 2*.

The calculated minimum IRs corresponding to the various prescribed energy code minimums and distributions are 0.28 for Climate Zones 1 and 2, and 0.37 for Climate Zones 3 through 8. The ratios are delineated in *Table 2* using orange and blue lines, respectively. The exterior temperature and RH combinations below these energy code minimum lines remain at risk for convective condensation on the exterior sheathing. For example, for 5°F exterior temperature and 72°F and 35 percent RH interior conditions, a wall constructed in compliance with the IR corresponding to the energy code requirements (0.37, assuming Climate Zone 5) would be at significant risk for convective condensation, given the calculated required minimum IR is 0.56.

While the codes require a minimum of R-13 insulation within the stud cavities, R-19 insulation is typically specified with 2x6 metal studs, which are more commonly used in commercial construction. Since the code provides minimum values, many designers assume more insulation is better; however, this would result in an IR of

0.21 for Climate Zones 1 and 2, and 0.28 for Climate Zones 3 and up. This shifts the colored lines further up in Table 2, resulting in more risk of condensation and/or elevated surface RH at the inboard face of the exterior sheathing.

Since *Table 2* only considers thermal conduction, ratios that fall close to the minimum ratio may experience performance problems other than condensation. For example, ratios above the colored lines may result in an elevated surface RH (greater than 80 percent) that can promote microbial growth on certain sheathing facers without the development of liquid condensate. Conversely, systems slightly above minimum ratios (colored threshold lines in *Table 2*) may not develop condensation if the actual air leakage rate is low, since this table assumes sufficient air leakage to transport enough moisture from the indoor air to the exterior sheathing.

Ratio of Continuous Exterior Insulation to Total Insulation									
Interior Temperature 72 °F	RH	15	20	25	30	35	40	45	50
	T_d, °F	22	29	34	39	43	46	49	52
Exterior Temperature, °F	40	0	0	0	0	0.09	0.20	0.30	0.39
	35	0	0	0	0.10	0.21	0.31	0.39	0.47
	30	0	0	0.10	0.21	0.31	0.39	0.46	0.53
	25	0	0.08	0.20	0.29	0.38	0.45	0.52	0.58
	20	0.03	0.17	0.27	0.36	0.44	0.51	0.57	0.62
	15	0.12	0.24	0.34	0.42	0.49	0.55	0.61	0.66
	10	0.19	0.30	0.39	0.47	0.53	0.59	0.64	0.68
	5	0.25	0.35	0.44	0.51	0.56	0.62	0.66	0.71
	0	0.30	0.40	0.48	0.54	0.59	0.64	0.69	0.73
	-5	0.35	0.44	0.51	0.57	0.62	0.67	0.71	0.74
	-10	0.39	0.47	0.54	0.60	0.64	0.69	0.73	0.76
	-15	0.42	0.50	0.57	0.62	0.66	0.71	0.74	0.77
	-20	0.45	0.53	0.59	0.64	0.68	0.72	0.76	0.79

Table 2 – Minimum IRs necessary to maintain the inboard surface temperature of exterior sheathing at the interior ambient dew point temperature for various interior RH and exterior temperature combinations and an interior ambient temperature of 72° Fahrenheit. The orange and blue lines represent the IR for Climate Zones 1 and 2 and Climate Zones 3 and up, respectively. It should be noted that an interior RH between 20 and 30 percent is the ideal range for typical human thermal comfort as published in ASHRAE Standard 55.

HYGROTHERMAL MODELING

WUFI® Pro 5 (WUFI) is modeling software that can assess the response of a multi-layered system in terms of one-dimensional simultaneous heat and moisture transport. WUFI can model trends in the moisture content and wetting and drying cycles of each component in the system over a period of multiple years using historical climatic conditions for a given geographic location. The effects of air leakage can be modeled by the Fraunhofer IBP air exfiltration model, which takes into account pressure difference due to stack effect and global building air leakage rates, which can be derived by blower door measurements.

WUFI simulations were used to characterize the influence of air leakage rates and elevated surface RH on a prototype wall assembly in an example location. The framed wall section shown in *Figures 2* and *3*, with a glass-mat-faced gypsum board as the exterior sheathing, was assumed to be oriented north in Chicago, Climate Zone 5. Further, 2x6 studs with R-19 batt insulation were modeled. The combination of the following conditions resulted in nearly 2000 combinations simulated with WUFI:

- Continuous insulation R-Value from R-5 to R-20
- Interior RH during winter conditions from 25 to 60 percent
- Airtightness at 75 Pascals from 0 to 1 CFM/ft^2
- Interior vapor retarder: none, Class I, and Class II

The output data were analyzed and are conveyed in terms of ANSI/ASHRAE 160-2016, *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 160). The main criterion is based on a mold growth model developed by TEKES and VTT[1], which has been validated on actual laboratory and field measurements on mold growth and takes the temperature, RH, time, and substrate class into account. The main criterion defines index values of three and above as unacceptable Mold Indices in Section 6 of the ASHRAE 160 standard, and are as shown in *Table 3*:

RESULTS

WJE compiled the resulting mold growth index (MGI) in conjunction with the IR to provide a more detailed assessment of the hygrothermal performance of code-minimum R-values in ASHRAE 90.1 and IECC. For example, *Tables 4* and *5* illustrate the results, exemplarily for an R-7.5 continuous insulation, which yields an IR equal to 0.28 for the wall system with R-19 stud

Index	Description of Growth
0	No Growth
1	Small amounts of mold on surface (microscope), initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, <10% coverage, or <50% coverage of mold (microscope)
4	Visual findings of mold on surface, 10%-50% coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

***Table 3 – Mold Indices from* Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials.**

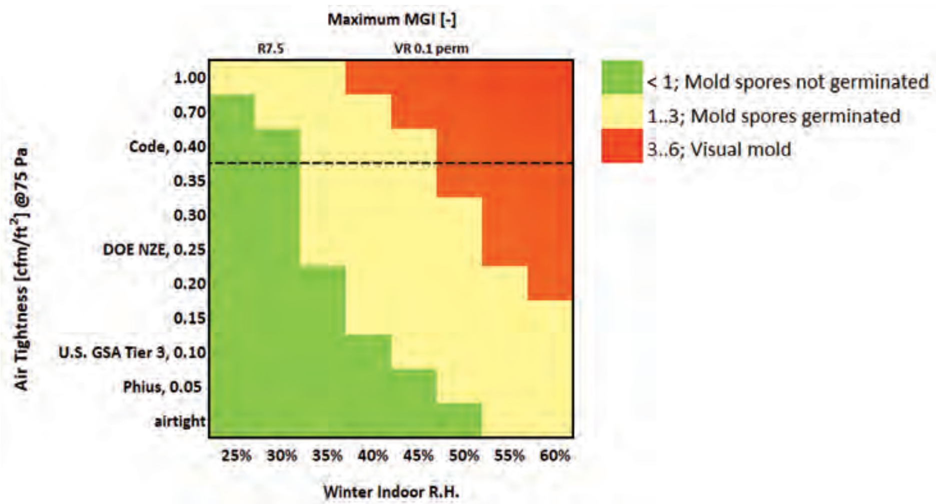

Table 4 – Maximum MGI for variable air leakage rates and interior RH with a Class I vapor retarder.

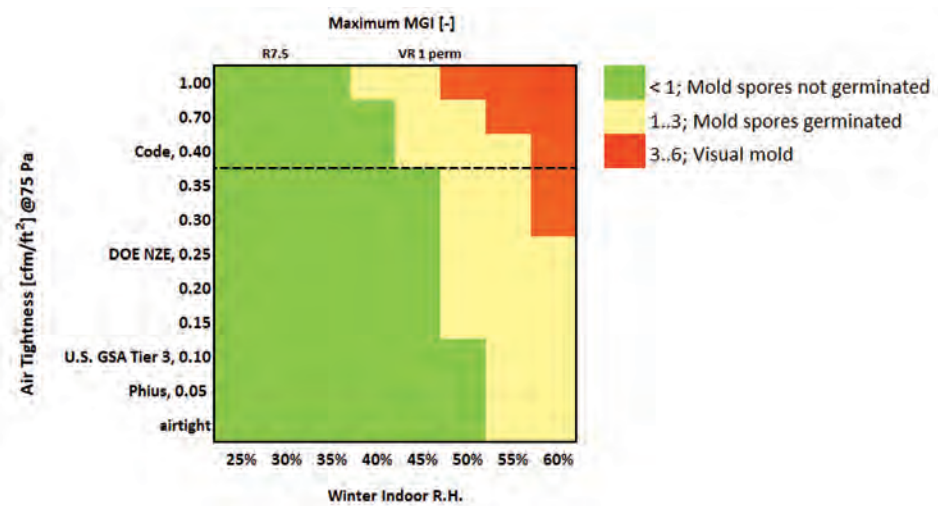

Table 5 – Maximum MGI for variable air leakage rates and interior RH with a Class II vapor retarder.

cavity insulation. The tables show the predicted maximum mold growth index after a 10-year simulation on the interior surface of the exterior gypsum sheathing, depending on the air leakage rate and the indoor winter RH. The table also states the air leakage requirements according to several organizations: Passive House Institute US (PHIUS), Department of Energy Net-Zero Energy Building (DOE NZEB), U.S. General Service Administration (U.S. GSA) Level Tier 3, and IECC code requirements. The other results can be found in *Tables A.1* through *A.7* in Appendix A.

All the diagrams show a similar basic and predictable behavior in that all wall assemblies at higher airtightness and lower indoor RH in winter are at lower risk for development of mold (i.e., green colors in the lower left corner of the diagrams). Altering conditions toward the upper right corner of the diagrams—meaning lower airtightness and higher indoor RH in winter—results in higher risk for development of mold, which can be seen by the colors turning from yellow to orange.

Continuous Insulation	Vapor Retarder None	Class II	Class I
R5	40%	50%	40%
R7.5	45%	55%	45%
R10	45%	60%	50%
R12.5	50%	60%	55%
R15	55%	60%	55%
R17.5	55%	55%	60%
R20	60%	60%	60%

Table 6 – Recommended maximum indoor RH for the simulated wall assembly with code-compliant airtightness or better in Climate Zone 5.

It is obvious from the results in Appendix A that an increasing R-value of the continuous insulation leads to better-performing assemblies, which can be explained by the fact that the exterior sheathing will be at a higher temperature, hence a lower risk of condensation of indoor moisture.

Further, a Class II vapor retarder results in overall reduced risk for mold development in all of the combinations compared to no vapor retarder or a Class I vapor retarder. The study suggests that a Class II vapor retarder is the best compromise between vapor control in winter and drying accumulated moisture in the exterior gypsum sheathing back to the interior during summer conditions.

Finally, from the results in Appendix A, we can establish the maximum indoor RH listed in *Table 6* for the example wall assembly in Climate Zone 5 assuming code-compliant or better airtightness (0.4 CFM/ft^2 at 75 Pascals) to achieve acceptable ASHRAE Standard 160 criterion.

CONCLUSIONS

Tables 4 and *5* show that even if the construction follows code and has even more continuous insulation than required, a hygrothermal safe performance is only predicted for low enough indoor RH in winter and low enough air leakage. As the title suggests, compliance with the energy code does not guarantee condensation- or mold-free wall performance.

Hygrothermal performance of wall assemblies is exceptionally complex—a function of numerous variables and assumptions. Thus, simplified empirical design guides may not provide prudent direction.

While this study focused on a single city in Climate Zone 5, additional simulations to include more geographic locations and prototype wall assemblies would provide a more-encompassing design guideline for designers to comply with the current energy codes and avoid moisture accumulation and microbial growth due to condensation.

REFERENCES

1. T. Ojanen, H. Viitanen, et. al. "Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials." ASHRAE 2010.

APPENDIX A: Hygrothermal Modeling Results

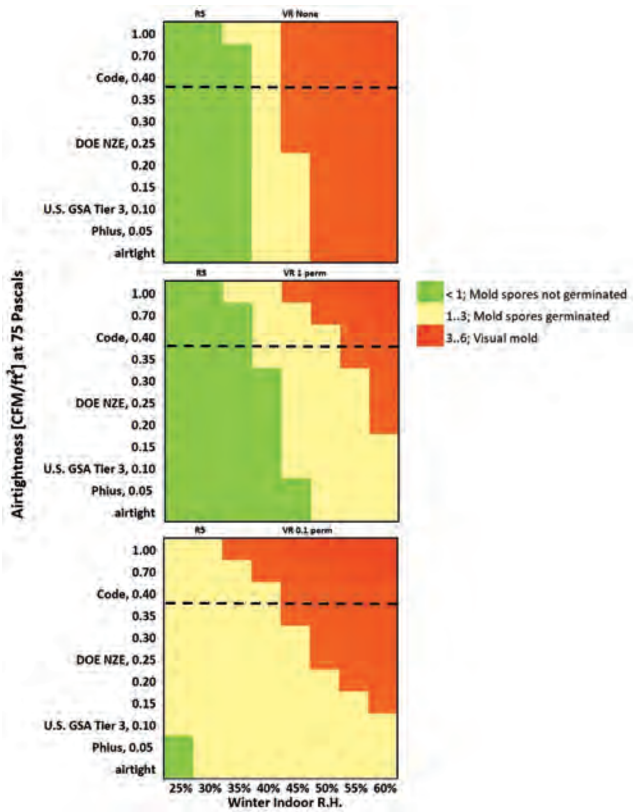

Table A.1 – Maximum MGI for R-5 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

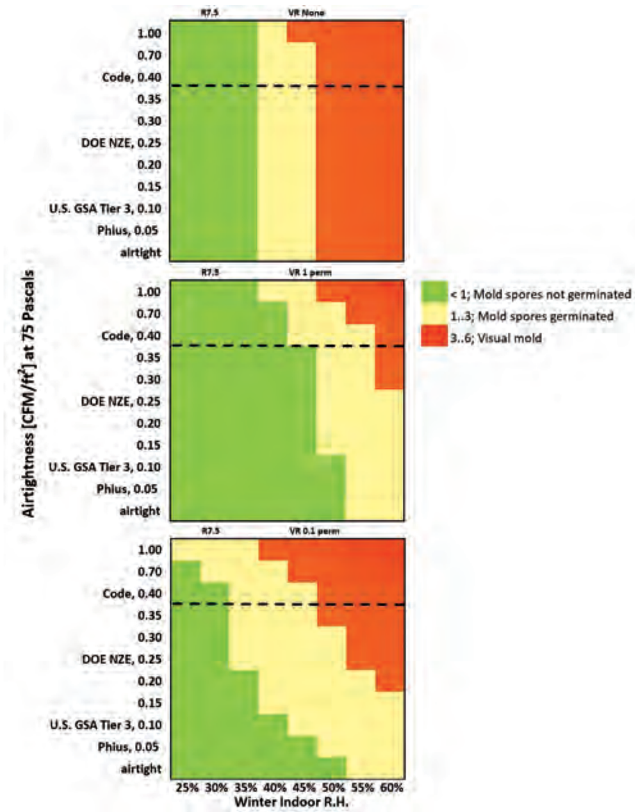

Table A.2 – Maximum MGI for R-7.5 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

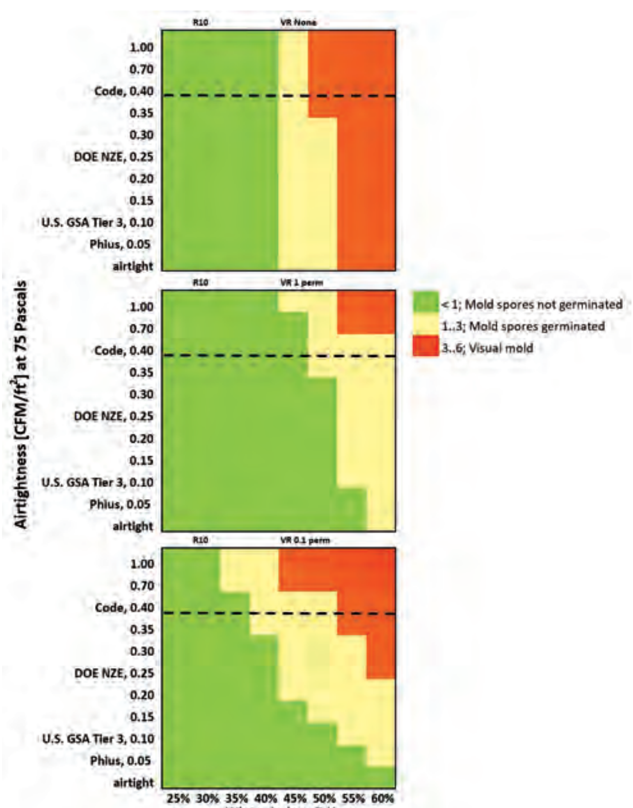

Table A.3 – Maximum MGI for R-10 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

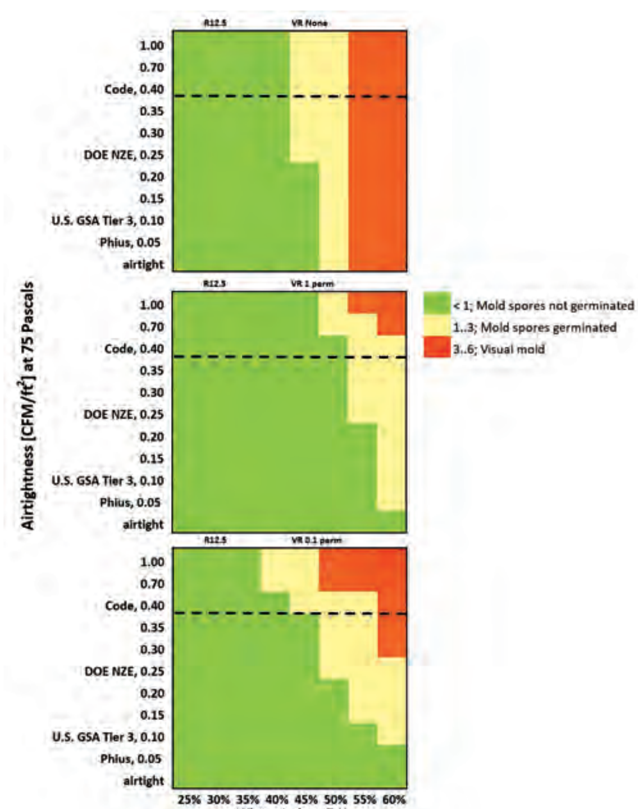

Table A.4 – Maximum MGI for R-12.5 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

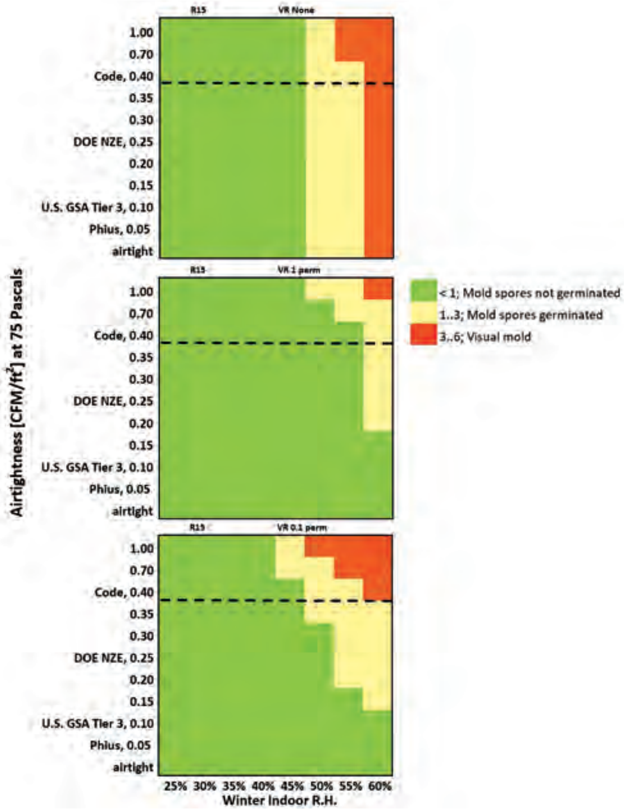

Table A.5 – Maximum MGI for R-15 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

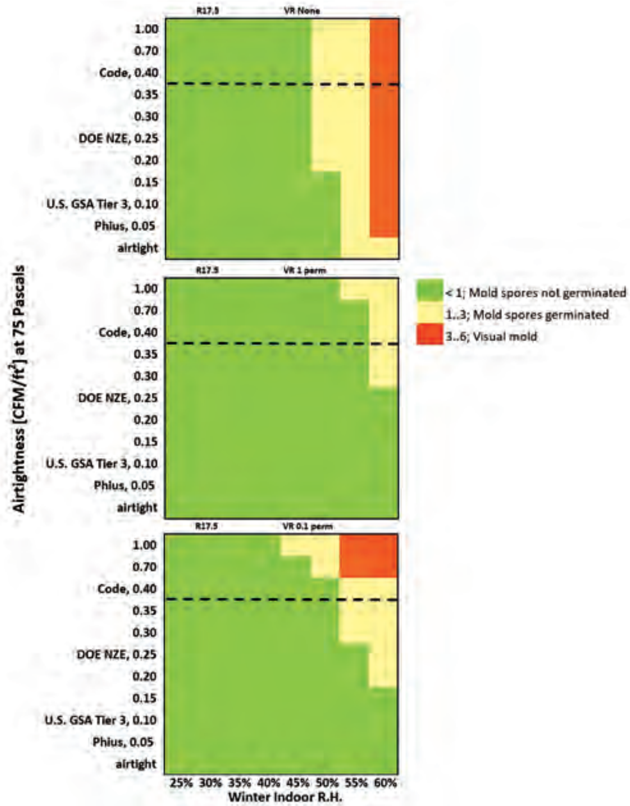

Table A.6 – Maximum MGI for R-17.5 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

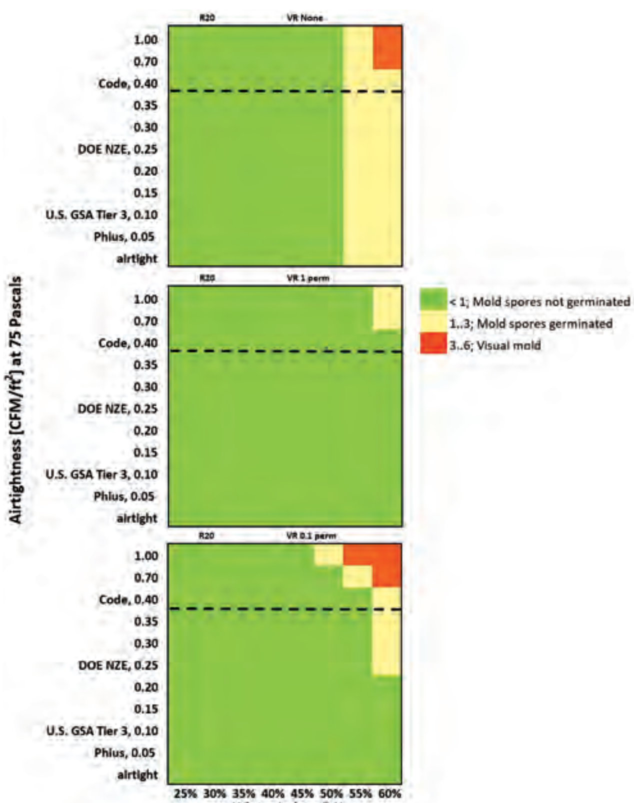

Table A.7 – Maximum MGI for R-20 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.