Air Infiltration and Its Consequences for Building Enclosures in Hot/Humid Climate Zones

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To maximize the efficacy and performance of building enclosure walls, the four major building enclosure control layers (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 (movement of heat and moisture) of an exterior wall. In a previous study,[1,2] we reviewed the risk of microbial growth within energy code—compliant exterior walls that use a split insulation arrangement, both exterior continuous insulation and batt insulation within the stud cavities, located in Climate Zones 4 and higher, as defined in the *International Energy Conservation Code* (IECC).[3]

In this study, we focus on quantifying the risk of microbial growth and potential deterioration of the interior gypsum wallboard for energy code—compliant exterior walls in hot and humid climate zones (such as Climate Zones 1 and 2) because of unintentional exterior air infiltration.

EFFECTS OF INSULATION

Because the introduction of insulation in any exterior wall system reduces the heat flow through the wall assembly, the surface temperatures of materials inboard of the insulation are reduced in hot and humid climates (especially when air conditioning is used). In addition to the temperature drop in the interior space caused by the insulation, a subsequent and greater reduction in the saturation vapor pressure P_{ws} occurs, as shown in **Eq. (1)**, which can cause the development of condensation.

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

where

T = temperature (°K)

Note that P_{ws} will drop exponentially relative to T.

Equation 1

Saturation vapor pressure is the maximum pressure of water vapor, or absolute humidity, that can exist within the air. Relative humidity (RH) is the ratio of actual water vapor in the air to the maximum amount of water vapor at saturation (**Eq. [2]**). Therefore, the RH of saturated air (that is, actual vapor pressure equal to the saturation vapor pressure) is 100%.

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

where

P_w = vapor pressure

Equation 2

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 inboard of the insulation layer is expected. Therefore, it is important and ideal to place the thermal control entirely outboard of the other building enclosure control layers, thereby protecting the structure and moisture-sensitive finishes from elevated RH and potential condensation development. However, the energy codes allow either splitting the thermal control layer so that it sandwiches some of the other control layers or placing it entirely inboard of the control layers within the stud cavity. If the insulation is placed in a split or inboard position, it is imperative to control or reduce the vapor and air transport into and through the 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.

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

where

T_{dp} = dew point temperature (°C)

T_i = interior temperature (°C)

A = 17.62

B = 243.12

Equation 3

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.

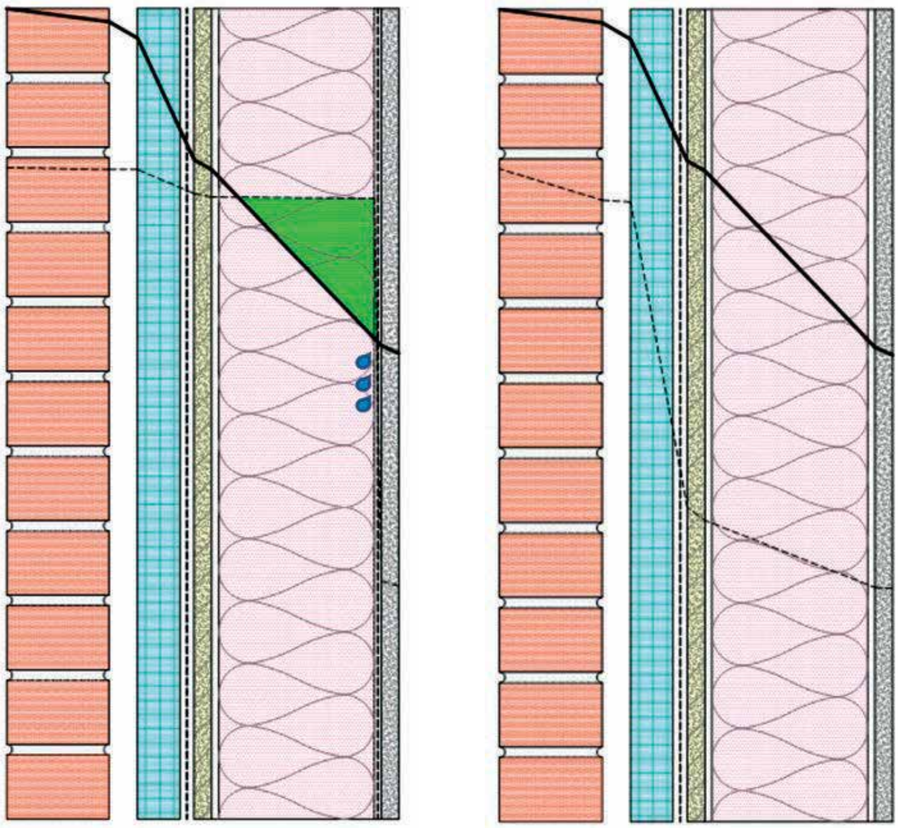


Figure 1. ***Predicted vapor pressure profile of a typical split insulation system in a hot and humid climate. The dashed lines represent the predicted vapor pressure, and the solid lines represent the saturation vapor pressure. The green shaded region indicates the area where the predicted vapor pressure exceeds the saturation pressure or where the predicted relative humidity exceeds 100% (left). The pressure profile for the same assembly but with a vapor-impermeable water-resistive air barrier (right).***

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 airflow. Nonetheless, the placement of vapor retarders within an exterior wall assembly with respect to the location of the insulation 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 were to exceed the saturation vapor pressure, condensation would be predicted to occur to satisfy equilibrium (**Fig. 1**). It should be noted that the rate of condensation development is typically extremely low.

To control diffusive condensation, a vapor retarder (typically the water-resistive air barrier), should be generally placed on the warm side of all insulation, outboard of the inherent drop in saturation vapor pressure, to locally reduce vapor pressure; however, split insulation assemblies make this challenging in hot-humid climates (**Fig. 1**).

CONVECTIVE CONDENSATION

Because airflow through discontinuities can carry moisture into a wall assembly at a much greater rate than diffusion through materials can, air leakage is often the primary source of moisture transfer associated with condensation within a wall assembly.

Airflow occurs when there is an air pressure differential across an assembly. The differential may be caused by wind, mechanical pressurization, stack effect, or other factors, and the airflow travels from a higher to a lower air pressure. Depending on the direction of airflow, ambient air temperatures, and the RH of the air and wall system materials, airflow may cause either wetting of the assembly's materials via condensation or drying of the materials through evaporation.

For example, if hot and humid exterior air flows into the exterior wall assembly due to a pressure differential, moisture can condense on surfaces of wall components that are below the dew point of the infiltrating interior air. With air-permeable batt insulation within the stud cavity, it can be expected that some infiltrating exterior air will be able to reach the inboard face of the gypsum wallboard, which may have a surface temperature below the dew point temperature of the outdoor air, and that could promote condensation. Paths for this type of airflow include discontinuities within the water-resistive air barrier and exterior sheathing; such discontinuities are commonly found around penetrations and along terminal edges at interfaces with floors, roofing assemblies, and fenestration.

In general, there are two primary air leakage paths: direct and circuitous. Direct paths, like the one shown on the left in **Fig. 2**,[4] are typical of a through-wall connection or penetration,

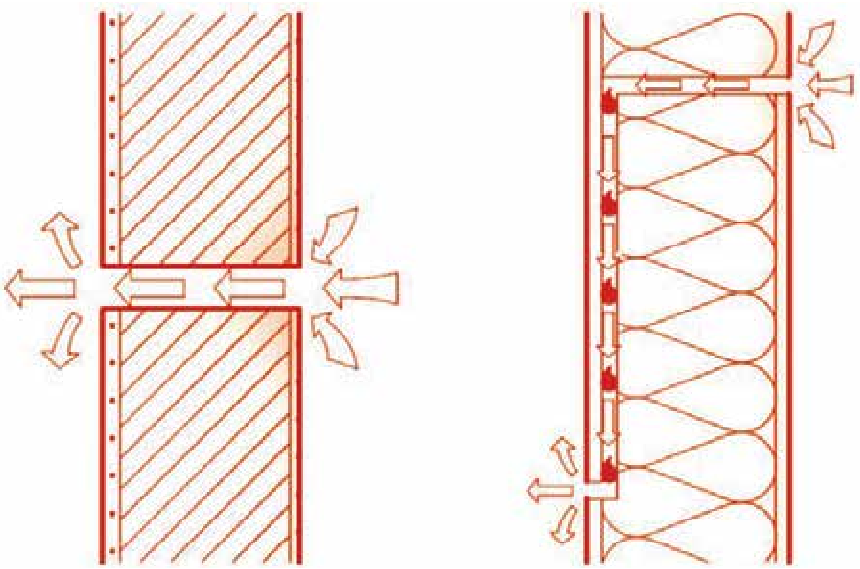


Figure 2. ***Diagram showing direct airflow paths (left) and circuitous airflow paths (right) for a cold weather situation. Figure: Reprinted from reference 4.***

where the air flows directly from the outside to the inside 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 may develop on either the interior or exterior surface of the wall assembly. 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 Fig. 2, do not sufficiently warm or cool the greater area of the crossed surfaces; therefore, there is a 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.

To prevent direct and circuitous air paths, all materials, components, and assemblies should be integrated to provide a continuous air-control layer. However, even with a "continuous" air-control layer, construction practices and general operation and service of the building will allow some unintended air leakage, which will likely increase during the service life of the building as materials age and weather. But how much is too much, and are there energy code–compliant wall assemblies that fare better when some air leakage occurs?

To provide insight on these questions for hot and humid climates, we conducted transient hygrothermal analyses that considered several combinations of partially unknown parameters, namely air infiltration rates depending on airtightness, actual indoor temperatures, perm ratings of interior paints and exterior water-resistive air barriers, and their impact on the hygrothermal performance.

HYGROTHERMAL MODELING

In our study, we used WUFI Pro 6 (WUFI), which is modeling software that can assess the response of a multilayered system in terms of one-dimensional simultaneous heat and moisture transport. Using historical climatic conditions for a given geographic location, 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.

The model we developed—which is similar to the air exfiltration model in cold climate zones that is incorporated in WUFI—can account for the effects of air leakage. Our approach takes pressure difference due to stack effect and global building air leakage rates, which can be derived by blower door measurements, into account. It should be noted that this air infiltration model is not yet validated, although the authors of the air exfiltration model agree that it is viable.

Table 1. Mold indices

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%

Source: Adapted from reference 6.

In our study, we used WUFI simulations to characterize the influence of air leakage rates and elevated surface RH on a prototype wall assembly in an example location. A brick masonry—clad, framed wall section with a vapor-impermeable (0.1 perm) water-resistive air barrier over glass-matt-faced gypsum board as the exterior sheathing was assumed to be oriented south in Houston, Texas, which is in Climate Zone 2. Further, *R*-20 batt insulation placed between 2 × 6 wood studs and interior gypsum wallboard was modeled. The combination of the following conditions resulted in more than 500 combinations simulated with WUFI:

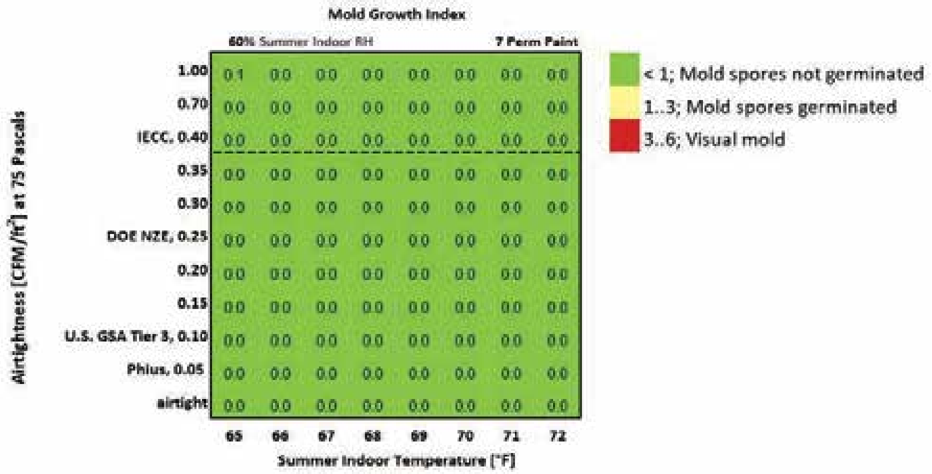
- Interior temperatures from 65°F to 72°F
- Interior RH 50% and 60%
- Building airtightness at 75 Pa from 0 to 1 $ft^3/min/ft^2$
- Interior finish: latex paint (7 and 1 perm), vinyl wallpaper

The output data were analyzed and are conveyed in terms of ANSI/ASHRAE 160-2016, *Criteria for Moisture-Control Design Analysis in Buildings*,[5] at the interior paper-faced gypsum board. The main criterion is based on a mold growth model developed by TEKES (the Finnish Funding Agency for Technology and Innovation) and VTT (the Technical Research Council of Finland),[6] which has been validated on actual laboratory and field measurements on mold growth and takes the temperature, RH, time, and substrate class into account. This main criterion is based on the mold index values in Section 6 of ASHRAE 160 (**Table 1**), and it defines values equal to greater than 3 as unacceptable.

RESULTS

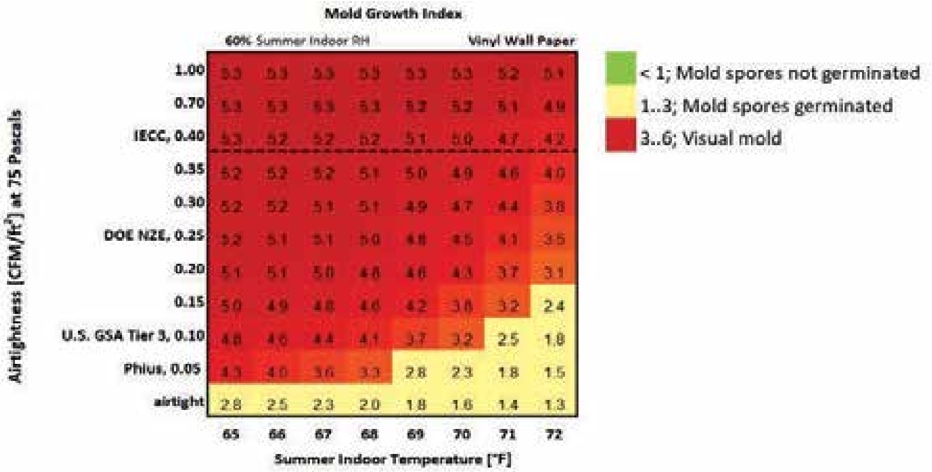
We compiled the resulting mold growth index (MGI) to provide a more detailed assessment of the hygrothermal performance of code minimum *R*-values in ASHRAE 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*,[7] and the IECC.[3] For example, **Figs. 3** through **8** illustrate the results after

Depending on climatic conditions, liquid condensation may develop on either the interior or exterior surface of the wall assembly. The primary concern with direct leakage paths is typically thermal shorts ("energy leaks") within the building enclosure.



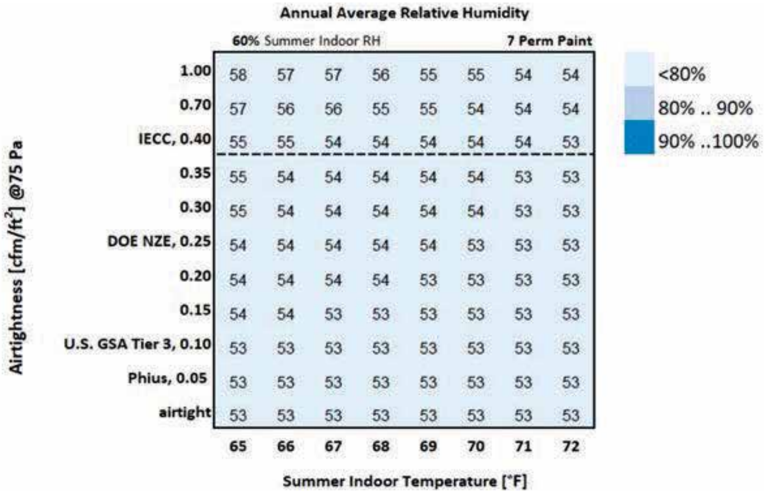
Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IECC, 0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOE NZE, 0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U.S. GSA Tier 3, 0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phius, 0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
airtight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 3. *Maximum mold growth index values for variable air leakage rates and interior temperatures with 7-perm latex paint. DOE NZE = US Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; US GSA Tier 3 = US General Services Administration, Level Tier 3.*



Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	5.3	5.3	5.3	5.3	5.3	5.3	5.2	5.1
0.70	5.3	5.3	5.3	5.3	5.2	5.2	5.1	4.9
IECC, 0.40	5.3	5.2	5.2	5.2	5.1	5.0	4.7	4.2
0.35	5.2	5.2	5.2	5.1	5.0	4.9	4.6	4.0
0.30	5.2	5.2	5.1	5.1	4.9	4.7	4.4	3.8
DOE NZE, 0.25	5.2	5.1	5.1	5.0	4.8	4.5	4.1	3.5
0.20	5.1	5.1	5.0	4.8	4.6	4.3	3.7	3.1
0.15	5.0	4.9	4.8	4.6	4.2	3.8	3.2	2.4
U.S. GSA Tier 3, 0.10	4.8	4.6	4.4	4.1	3.7	3.2	2.5	1.8
Phius, 0.05	4.3	4.0	3.6	3.3	2.8	2.3	1.8	1.5
airtight	2.8	2.5	2.3	2.0	1.8	1.6	1.4	1.3

Figure 4. *Maximum mold growth index for variable air leakage rates and interior temperatures with vinyl wallpaper. DOE NZE = US Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; US GSA Tier 3 = US General Services Administration, Level Tier 3.*



Airtightness [cfm/ft²] @75 Pa	65	66	67	68	69	70	71	72
1.00	58	57	57	56	55	55	54	54
0.70	57	56	56	55	55	54	54	54
IECC, 0.40	55	55	54	54	54	54	54	53
0.35	55	54	54	54	54	54	53	53
0.30	55	54	54	54	54	54	53	53
DOE NZE, 0.25	54	54	54	54	54	53	53	53
0.20	54	54	54	54	53	53	53	53
0.15	54	54	53	53	53	53	53	53
U.S. GSA Tier 3, 0.10	53	53	53	53	53	53	53	53
Phius, 0.05	53	53	53	53	53	53	53	53
airtight	53	53	53	53	53	53	53	53

Figure 5. *Maximum relative humidity for variable air leakage rates and interior temperatures with 7-perm latex paint. DOE NZE = US Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; US GSA Tier 3 = US General Services Administration, Level Tier 3.*

a 10-year simulation on the exterior surface of the interior paper-faced gypsum wallboard example wall with either a 7-perm latex paint or vinyl wallpaper finish under 60% interior RH. The diagrams show the predicted maximum MGI, maximum RH, and maximum water content (percent by weight) depending on the air leakage rate and the indoor temperature. The figures also identify the air leakage requirements from the IECC and from the following organizations and programs: the Passive House Institute, the US Department of Energy Net Zero Energy Buildings, and the US General Services Administration Level Tier 3. Sources can be found in references 8 and 9. Other results can be found in Figs. A.1 through A.6 in the **Appendix**.

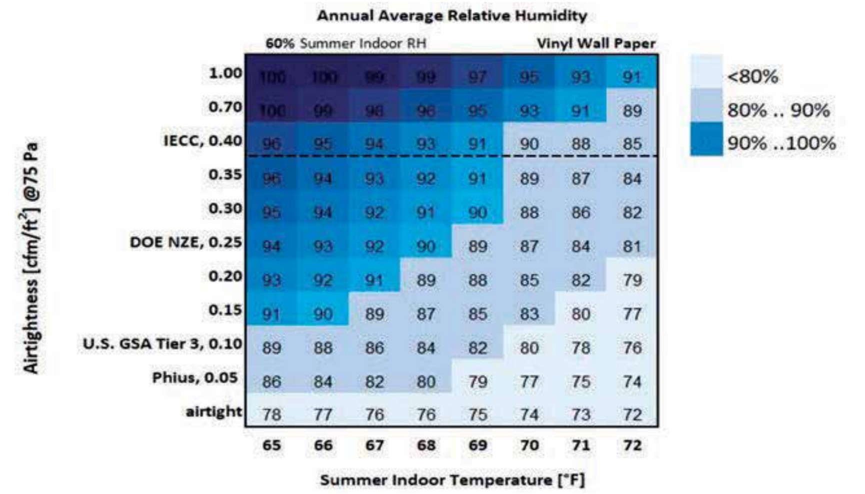
All the diagrams show a similar basic and predictable behavior: Wall assemblies at higher airtightness levels and higher interior temperatures are at lower risk for development of mold (as represented by the green colors in the lower right corners of the diagrams). Altering conditions toward the upper left corners of the diagrams, meaning higher airtightness levels and lower interior temperatures, results in higher risk for development of mold, as represented by the colors turning from yellow/orange to red.

It is obvious from the results in the Appendix that decreasing air leakage leads to better-performing assemblies. Further, increased interior operating temperatures also help the exterior wall perform better: Because the interior drywall will be at a higher temperature, the risk of condensation for the example wall assembly in Climate Zone 2 is lower, assuming the levels of airtightness are at least code compliant (0.4 ft³/min/ft² at 75 Pa) to achieve acceptable ASHRAE 160 criterion.

Finally, from the results in the Appendix, we can establish that use of a Class I or II vapor retarder (less than 1 perm) is associated with a significantly higher risk for mold development in all the combinations when compared with the use of variable latex paint permeances (greater than or equal to 1 perm). This validates the code restriction on the use of Class I vapor retarders on the interior side of framing in Climate Zones 1 and 2.

CONCLUSION

Figures 4 through 8 show that even if construction follows the energy code, a hygrothermal safe performance is associ-



Annual Average Relative Humidity

60% Summer Indoor RH — Vinyl Wall Paper

Airtightness [cfm/ft^2] @75 Pa	65	66	67	68	69	70	71	72
1.00	100	100	99	99	97	95	93	91
0.70	100	99	98	96	95	93	91	89
IECC, 0.40	96	95	94	93	91	90	88	85
0.35	96	94	93	92	91	89	87	84
0.30	95	94	92	91	90	88	86	82
DOE NZE, 0.25	94	93	92	90	89	87	84	81
0.20	93	92	91	89	88	85	82	79
0.15	91	90	89	87	85	83	80	77
U.S. GSA Tier 3, 0.10	89	88	86	84	82	80	78	76
Phius, 0.05	86	84	82	80	79	77	75	74
airtight	78	77	76	76	75	74	73	72

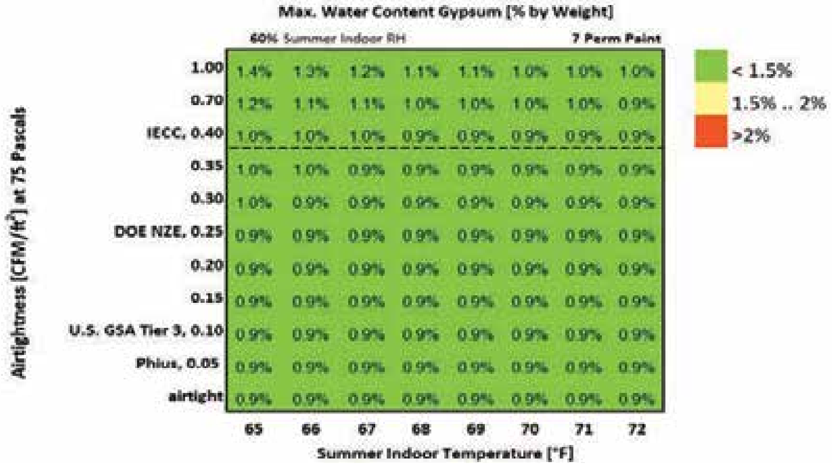
Summer Indoor Temperature [°F]

<80%

80% .. 90%

90% ..100%

Figure 6. *Maximum relative humidity for variable air leakage rates and interior temperatures with vinyl wallpaper. DOE NZE = US Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; US GSA Tier 3 = US General Services Administration, Level Tier 3.*



Max. Water Content Gypsum [% by Weight]

60% Summer Indoor RH — 7 Perm Paint

Airtightness [CFM/ft^2] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	1.4%	1.3%	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%
0.70	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%	1.0%	0.9%
IECC, 0.40	1.0%	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%
0.35	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
0.30	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
DOE NZE, 0.25	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
0.20	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
0.15	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
U.S. GSA Tier 3, 0.10	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
Phius, 0.05	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
airtight	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%

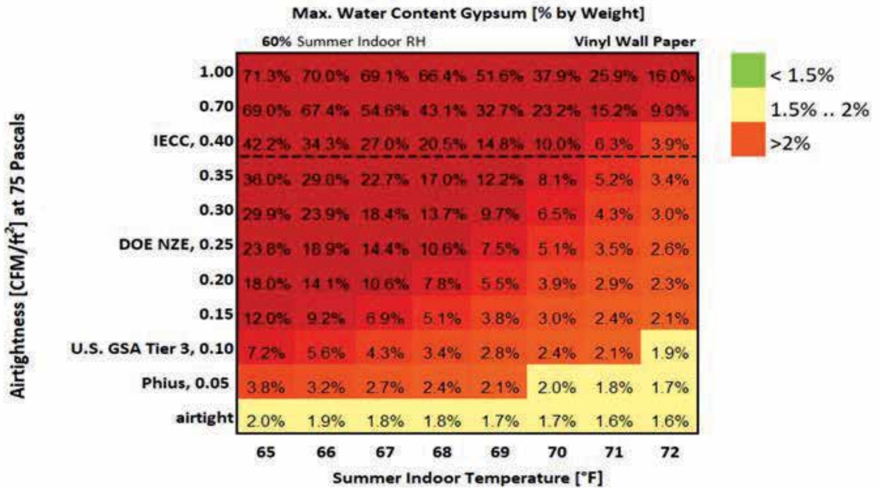
Summer Indoor Temperature [°F]

< 1.5%

1.5% .. 2%

>2%

Figure 7. *Maximum water content for variable air leakage rates and interior temperatures with 7-perm latex paint. DOE NZE = US Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; US GSA Tier 3 = US General Services Administration, Level Tier 3.*



Max. Water Content Gypsum [% by Weight]

60% Summer Indoor RH — Vinyl Wall Paper

Airtightness [CFM/ft^2] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	71.3%	70.0%	69.1%	66.4%	51.6%	37.9%	25.9%	16.0%
0.70	69.0%	67.4%	54.6%	43.1%	32.7%	23.2%	15.2%	9.0%
IECC, 0.40	42.2%	34.3%	27.0%	20.5%	14.8%	10.0%	6.3%	3.9%
0.35	36.0%	29.0%	22.7%	17.0%	12.2%	8.1%	5.2%	3.4%
0.30	29.9%	23.9%	18.4%	13.7%	9.7%	6.5%	4.3%	3.0%
DOE NZE, 0.25	23.8%	18.9%	14.4%	10.6%	7.5%	5.1%	3.5%	2.6%
0.20	18.0%	14.1%	10.6%	7.8%	5.5%	3.9%	2.9%	2.3%
0.15	12.0%	9.2%	6.9%	5.1%	3.8%	3.0%	2.4%	2.1%
U.S. GSA Tier 3, 0.10	7.2%	5.6%	4.3%	3.4%	2.8%	2.4%	2.1%	1.9%
Phius, 0.05	3.8%	3.2%	2.7%	2.4%	2.1%	2.0%	1.8%	1.7%
airtight	2.0%	1.9%	1.8%	1.8%	1.7%	1.7%	1.6%	1.6%

Summer Indoor Temperature [°F]

< 1.5%

1.5% .. 2%

>2%

Figure 8. *Maximum water content for variable air leakage rates and interior temperatures with vinyl wallpaper. DOE NZE = US Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; US GSA Tier 3 = US General Services Administration, Level Tier 3.*

ated with higher interior temperatures and lower air leakage rates. Our findings suggest that 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.

This study focused on a single city in Climate Zone 2. 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.

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ABOUT THE AUTHORS

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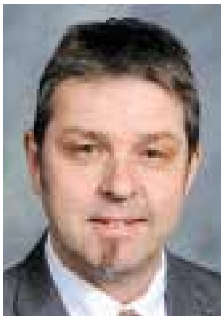
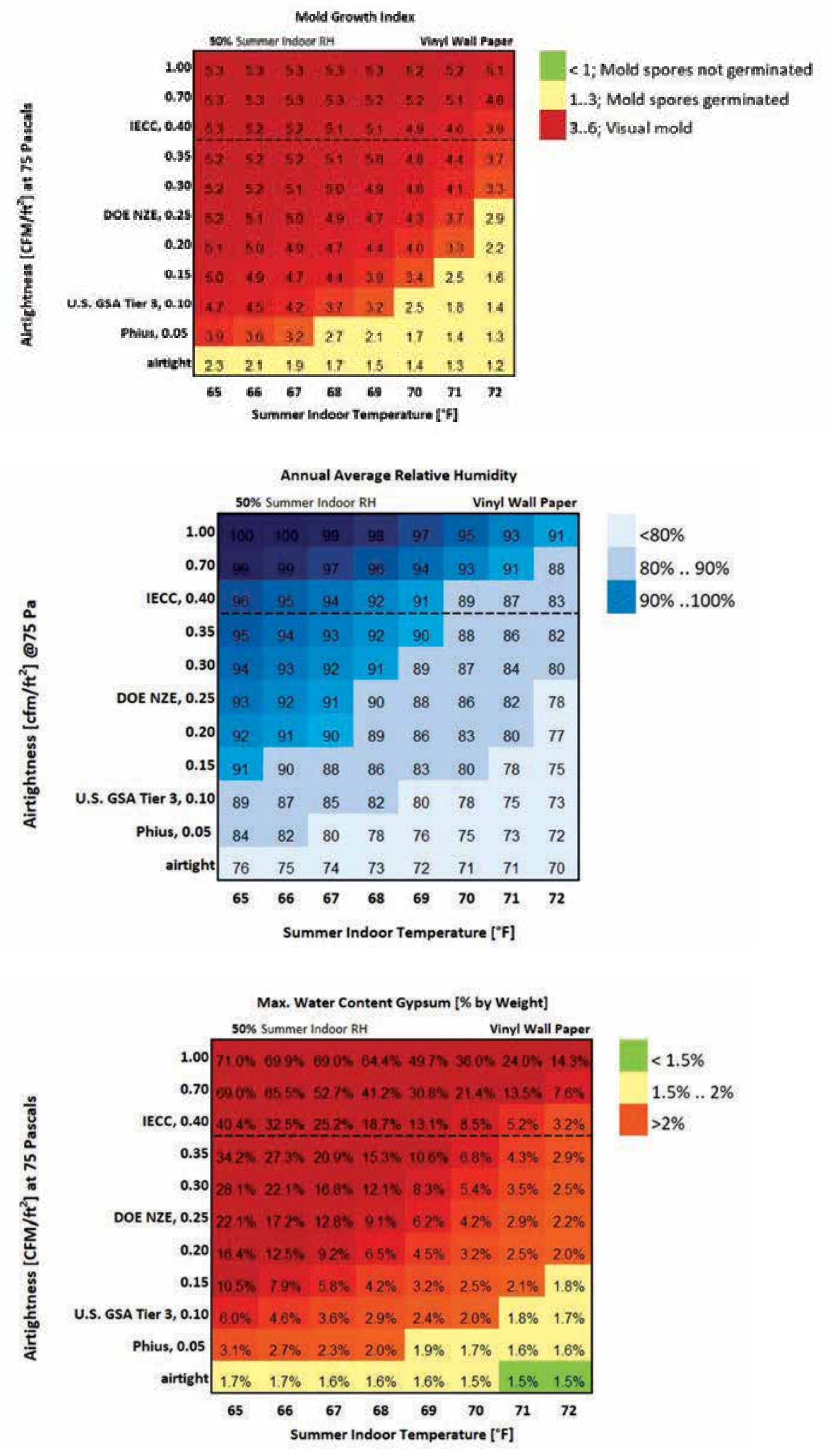
__David Finley__ is involved in a wide range of architectural investigations. His building enclosure experience includes water infiltration testing of windows, curtainwalls, masonry facades, and plaza and below-grade waterproofing, as well as condensation and air leakage testing of glazed fenestrations and masonry facades. 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__ is a senior associate at Wiss, Janney, Elstner Associates Inc. (WJE), who has been active in the field of building science for more than 30 years. After more than 20 years at Fraunhofer IBP, Germany, where he was active in the laboratory and leading development of WUFI software, he worked for the Oak Ridge National Laboratory for 5 years as a senior researcher and then served for 1 year as president of the start-up consulting company justSmartSolutions LLC. At WJE, Kehrer is in charge of building science solutions for a variety of problems in construction practice. He is a voting member, chair, and vice chair for several American Society of Heating, Refrigerating and Air-Conditioning Engineers and ASTM International committees, serves on the editorial board of the journal Frontiers in Built Environment, and has won several awards.

Appendix: Hygrothermal Modeling Results



Mold Growth Index

50% Summer Indoor RH — Vinyl Wall Paper

Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	5.3	5.3	5.3	5.3	5.3	5.2	5.2	5.1
0.70	5.3	5.3	5.3	5.3	5.2	5.2	5.1	4.8
IECC, 0.40	5.3	5.2	5.2	5.1	5.1	4.9	4.6	3.9
0.35	5.2	5.2	5.2	5.1	5.0	4.8	4.4	3.7
0.30	5.2	5.2	5.1	5.0	4.9	4.6	4.1	3.3
DOE NZE, 0.25	5.2	5.1	5.0	4.9	4.7	4.3	3.7	2.9
0.20	5.1	5.0	4.9	4.7	4.4	4.0	3.3	2.2
0.15	5.0	4.9	4.7	4.4	3.9	3.4	2.5	1.6
U.S. GSA Tier 3, 0.10	4.7	4.5	4.2	3.7	3.2	2.5	1.8	1.4
Phius, 0.05	3.9	3.6	3.2	2.7	2.1	1.7	1.4	1.3
airtight	2.3	2.1	1.9	1.7	1.5	1.4	1.3	1.2

Summer Indoor Temperature [°F]

🟩 < 1; Mold spores not germinated
🟨 1..3; Mold spores germinated
🟥 3..6; Visual mold

Annual Average Relative Humidity

50% Summer Indoor RH — Vinyl Wall Paper

Airtightness [cfm/ft²] @75 Pa	65	66	67	68	69	70	71	72
1.00	100	100	99	98	97	95	93	91
0.70	99	99	97	96	94	93	91	88
IECC, 0.40	96	95	94	92	91	89	87	83
0.35	95	94	93	92	90	88	86	82
0.30	94	93	92	91	89	87	84	80
DOE NZE, 0.25	93	92	91	90	88	86	82	78
0.20	92	91	90	89	86	83	80	77
0.15	91	90	88	86	83	80	78	75
U.S. GSA Tier 3, 0.10	89	87	85	82	80	78	75	73
Phius, 0.05	84	82	80	78	76	75	73	72
airtight	76	75	74	73	72	71	71	70

Summer Indoor Temperature [°F]

<80%
80% .. 90%
90% ..100%

Max. Water Content Gypsum [% by Weight]

50% Summer Indoor RH — Vinyl Wall Paper

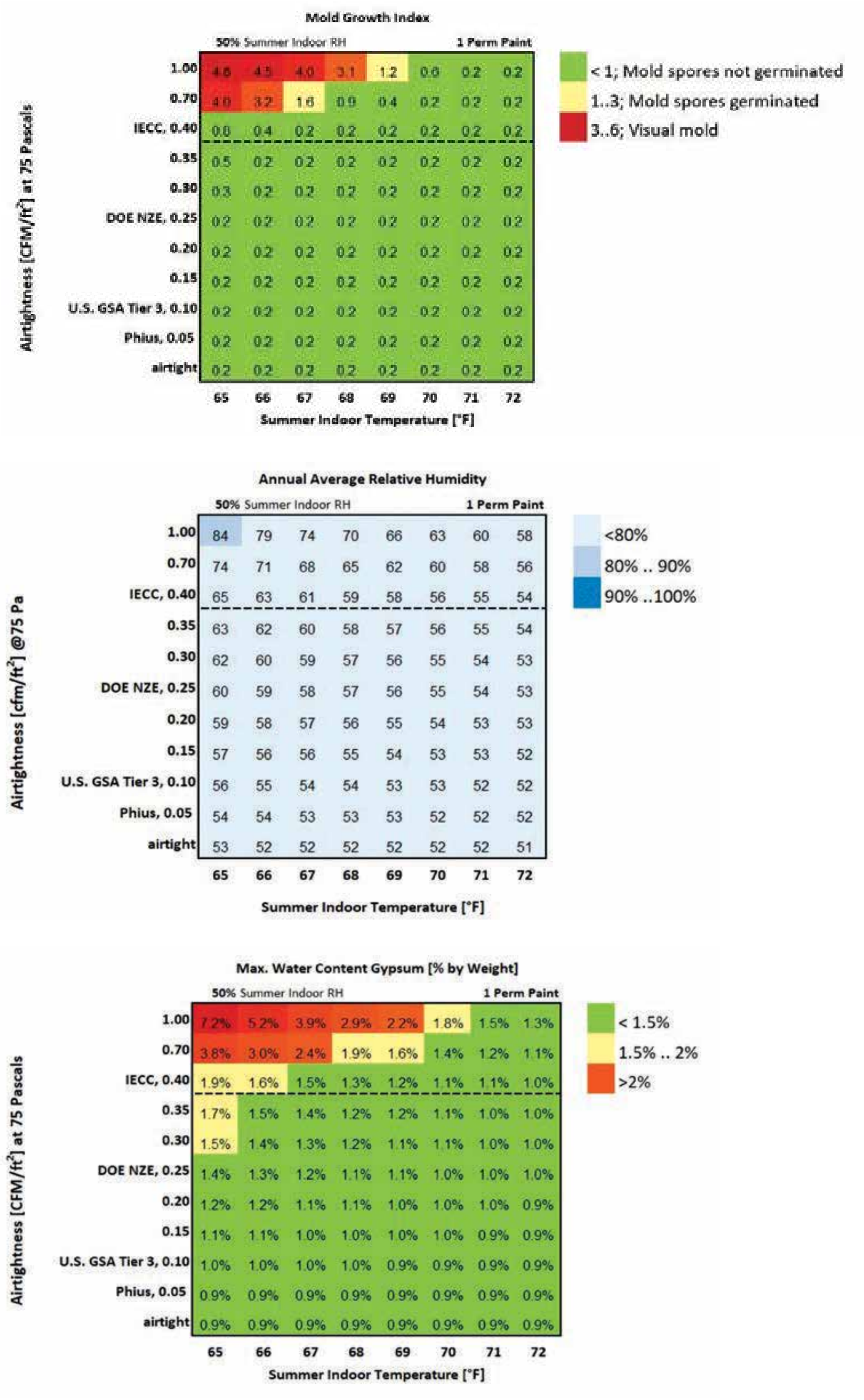
Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	71.0%	69.9%	69.0%	64.4%	49.7%	36.0%	24.0%	14.3%
0.70	69.0%	65.5%	52.7%	41.2%	30.8%	21.4%	13.5%	7.6%
IECC, 0.40	40.4%	32.5%	25.2%	18.7%	13.1%	8.5%	5.2%	3.2%
0.35	34.2%	27.3%	20.9%	15.3%	10.6%	6.8%	4.3%	2.9%
0.30	28.1%	22.1%	16.8%	12.1%	8.3%	5.4%	3.5%	2.5%
DOE NZE, 0.25	22.1%	17.2%	12.8%	9.1%	6.2%	4.2%	2.9%	2.2%
0.20	16.4%	12.5%	9.2%	6.5%	4.5%	3.2%	2.5%	2.0%
0.15	10.5%	7.9%	5.8%	4.2%	3.2%	2.5%	2.1%	1.8%
U.S. GSA Tier 3, 0.10	6.0%	4.6%	3.6%	2.9%	2.4%	2.0%	1.8%	1.7%
Phius, 0.05	3.1%	2.7%	2.3%	2.0%	1.9%	1.7%	1.6%	1.6%
airtight	1.7%	1.7%	1.6%	1.6%	1.6%	1.5%	1.5%	1.5%

Summer Indoor Temperature [°F]

🟩 < 1.5%
🟨 1.5% .. 2%
🟧 >2%

Figure A.1. Interior gypsum wallboard with vinyl wallpaper under 50% relative humidity: (a) mold growth index, (b) maximum relative humidity, and (c) maximum water content (percent by weight). DOE NZE = U.S. Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; U.S. GSA Tier 3 = U.S. General Service Administration, Level Tier 3.

Appendix: Hygrothermal Modeling Results



Mold Growth Index

50% Summer Indoor RH — 1 Perm Paint

Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	4.8	4.5	4.0	3.1	1.2	0.6	0.2	0.2
0.70	4.0	3.2	1.6	0.9	0.4	0.2	0.2	0.2
IECC, 0.40	0.8	0.4	0.2	0.2	0.2	0.2	0.2	0.2
0.35	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.30	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
DOE NZE, 0.25	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.20	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.15	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
U.S. GSA Tier 3, 0.10	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Phius, 0.05	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
airtight	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Summer Indoor Temperature [°F]

🟩 < 1; Mold spores not germinated
🟨 1..3; Mold spores germinated
🟥 3..6; Visual mold

Annual Average Relative Humidity

50% Summer Indoor RH — 1 Perm Paint

Airtightness [cfm/ft²] @75 Pa	65	66	67	68	69	70	71	72
1.00	84	79	74	70	66	63	60	58
0.70	74	71	68	65	62	60	58	56
IECC, 0.40	65	63	61	59	58	56	55	54
0.35	63	62	60	58	57	56	55	54
0.30	62	60	59	57	56	55	54	53
DOE NZE, 0.25	60	59	58	57	56	55	54	53
0.20	59	58	57	56	55	54	53	53
0.15	57	56	56	55	54	53	53	52
U.S. GSA Tier 3, 0.10	56	55	54	54	53	53	52	52
Phius, 0.05	54	54	53	53	53	52	52	52
airtight	53	52	52	52	52	52	52	51

Summer Indoor Temperature [°F]

▢ <80%
▨ 80% .. 90%
■ 90% ..100%

Max. Water Content Gypsum [% by Weight]

50% Summer Indoor RH — 1 Perm Paint

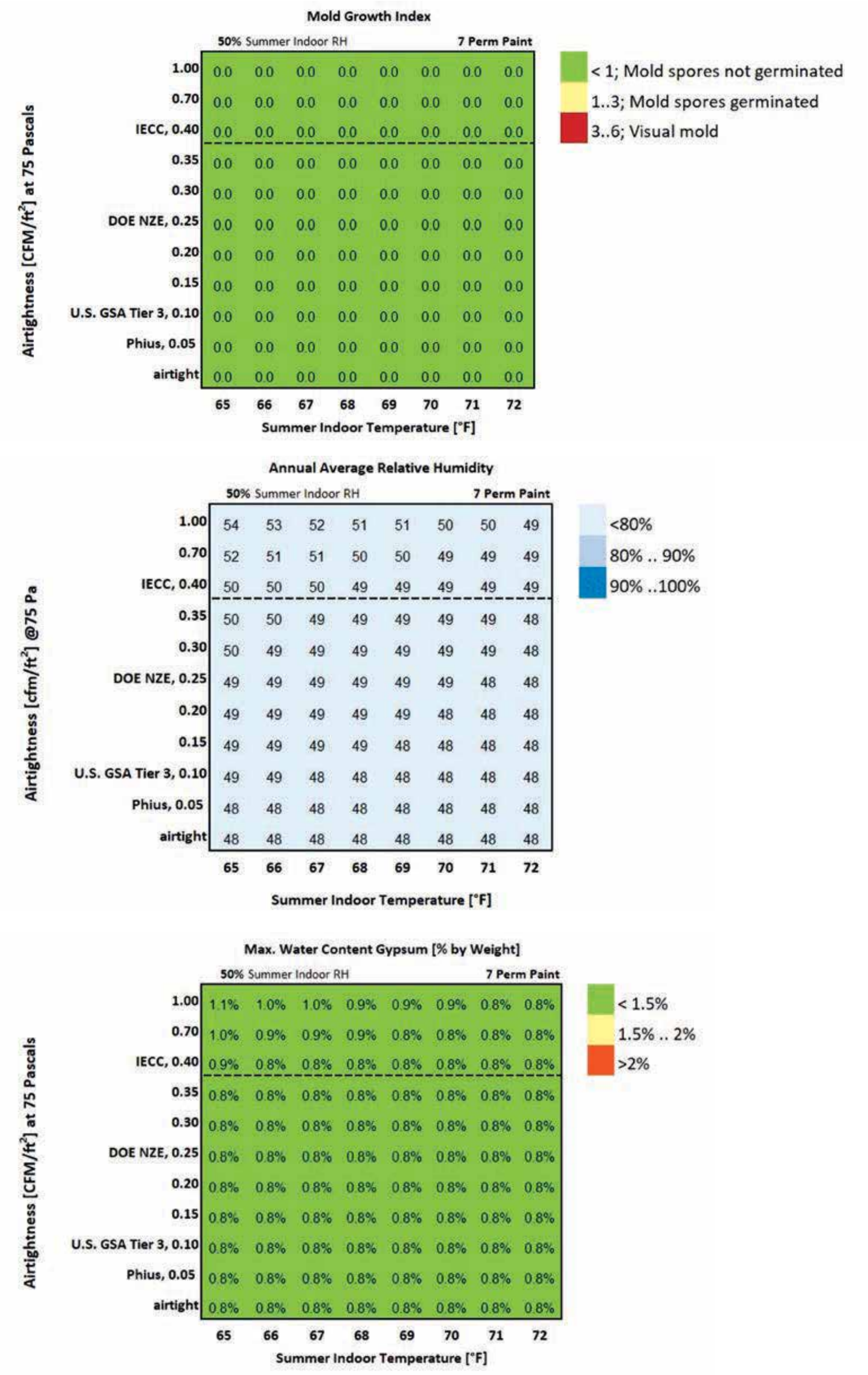
Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	7.2%	5.2%	3.9%	2.9%	2.2%	1.8%	1.5%	1.3%
0.70	3.8%	3.0%	2.4%	1.9%	1.6%	1.4%	1.2%	1.1%
IECC, 0.40	1.9%	1.6%	1.5%	1.3%	1.2%	1.1%	1.1%	1.0%
0.35	1.7%	1.5%	1.4%	1.2%	1.2%	1.1%	1.0%	1.0%
0.30	1.5%	1.4%	1.3%	1.2%	1.1%	1.1%	1.0%	1.0%
DOE NZE, 0.25	1.4%	1.3%	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%
0.20	1.2%	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%	0.9%
0.15	1.1%	1.1%	1.0%	1.0%	1.0%	1.0%	0.9%	0.9%
U.S. GSA Tier 3, 0.10	1.0%	1.0%	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%
Phius, 0.05	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
airtight	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%

Summer Indoor Temperature [°F]

🟩 < 1.5%
🟨 1.5% .. 2%
🟧 >2%

Figure A.2. Interior gypsum wallboard with 1-perm latex paint under 50% relative humidity: (a) mold growth index, (b) maximum relative humidity, and (c) maximum water content (percent by weight). DOE NZE = U.S. Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; U.S. GSA Tier 3 = U.S. General Service Administration, Level Tier 3.

Appendix: Hygrothermal Modeling Results



Mold Growth Index

50% Summer Indoor RH — 7 Perm Paint

Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IECC, 0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOE NZE, 0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U.S. GSA Tier 3, 0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phius, 0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
airtight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Summer Indoor Temperature [°F]

🟩 < 1; Mold spores not germinated
🟨 1..3; Mold spores germinated
🟥 3..6; Visual mold

Annual Average Relative Humidity

50% Summer Indoor RH — 7 Perm Paint

Airtightness [cfm/ft²] @75 Pa	65	66	67	68	69	70	71	72
1.00	54	53	52	51	51	50	50	49
0.70	52	51	51	50	50	49	49	49
IECC, 0.40	50	50	50	49	49	49	49	49
0.35	50	50	49	49	49	49	49	48
0.30	50	49	49	49	49	49	49	48
DOE NZE, 0.25	49	49	49	49	49	49	48	48
0.20	49	49	49	49	49	48	48	48
0.15	49	49	49	49	48	48	48	48
U.S. GSA Tier 3, 0.10	49	49	48	48	48	48	48	48
Phius, 0.05	48	48	48	48	48	48	48	48
airtight	48	48	48	48	48	48	48	48

Summer Indoor Temperature [°F]

<80%
80% .. 90%
90% ..100%

Max. Water Content Gypsum [% by Weight]

50% Summer Indoor RH — 7 Perm Paint

Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	1.1%	1.0%	1.0%	0.9%	0.9%	0.9%	0.8%	0.8%
0.70	1.0%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.8%
IECC, 0.40	0.9%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
0.35	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
0.30	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
DOE NZE, 0.25	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
0.20	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
0.15	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
U.S. GSA Tier 3, 0.10	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
Phius, 0.05	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
airtight	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%

Summer Indoor Temperature [°F]

🟩 < 1.5%
🟨 1.5% .. 2%
🟧 >2%

Figure A.3. Interior gypsum wallboard with 7-perm latex paint under 50% relative humidity: (a) mold growth index, (b) maximum relative humidity, and (c) maximum water content (percent by weight). DOE NZE = U.S. Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; U.S. GSA Tier 3 = U.S. General Service Administration, Level Tier 3.

Appendix: Hygrothermal Modeling Results

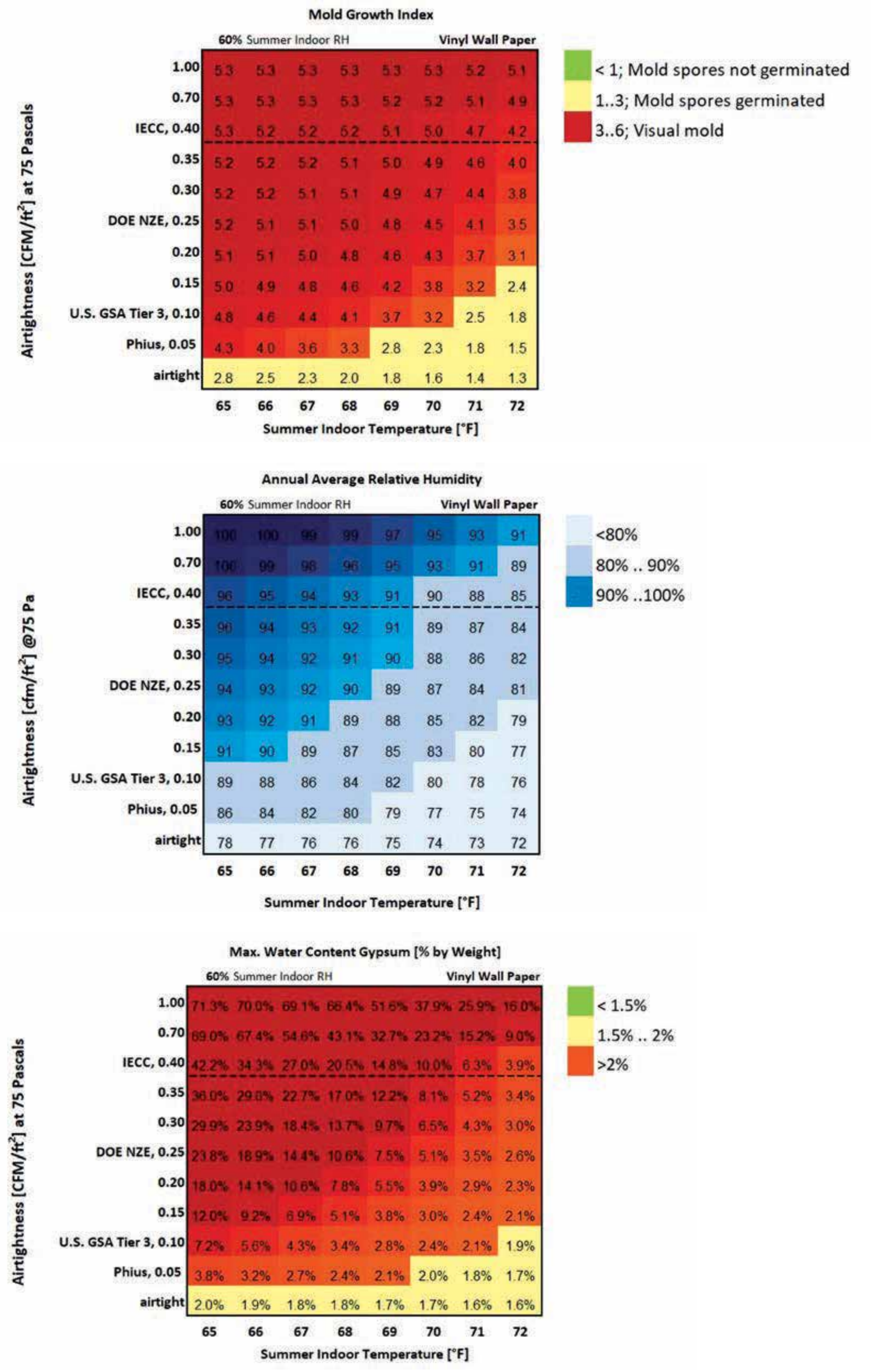
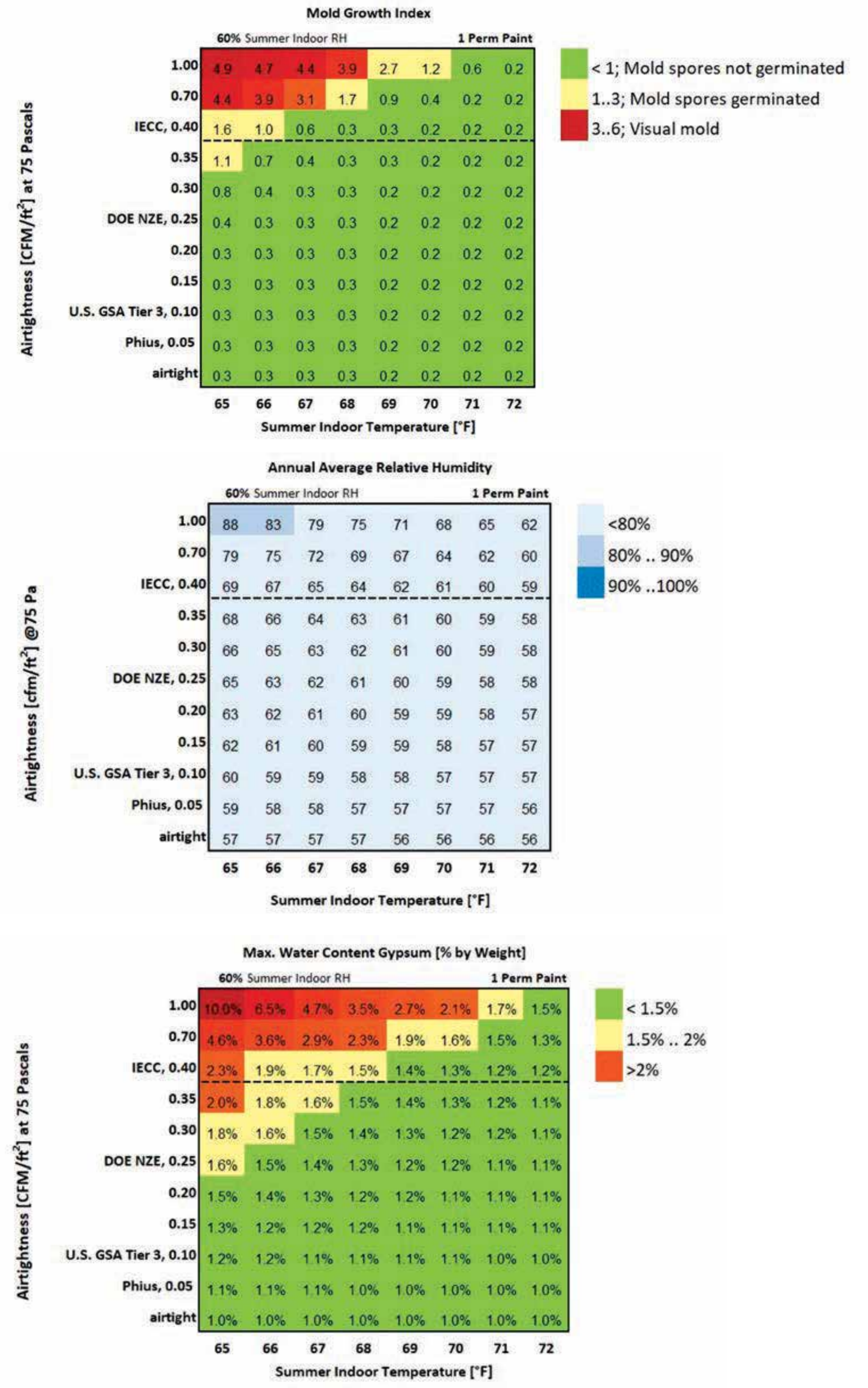


Figure A.4. Interior gypsum wallboard with vinyl wallpaper under 60% relative humidity: (a) mold growth index, (b) maximum relative humidity, and (c) maximum water content (percent by weight). DOE NZE = U.S. Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; U.S. GSA Tier 3 = U.S. General Service Administration, Level Tier 3.

Appendix: Hygrothermal Modeling Results



Mold Growth Index

60% Summer Indoor RH — 1 Perm Paint

Airtightness [CFM/ft^2] at 75 Pascals

	65	66	67	68	69	70	71	72
1.00	4.9	4.7	4.4	3.9	2.7	1.2	0.6	0.2
0.70	4.4	3.9	3.1	1.7	0.9	0.4	0.2	0.2
IECC, 0.40	1.6	1.0	0.6	0.3	0.3	0.2	0.2	0.2
0.35	1.1	0.7	0.4	0.3	0.3	0.2	0.2	0.2
0.30	0.8	0.4	0.3	0.3	0.2	0.2	0.2	0.2
DOE NZE, 0.25	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2
0.20	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
0.15	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
U.S. GSA Tier 3, 0.10	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Phius, 0.05	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
airtight	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2

Summer Indoor Temperature [°F]

- 🟩 < 1; Mold spores not germinated
- 🟨 1..3; Mold spores germinated
- 🟥 3..6; Visual mold

Annual Average Relative Humidity

60% Summer Indoor RH — 1 Perm Paint

Airtightness [cfm/ft^2] @75 Pa

	65	66	67	68	69	70	71	72
1.00	88	83	79	75	71	68	65	62
0.70	79	75	72	69	67	64	62	60
IECC, 0.40	69	67	65	64	62	61	60	59
0.35	68	66	64	63	61	60	59	58
0.30	66	65	63	62	61	60	59	58
DOE NZE, 0.25	65	63	62	61	60	59	58	58
0.20	63	62	61	60	59	59	58	57
0.15	62	61	60	59	59	58	57	57
U.S. GSA Tier 3, 0.10	60	59	59	58	58	57	57	57
Phius, 0.05	59	58	58	57	57	57	57	56
airtight	57	57	57	57	56	56	56	56

Summer Indoor Temperature [°F]

- 🟦 <80%
- 🟦 80% .. 90%
- 🟦 90% ..100%

Max. Water Content Gypsum [% by Weight]

60% Summer Indoor RH — 1 Perm Paint

Airtightness [CFM/ft^2] at 75 Pascals

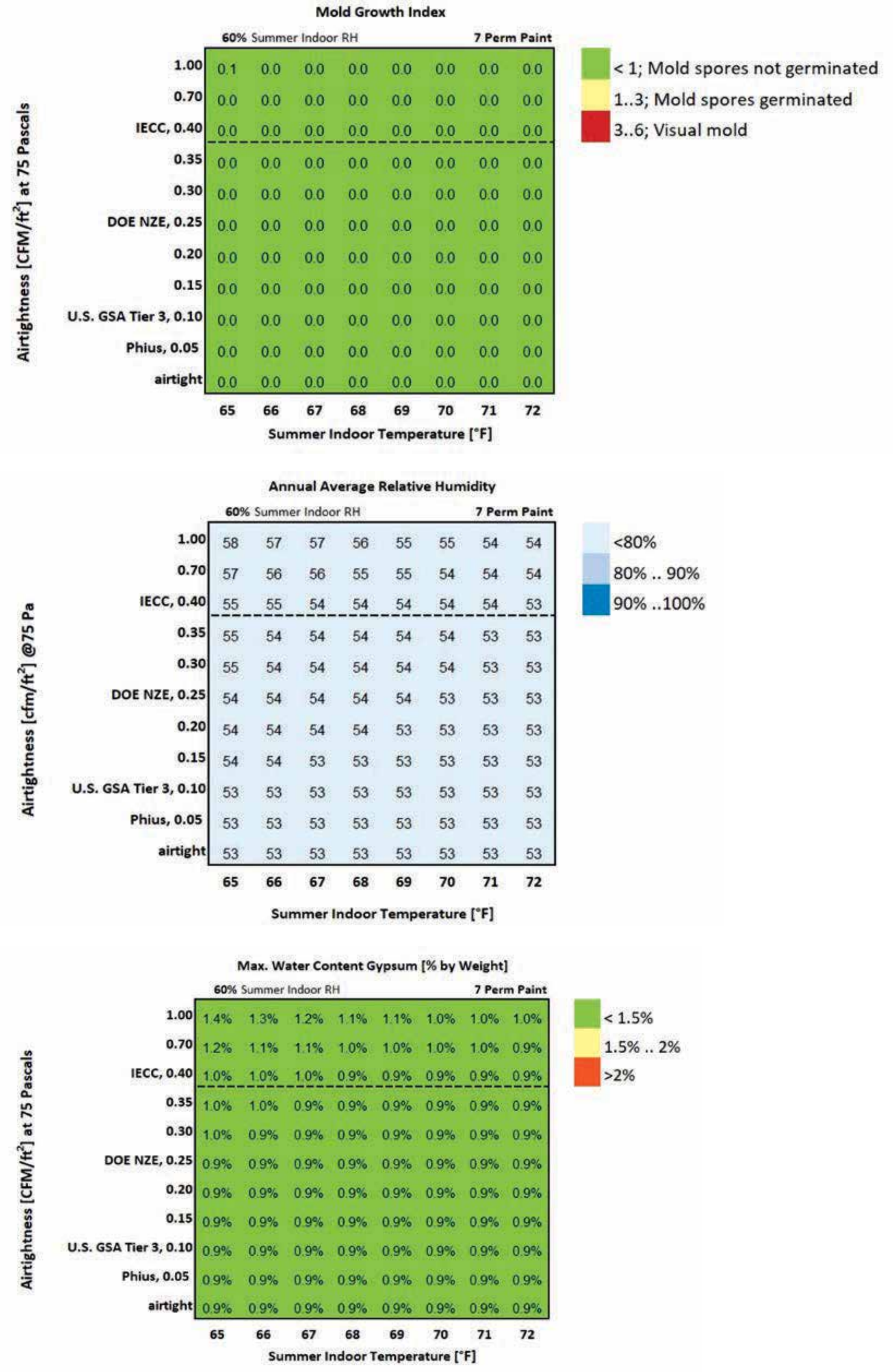
	65	66	67	68	69	70	71	72
1.00	10.0%	6.5%	4.7%	3.5%	2.7%	2.1%	1.7%	1.5%
0.70	4.6%	3.6%	2.9%	2.3%	1.9%	1.6%	1.5%	1.3%
IECC, 0.40	2.3%	1.9%	1.7%	1.5%	1.4%	1.3%	1.2%	1.2%
0.35	2.0%	1.8%	1.6%	1.5%	1.4%	1.3%	1.2%	1.1%
0.30	1.8%	1.6%	1.5%	1.4%	1.3%	1.2%	1.2%	1.1%
DOE NZE, 0.25	1.6%	1.5%	1.4%	1.3%	1.2%	1.2%	1.1%	1.1%
0.20	1.5%	1.4%	1.3%	1.2%	1.2%	1.1%	1.1%	1.1%
0.15	1.3%	1.2%	1.2%	1.2%	1.1%	1.1%	1.1%	1.1%
U.S. GSA Tier 3, 0.10	1.2%	1.2%	1.1%	1.1%	1.1%	1.1%	1.0%	1.0%
Phius, 0.05	1.1%	1.1%	1.1%	1.0%	1.0%	1.0%	1.0%	1.0%
airtight	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%

Summer Indoor Temperature [°F]

- 🟩 < 1.5%
- 🟨 1.5% .. 2%
- 🟧 >2%

Figure A.5. Interior gypsum wallboard with 1-perm latex paint under 60% relative humidity: (a) mold growth index, (b) maximum relative humidity, and (c) maximum water content (percent by weight). DOE NZE = U.S. Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; U.S. GSA Tier 3 = U.S. General Service Administration, Level Tier 3.

Appendix: Hygrothermal Modeling Results



Mold Growth Index

60% Summer Indoor RH — 7 Perm Paint

Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IECC, 0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOE NZE, 0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U.S. GSA Tier 3, 0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phius, 0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
airtight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Summer Indoor Temperature [°F]

- 🟩 < 1; Mold spores not germinated
- 🟨 1..3; Mold spores germinated
- 🟥 3..6; Visual mold

Annual Average Relative Humidity

60% Summer Indoor RH — 7 Perm Paint

Airtightness [cfm/ft²] @75 Pa	65	66	67	68	69	70	71	72
1.00	58	57	57	56	55	55	54	54
0.70	57	56	56	55	55	54	54	54
IECC, 0.40	55	55	54	54	54	54	54	53
0.35	55	54	54	54	54	54	53	53
0.30	55	54	54	54	54	54	53	53
DOE NZE, 0.25	54	54	54	54	54	53	53	53
0.20	54	54	54	54	53	53	53	53
0.15	54	54	53	53	53	53	53	53
U.S. GSA Tier 3, 0.10	53	53	53	53	53	53	53	53
Phius, 0.05	53	53	53	53	53	53	53	53
airtight	53	53	53	53	53	53	53	53

Summer Indoor Temperature [°F]

- ▢ <80%
- ▨ 80% .. 90%
- ■ 90% ..100%

Max. Water Content Gypsum [% by Weight]

60% Summer Indoor RH — 7 Perm Paint

Airtightness [CFM/ft²] at 75 Pascals	65	66	67	68	69	70	71	72
1.00	1.4%	1.3%	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%
0.70	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%	1.0%	0.9%
IECC, 0.40	1.0%	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%
0.35	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
0.30	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
DOE NZE, 0.25	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
0.20	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
0.15	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
U.S. GSA Tier 3, 0.10	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
Phius, 0.05	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
airtight	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%

Summer Indoor Temperature [°F]

- 🟩 < 1.5%
- 🟨 1.5% .. 2%
- 🟧 >2%

Figure A.6. Interior gypsum wallboard with 7-perm latex paint under 60% relative humidity: (a) mold growth index, (b) maximum relative humidity, and (c) maximum water content (percent by weight). DOE NZE = U.S. Department of Energy, Net Zero Energy Buildings; IECC = International Energy Conservation Code; Phius = Passive House Institute; U.S. GSA Tier 3 = U.S. General Service Administration, Level Tier 3.