

Quantitative and Qualitative Analysis of Thermal and Moisture Transmission Through Building Enclosures: *Upgraded Energy Code Edition*

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ABSTRACT

Many building owners and developers are concerned with the implications of upgrades in the energy code, and specifically, the requirement for continuous exterior insulation around the building enclosure. There is concern over the initial cost, the lack of information that they currently have regarding the payback period, and the question, “Will this really make a difference?” The more pertinent question, however, may be, “How will this make a difference?” The answer is not necessarily as direct as initially expected. The coupled use of hygrothermal modeling during design and performance testing of building enclosures with continuous exterior insulation during the construction of a facility provide much-needed information on how these upgraded energy requirements affect the hygrothermal performance of the exterior walls of a building. As one may expect with simulating the hygrothermal performance of the building enclosure with continuous exterior insulation, the thermal transmission through the exterior wall is substantially decreased. Inherently, with this decrease in thermal transmission, there is a decrease in moisture transport as well. When moisture content is reduced, there is, intrinsically, a decrease in thermal transmission; and from there, the cycle continues.

The author will demonstrate how hygro-

thermal modeling software can be used to predict the location of a dew point within a building enclosure assembly, and thereby, assist designers in determining the appropriate placement and permeance of air and vapor retarders when continuous exterior insulation is used, as well as what changes may occur to the traditional position of the dew point. When permeance and psychrometry are not considered in tandem with the upgraded energy code requirements, how do we stop ourselves from hurting ourselves?

INTRODUCTION

Consider a glass of iced tea on a hot summer day. Intuitively, we know that this glass is going to “sweat.” This same phenomenon can occur in building wall systems. As water vapor migrates through the building enclosure and moves toward the colder components with surface temperatures below the dew point temperature, condensation occurs on those surfaces. Condensation is the change in physical state from vapor into liquid (water) when in contact with a solid surface. Condensation in building construction can be an undesirable condition, as it may cause discomfort through humid interior conditions, biological growth, corrosion, and deterioration, as well as decreased energy efficiency of mechanical and building enclosure systems.

HVAC systems can be adjusted to

account for issues with elevated condensation levels by pressurizing the building and removing moisture through increased wall section drying potential or by increasing the temperature, which in turn allows for increased vapor storage in the air. This is impractical for a variety of reasons, not the least of which is exposing building occupants to greater discomfort.

A more appropriate method of vapor control is to design and construct the building enclosure with hygrothermal control. This creates the design necessity to manage vapor transmission and condensation formation, utilizing various approaches, including air barriers, vapor retarders, and insulation in exterior walls. Building components need to be designed and constructed in the appropriate locations to manage where condensation occurs within the wall assembly. The design intent is not to prevent condensation, but to manage where it will occur in order to minimize the effect on the building or its occupants.

The appropriate design and construction of exterior wall systems has become something of a moving target as we attempt to build lighter, more sustainable buildings. The industry is consistently learning more about how wall configuration changes will affect performance and the proper roles that air barriers, vapor retarders, and insulation should play in the ongoing transition from

the mass-wall mindset to rainscreens and drainage walls. In addition to the consideration for advanced HVAC systems, we now have the factors of permeance and diffusion to consider, which will be further discussed in this study.

As one may expect with continuous insulation (CI), thermal transmission through the exterior wall is substantially decreased when compared to walls where the insulation is not continuous (e.g., stud walls with insulation between studs). Inherently, with this decrease in thermal transmission, there is also a decrease in moisture transport. When moisture content is reduced, there is also a decrease in thermal transmission. In other words, generally, when you improve one, you improve the other.

As one of the updated provisions in the 2015 International Energy Conservation Code (IECC),^[1,2] building enclosure testing has been incorporated as a key tool in the verification of performance of the building via air leakage testing of the thermal envelope, which is now mandatory. In alignment with this provision, another key to avoiding performance issues and potentially costly failures in building design and construction has become more than just planning—it is establishing and validating that the exterior of the facility meets the owner's objectives.

This can be done through the verification process of building enclosure commissioning (BECx). It is through the holistic lens of building wall comparison throughout the commissioning process—encompassing design, construction, and testing—that this study will view performance and considerations for multiple methods of insulating exterior walls based upon the IECC prescriptive requirements. The focus of this paper will be on exterior stud walls with combinations of both CI and insulation within the stud cavity. This study is based on computer-based hygrothermal simulation and modeling. These modeled wall systems will rely upon data from previously conducted field testing for validation, as conducting field tests for each configuration and climate type has proven to be inefficient.

RESEARCH BACKGROUND

A thermal study was conducted by Kosny, Christian, and Desjarlais^[30] on effective systems for thermal insulation in metal stud wall systems. The apparent goal of this study was to determine if metal stud walls were an effective system for low-cost and energy-efficient buildings in various regions

of the world, and whether or not those systems would perform as well as wood stud walls. Research completed during this study accounts for in-depth information on system thermal performance of various insulation configurations of stud walls by use of the ASTM C236 method, which has now been replaced by ASTM C1363, *Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*. Information from the testing of the assemblies contained in the aforementioned study has shown that continuous exterior insulation has realized benefits regarding thermal transmission of wall systems.

A second study completed by Mukhopadhyaya, Ping, Kumaran, and van Reenen^[3] investigated the role of Class I, II, and III vapor retarders in exterior wood-framed stucco walls utilizing a 2-D simulation tool, hygIRC-2D.^[10] The above-referenced paper highlights the importance of placing a vapor retarder with the appropriate permeance correctly in the wall system and that the permeance of the total wall impacts moisture collection in the building components.

This paper is a collateral extension of the previously mentioned studies and utilizes the technology of a hygrothermal modeling tool that simulates heat, vapor, and moisture in one dimension. This simulator will be used to model various insulation and vapor retarder configurations in multiple climate types in North America. The intended outcome is a study that addresses the impacts of the updated IECC prescriptive insulation requirements and recommended configurations, and provides guidance on optimizing building enclosure performance.

WUFI® AND SIMULATION INPUT REQUIREMENTS

Hygrothermal modeling aids in the understanding of moisture conditions and the effects of humidity on building enclosure systems, in addition to accounting for the thermal response of those building systems and their components from thermal loading by the outdoor environment. Physically, the thermal and moisture conditions of buildings and their components are coupled

with the transfer of that heat and mass. For example, temperature conditions in a building influence moisture transport. Inversely and simultaneously, high moisture levels result in increased heat losses. The analysis of heat and moisture coupling is known as “hygrothermics.”

Warme und Feuchte instationär (WUFI) Pro 5.2^[11] is the computer software used in this study to anticipate the outcomes of the various wall systems under review by hygrothermal modeling. WUFI provides realistic, dynamic simulations regarding transient, coupled one-dimensional heat and moisture transmission in multilayered wall systems when they are exposed to various climatic conditions. Factors considered in the simulation include, but are not limited to, interstitial condensation, the influence of driving rain, airflow in the assembly, and the effects of proposed designs on building enclosure systems.

As with all software, there are many input requirements for beginning the model, and the accuracy of the model is highly dependent on the quality of the data input. With WUFI, the major considerations are: 1) components of the wall assembly, 2) orientation, 3) surface transfer coefficients, 4) initial conditions, 5) time horizon, 6) hygrothermal special options, and 7) climate information. These configurations are further expanded in subsequent paragraphs.

Components of the Wall Assembly

The basic wall assembly that was modeled in different configurations is as shown in *Figure 1*.

The material properties used for each of the building enclosure components are as outlined in the materials database in the WUFI software. The properties are as derived through detailed comparisons between known conditions and measurements taken through Germany's Institute

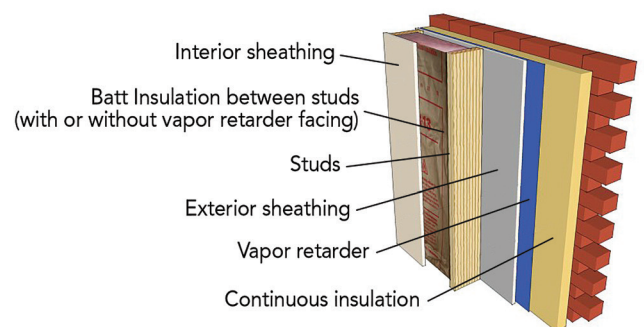


Figure 1 – Base wall assembly w/ CI, vapor retarder, sheathing, insulation, and wallboard from exterior to interior.

of Building Physics' outdoor testing and laboratory simulations.

Each component included in the WUFI materials database is comprised of basic values, such as:

1. Bulk density (lb/ft³)
2. Porosity (ft³/ft³)
3. Specific heat capacity (Btu/lb°F)
4. Thermal conductivity, dry, 10°C (Btu/h ft°F)
5. Permeability (perm in)

There are also hygrothermal functions inherent to each component included in the materials database, such as:

1. Moisture storage function
2. Liquid transport coefficient, suction
3. Liquid transport coefficient, redistribution
4. Permeability, moisture-dependent
5. Thermal conductivity, moisture-dependent
6. Thermal conductivity, temperature-dependent

7. Enthalpy, temperature-dependent

Orientation

Studies show that during a rain event, approximately 30% of bulk moisture is shed from the wall, and approximately 70% remains on the surface of the exterior cladding.^[19-21, 29] ASHRAE 160, Criteria for Moisture-Control Design Analysis in Buildings,^[29] prescribes that through vapor diffusion and conductivity, approximately 1% of the water retained on the surface penetrates through the cladding. Solar radiation that is incident on the wall surface plays a significant role in this process. Therefore, the orientation of the model is an important aspect of simulation. For the purposes of this study, the wall systems will be oriented in the worst-case scenario for the climate type for ease of data interpretation and to provide a more conservative model.

STUDIED CITIES AND CLIMATE ZONES	
Tucson, Arizona	Zone 2
Seattle, Washington	Zone Marine 4
Chicago, Illinois	Zone 5
New York, New York	Zone 4
Charlotte, North Carolina	Zone 3
Burlington, Vermont	Zone 6
Miami, Florida	Zone 1

Table 1 – Modeled cities.

radiation, and rain absorption. For the interior components, the modeler can include interior paints and other heat transfer specifics. In each model, the surface transfer coefficient has been used to model interior latex paint on the interior wallboard.

Initial Conditions

Much like the information regarding the material properties of the wall assembly contained within the software also generates initial moisture conditions for each component in the wall assembly. These initial moisture conditions are considered to be normalized. They are also derived from laboratory and field-testing data.

Time Horizon

The time horizon for this study will be three years, dated from the time of simulation.

Hygrothermal Special Conditions

These data are the inputs for options such as excluding capillary conduction or latent heat of evaporation, etc. For the purposes of this study, no special hygrothermal conditions were modeled.

Climate Information

There are several important functions of the climate information section of the data input. The first is selection of the city and/or climate type in which the simulation will take place for the exterior condition weather data. The cities that were modeled during this study were as shown in Table 1.^[1,2]

Secondly, there is the climate analysis factor in which the modeler has the ability to simulate the impacts of driving rain and sun radiation. This information is key in the selection of the aforementioned worst-case scenario orientation.

Finally, the interior climate is chosen to model the indoor conditions over the time

Surface Transfer Coefficients

These coefficients prescribe the extent to which the environment affects the most interior and exterior components in the building enclosure system. For the exterior components, the modeler can implement provisions for coatings,

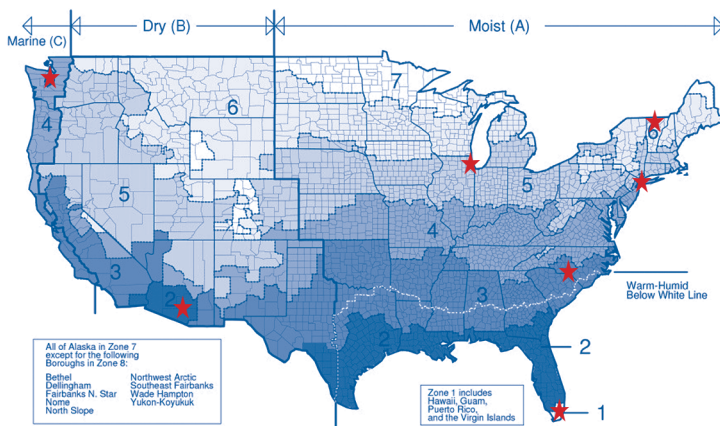


Figure 2 – Modeled city locations and corresponding climate types.

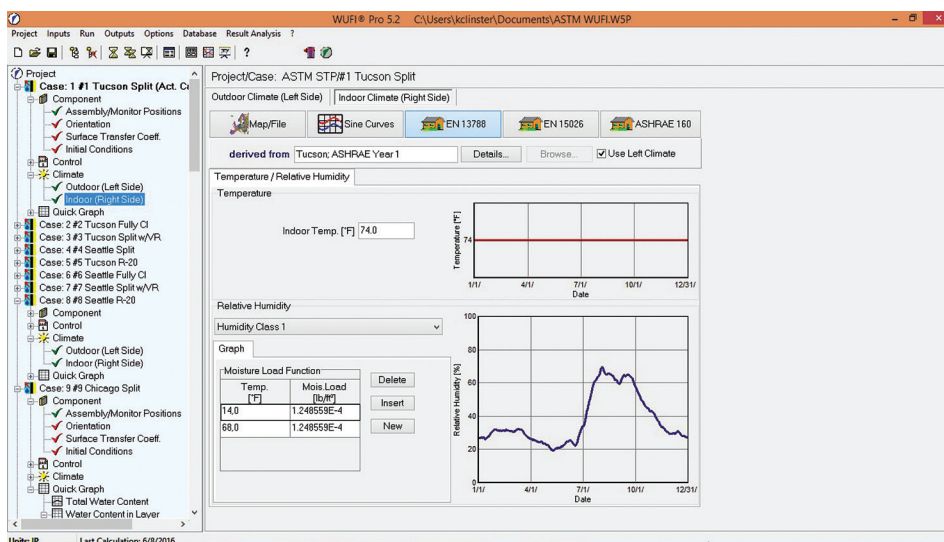


Figure 3 – Example of indoor climate model.

THERMAL ENVELOPE INSULATION COMPONENT MINIMUM REQUIREMENTS						
Climate Zone	1	2	3	4 Except Marine	5 and Marine 4	6
	All Other	All Other	All Other	All Other	All Other	All Other
Wood-Framed and Other	R-13 + R-3.8 CI or R-20	R-13 + R-3.8 CI or R-20	R-13 + R-3.8 CI or R-20	R-13 + R-3.8 CI or R-20	R-13 + R-3.8 CI or R-20	R-13 + R-7.5 CI or R-20 + 3.8 CI

Table 2 – Thermal envelope insulation component minimum requirements.

horizon. There are various options for the indoor conditions model, with those options being derived from the outdoor conditions based upon standard algorithms. This study utilizes the European Standard EN13788 for deriving indoor air humidity from the outdoor humidity using a variable moisture load, which is a function of outdoor temperature; and the interior conditions were modeled as a typical commercial facility.

STUDY PARAMETERS

Varying configurations of insulation wall components as prescribed in the 2015 IECC^[2] will be examined in the study. The variations will be simulated in seven different cities with unique climate types as stated above. A map of these cities and their unique

climate zones is shown in Figure 2.

In each city case, there will be varying wall system configurations, with the insulation type and cladding type remaining constant. The variables will be the thickness and placement of the insulation and the type of material used for the vapor retarder pursuant with the IECC requirements.

The interior conditions remained fixed at a room temperature of 74°F (23°C), regardless of the time of year or location of the modeled city. The humidity model used is Humidity Class 1 of European Standard EN13788. See Figure 3.

Unique climate-specific cases are used to simulate the impacts of differing insulation and vapor retarder configurations and products for each city modeled. A brick

veneer has been added to the base wall model in order to simulate the most realistic conditions for in-place construction. For the sheathing and interior wallboard, ½-in. gypsum board is used. The types of membranes used are a spun-bonded polyolefin material, a 1-PERM sheet product (Class II), and a polyethylene vapor retarder (Class I). The insulations used are fiberglass batt insulation in the stud cavity and extruded polystyrene in the models where continuous exterior insulation is used in varying thicknesses. The thicknesses of these two insulation types are based upon code requirements in most models and in typical standard board sizes for models beyond or outside of the building code.^[1]

In addition to the various products used

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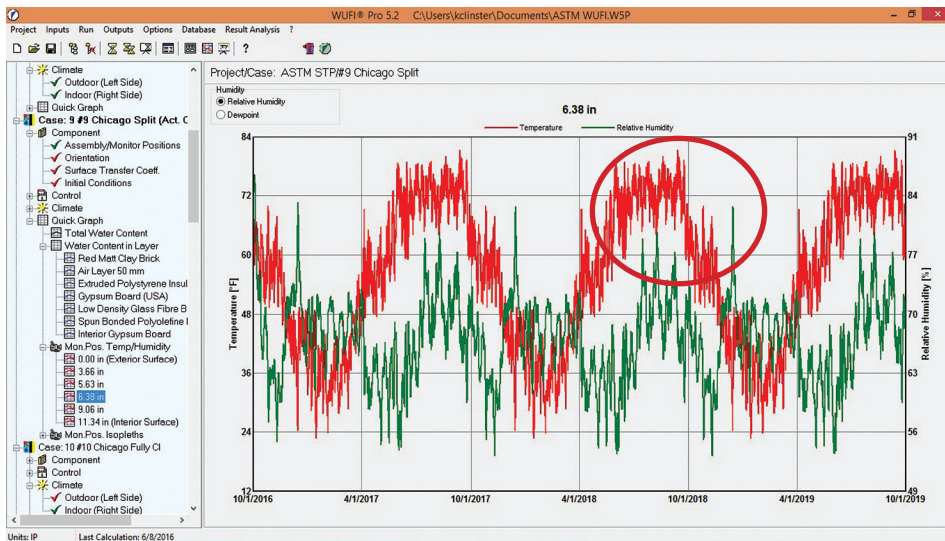


Figure 4 – RH graph with warm temperatures and isolated 80% RH days. Extended periods of 80% plus would promote mold growth.

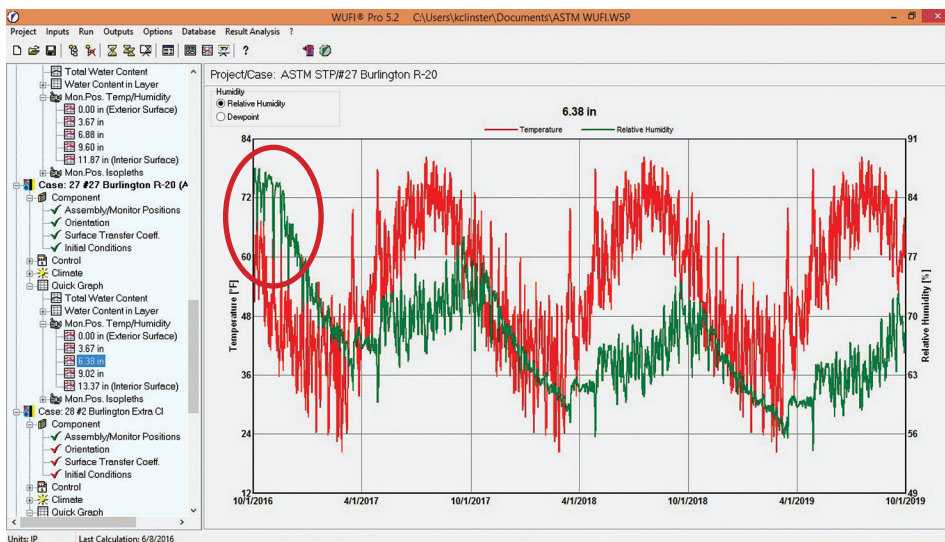


Figure 5 – RH in sheathing in Burlington, VT: R-20 + 3.8 CI.

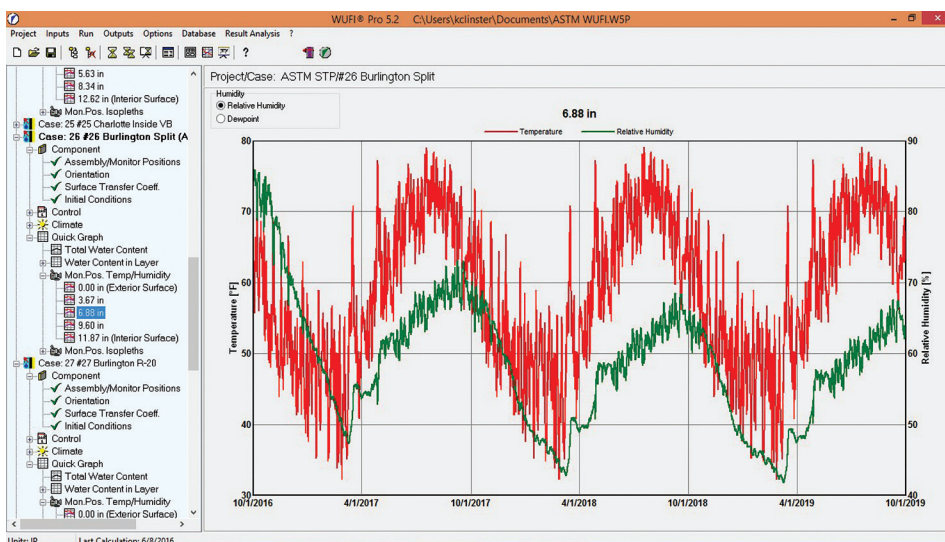


Figure 6 – RH in sheathing in Burlington, VT: vapor retarder, R-13 + 7.5 CI.

for simulation, the configurations of the wall models are also a variable in the overall simulation. The four wall systems modeled are in accordance with Table 2 from the 2015 IECC.

The climatic-specific systems are R-13 + R-3.8ci, R-20ci, R-13 + R-7.5ci, R-20, R-20 + 3.8ci, and R-25ci. The systems outside of the building code are the CI systems of R-20 and R-25. These two systems were modeled in each of the selected cities in addition to the prescriptive requirements outlined in the building code.

SIMULATION ANALYSIS

There are several categories of output collected during this study. The categories reviewed and analyzed are as follows:

1. Total water content
2. Water content in layer
3. Temperature/relative humidity (RH)
4. Temperature/dew point
5. Dynamic temperature/RH/moisture content

Each of these outputs is cross-referenced to compile the full analysis required in this study. When reviewing these outputs, several thresholds have been established to accompany known physical properties, as well as to follow traditionally accepted industry standards. In addition, there are other indicators of low-performing wall systems, such as extended periods of elevated heat and RH that do not necessarily surpass a predetermined threshold. This specific scenario is typically considered to be the most conducive for premature deterioration of wall systems.

The other previously mentioned thresholds are as follows:

1. RH at 100%
2. Intersection of temperature and dew point graphs
3. Water content in excess of allowable levels
4. Increased total water content over simulation
5. RH at or above 80% for 30 days (Figure 4), creating potential for mold growth^[29]

RESULTS AND DISCUSSION

The vapor permeance of the various vapor retarders modeled, coupled with the thermal resistance of the insulation in various configurations and thicknesses, has a tremendous impact on the overall performance of the wall systems modeled. Seven

cities were modeled with their specific climate types, with a minimum of four simulations for each city. When complete, the total number of models totaled over 35, and the ultimate number of simulations exceeded 50, as some models were simulated multiple times with slight variations. The coupling effect of heat and mass transfer was clearly illustrated in each of the climate zones, although the extent of this impact was less severe in dry climate zones. The impacts of this were most extreme in marine and the warmer, more-humid climate zones, as one would presume.

During the study, it was found that the lower the vapor permeance of the membrane, the more uniform the hygrothermal control of the wall system was found to be. It was also noted that the more insulation located outboard of the sheathing, such as with CI, the better the wall system performed from a hygrothermal control standpoint. This is outlined in representative example graphs (Figures 5-8) in order of worst to best performance. The focus of these representative graphs will be on the exterior gypsum sheathing in Burlington, Vermont, as this is the most severe case and best visually represents these findings.

It should be noted that the previously outlined thresholds for concern are exceeded for only a brief period of time for either of these models, and that is during the early winter. See Figure 5. There wasn't an increased possibility of reaching dew point in the sheathing during the simulation. However, it should be understood that these simulations focus on thermal impacts and dew point analysis and assume perfect construction without significant flashing breaches, discontinuities, etc., which would allow bulkwater intrusion. Minor inconsistencies in the wall system could increase the potential for condensation to form on the sheathing in the lower-performing wall systems as shown in Figure 9.

Higher-performing wall systems with more insulation outboard of the sheathing and a lower permeance membrane would perform as shown in Figure 10.

The amount of moisture content in the wall components followed a similar pattern, confirming the findings of these simulations regarding vapor transmission and condensation. This is known to be true, as the software models the performance of the wall system regarding bulk moisture using the ASHRAE 160^[29] model for shedding rainwater, as previously stated. Therefore,

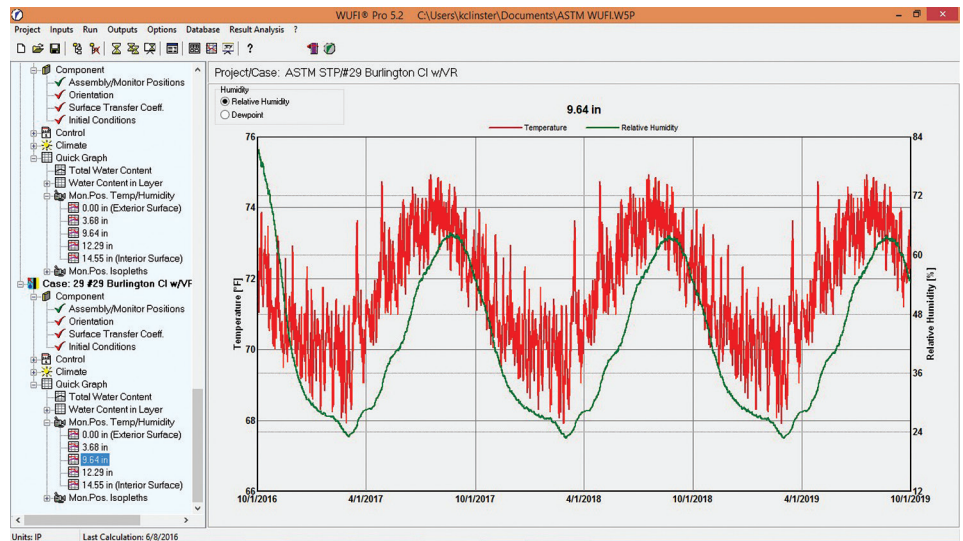


Figure 7 – RH in sheathing in Burlington, VT: fully CI with 1-perm vapor retarder.

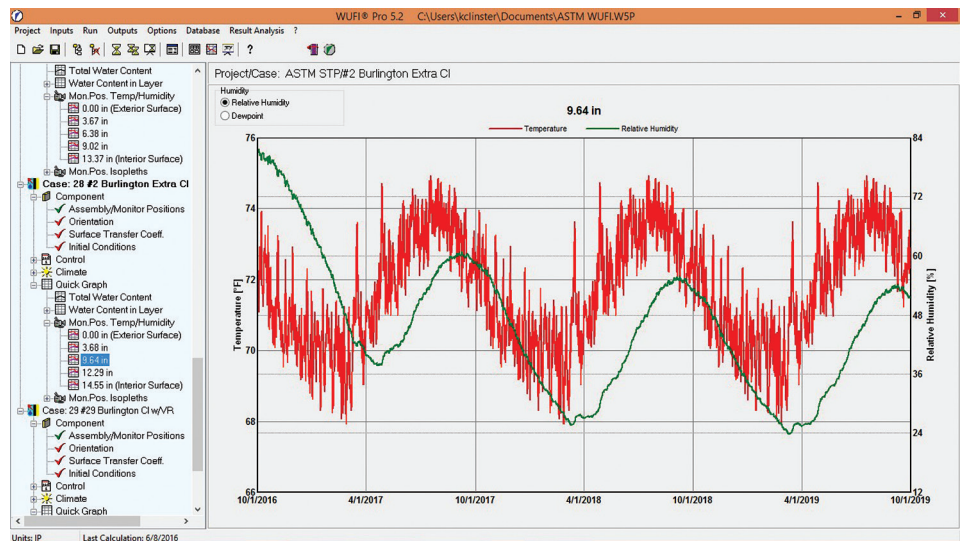


Figure 8 – RH in sheathing in Burlington, VT: fully CI with polyethylene membrane.

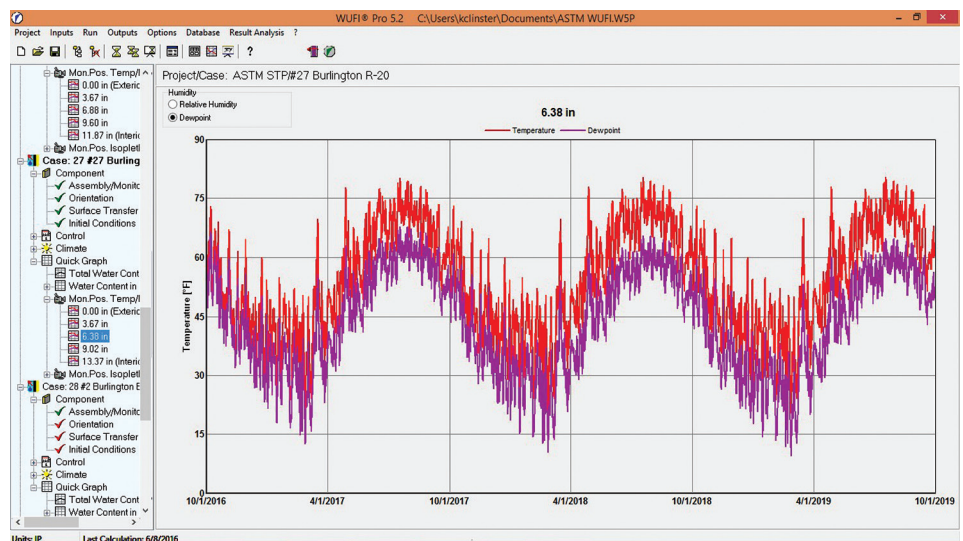


Figure 9 – Dew point in sheathing in Burlington, VT: R-20 + 3.8 CI. Less than 5°F gradient during summer.

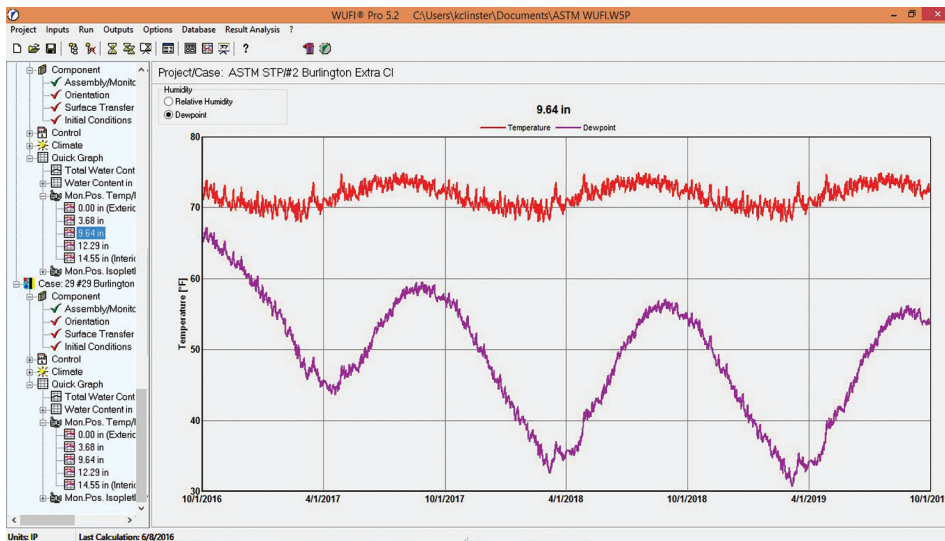


Figure 10 – Dew point in sheathing in Burlington, VT. Fully CI with polyethylene membrane at nearly 20°F minimum gradient after equilibrium.

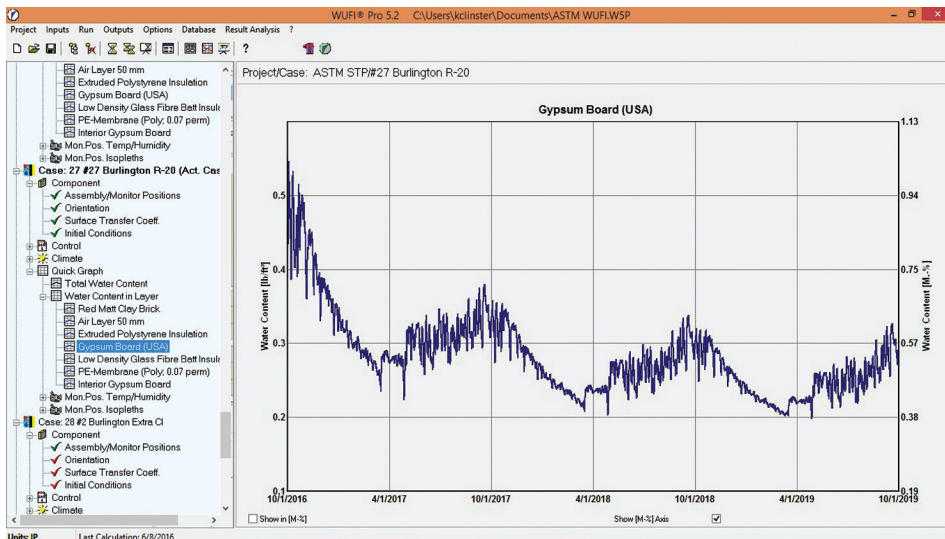


Figure 11 – Moisture content in sheathing in Burlington, VT: R-20 + 3.8 CI.

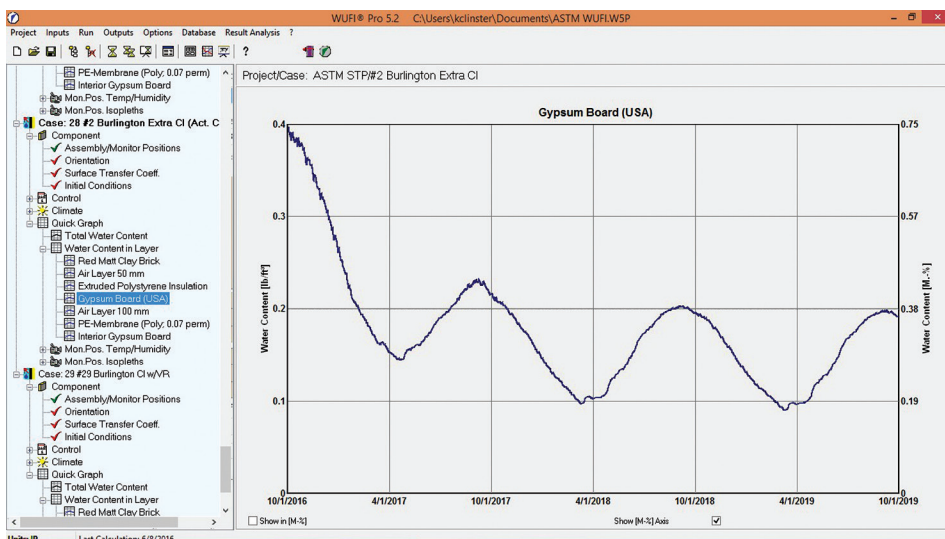


Figure 12 – Moisture content in sheathing in Burlington, VT: fully CI with polyethylene membrane.

if the cladding remains a constant across each system, then an increase in moisture content would not be due to driving rain and bulk moisture. It would be due to absorption of vapor due to less hygrothermal control of the total system. Further, the increases represented in moisture content are fractions of percentages, which implies that the absorption is that of vapor and not bulk moisture. Figures 11 and 12 represent this finding.

In order to balance these representative graphs, note that this severity is not present in all cities and climate types. To illustrate this, Figures 13 and 14 represent the hygrothermal impacts found in Tucson, Arizona, by outlining the moisture content in the exterior sheathing.

As can be seen in Figures 13 and 14, there is not the same drastic effect on moisture content increase in Tucson as there is in Burlington. This begs the question: Why does the building code require nearly the same thermal insulation configuration in climate Zones 1 through 7? And why is there ambiguity in the vapor retarder product selection and placement if there are such overwhelming impacts?

CONCLUSIONS AND RECOMMENDATIONS

The true focus of this paper is the exterior sheathing in framed design and construction. There are several reasons for this, including indoor environmental quality impacts and structural support of exterior cladding systems. When mold growth and moisture content are considered, most will look to the interior wallboard, as this is what is visible. However, the exterior sheathing is more closely the center of the wall system and acts as the base of protection from the exterior environment. Depending upon the climate type, the exterior sheathing may act as the surface for attaching the vapor retarder and continuous exterior insulation and/or serve as an initial air barrier in the wall system. Many may not consider this to be of such importance, but Figure 15 demonstrates otherwise.

The mold growth on this building component has as much impact on indoor air quality as mold growth on the interior wallboard would. Condensation only requires a temperature differential and a condensing surface. That condensing surface is very often the backside of the sheathing. Therefore, it becomes important for designers and construction professionals to consider the exte-

rior sheathing as a layer of great importance, and that is why the primary focus of this study became the exterior sheathing.

As seen throughout the course of this study, the requirements outlined by the 2015 IBC and IECC have a considerable impact on the exterior sheathing. These requirements are often considered adequate because they do not regularly cause problems that building occupants are readily aware of and report until they are directly impacted by mold. In terms of overall energy conservation, which the IECC certainly covers, it would also be of value to take a long-term view of building sustainability and optimize wall systems for higher performance alongside the code's mindset on durability. With this in mind, the list below outlines some observations produced from this study. It should be noted, however, that these observations and recommendations should only be taken in the light of the input conditions outlined herein.

1. There is a compounding negative effect on wall performance when the air transport, vapor permeance, and thermal insulation placement of a wall system are not optimized. For example, if the insulation placement is not optimized, the vapor permeance is not appropriate, and air transport is not controlled, that wall system will not perform nearly as well as one in which the insulation placement is not optimized but the vapor permeance and allowed air transport are adequate.
2. As much thermal insulation as is economically feasible and constructible should be moved outboard of the sheathing in the wall system to optimize performance, and it should be continuous to the maximum extent practical.
3. In several climate zones, splitting the insulation between the cavity and continuous exterior insulation performs well and provides a quality, economical, and constructible system. This, however, is not true for all climate zones as currently prescribed by the IECC. Further evaluation should be conducted in the climate zones with more extreme temperature gradients, such as Zones 6, 7, and 8. Designing split insulation wall systems that perform well and are durable in those climate zones is the underlying challenge.

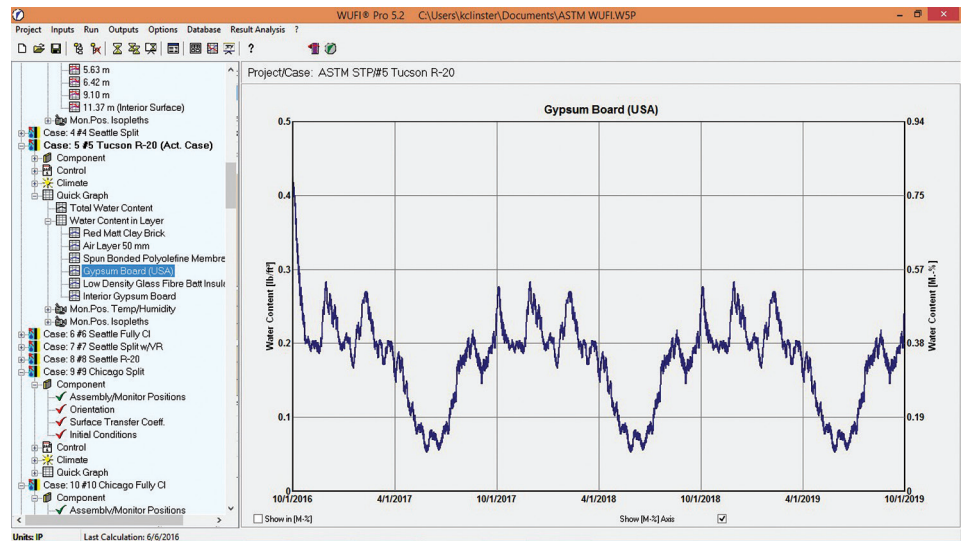


Figure 13 – Moisture content in sheathing in Tucson, AZ: R-20.

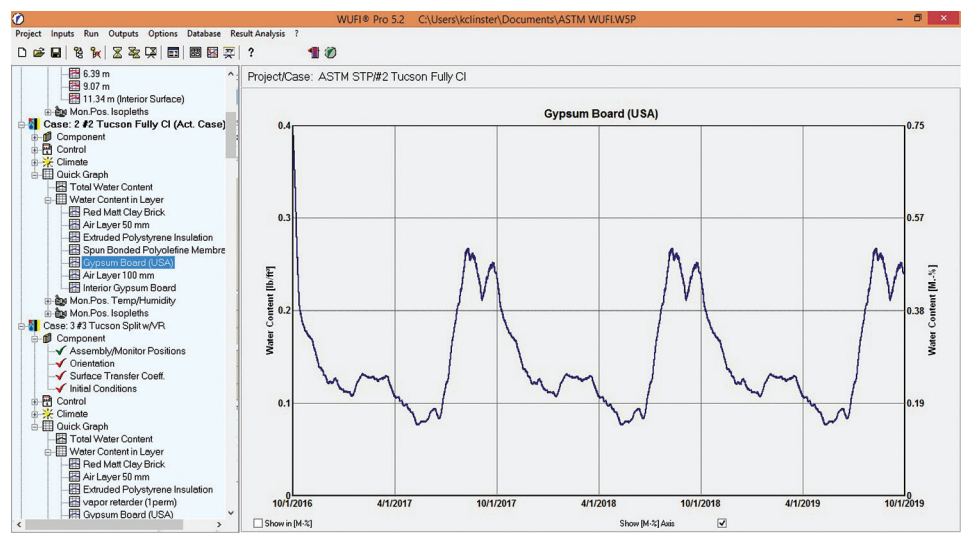



Figure 14 – Moisture content in sheathing in Tucson, AZ: fully CI.

4. A thorough understanding of the impacts of local climatic conditions and exterior wall best practices is essential to proper design. Knowledge of the building code-defined climate zones and prescribed thermal protection is also a necessity.
5. Clarity on the placement and permeance requirements of vapor retarders in wall systems for specific climate zones is critical to designing high-performing exterior wall systems. 

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Figure 15 – Mold growth on the interior side of exterior sheathing.

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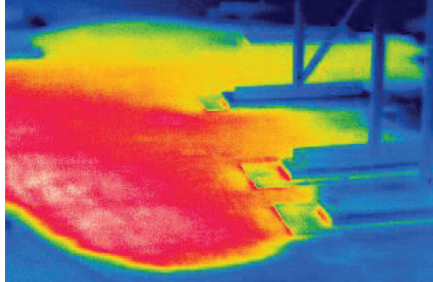
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