Prediction of Insulation Drying in Building Assemblies under Construction

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ABSTRACT

While numerical models are commonly used to evaluate the heat and moisture related performance of completed building envelope assemblies, it is sometimes necessary to predict the moisture performance of a building system and subsystems during construction, when the proper definition of the boundary conditions may be challenging. In the traditional modeling approach, the exterior climates are chosen based on actual weather data and the interior climates are typically considered to be controlled by the HVAC system. During construction, the envelope is only partially completed, and the HVAC system may not be operational. When insulation is installed using a spray system (fiberglass and cellulose are examples), moisture is added to the cavity and the builder must wait for proper drying prior to closing the cavity. Depending on the initial moisture content and the type of insulation, it may take from hours to days for the insulation to dry to acceptable levels. The present document describes an evaluation of the drying rates of damp-spray insulation, installed in a range of constructions, climates, and installation conditions using WUFI. A set of exterior and interior climates were defined, covering a broad range of temperatures and humidities, with the interior conditions represented the climate inside a building with framing, roof, sheathing, and insulation installed, but no operating HVAC system. Utilizing the defined climates and assemblies, drying rates were predicted for insulation material installed with different moisture concentrations. The resulting predictions, compared with laboratory measurements, showed that the need for drying ranged from none (0 hours) to nearly two weeks, depending on the installed conditions, climate, and construction type. These results suggest that more detailed guidance should be provided by manufacturers, to help builders prevent potential problems due to construction-introduced moisture.

INTRODUCTION

Moisture management in a building assembly may be regarded as a balance of wetting sources, assembly drying, and the assembly's safe moisture storage capacity (Straube and Burnett 2005). The wetting sources in this balance consist of moisture from the exterior of the building, moisture from the interior of the building, and construction moisture. Construction moisture is the amount of water built into the assembly, usually as a requirement of some material component. Concrete, spray-in insulation, or green lumber are common examples of materials that introduce construction moisture into a building assembly. During the design and construction of a building, construction moisture must be accounted for and managed, so as not to introduce a later potential failure mode for the building assembly. In particular, damp spray-in insulation systems, such as fiber glass or cellulose, introduce various amounts of construction moisture into framed wall cavities in thousands of residential structures every year. Most of the guidance from manufacturers to installers, builders, and building code officials, regarding when the spray-in products are 'dry', is based on laboratory studies under steady-state conditions. Steady-state laboratory conditions may be considerably different from the conditions experienced by an installed job in the field, and the manufacturer's guidance for drying time may not be accurate.

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A useful approach would be to utilize commercially available software to predict the drying of damp spray-in insulation, which allows drying to be predicted under a variety of climatic conditions and construction scenarios. However, there are some challenges associated with this approach:

- Most building performance simulation programs are designed to predict the behavior of an assembly in a finished building, with a functional heating, ventilation and air-conditioning (HVAC) system. This results in an interior climatic boundary condition that is relatively constant, and not applicable to an unfinished structure. To predict performance in an unfinished building, without an operating HVAC system, a different approach is required to define the interior climate of the building.
- The exterior climatic conditions used are typically based on actual climatic data for a specific location. To create a generally applicable guide for insulation drying, a generic set of exterior climates must be generated to simulate a broad range of temperature and atmospheric moisture conditions.

In this paper, the prediction of drying of spray-in insulation in building assemblies in a building under construction is discussed. The predictive methods used are reviewed, including assumptions and modifications to the typical application of the model. The predictive results are analyzed, including a definition of when an insulation material could be considered 'dry', with some accompanying validation measurements. Finally, extensions to this work are discussed, along with recommendations for manufacturers and installers of damp spray-in insulations.

MODEL DEVELOPMENT

Assumptions

This study utilized WUFI Pro v3.0 (Kuenzel and Kiessl, 1997), as the simulation modeling environment. The software solves the coupled transient heat and moisture transport equations in one dimension, through a system of material layers, representing an actual building assembly. The simulations account for heat flow through the material layers, via conduction and moisture transport and for water vapor diffusion, water sorption, and liquid water transport via capillarity within and through each material.

The one dimensional nature of the simulations does not account for heat or moisture transfer into framing or due to air leakage. All heat and moisture transfer was assumed to pass through the material layers, into the interior or exterior climates.

Model Parameters

The focus of the study was the drying of spray-in fiber glass insulation, installed in a residential wall construction, as shown in Figure 1. The parameters considered in the study were insulation thickness (corresponding to framing thickness), exterior sheathing materials, temperature, and relative humidity. The values of the primary study parameters, along with other parameters that were held constant, are presented in Table 1.

No interior sheathing or vapor retarder membrane was included, since the purpose of the study was to determine the amount of time required to wait before installing these elements. No exterior cladding system was included in the simulations. The effects of wind, precipitation, and solar load on the exterior surface of the assembly were not included (fixed constant at zero), to allow for the development of a general study of drying as a function of the main study parameters only. The study consisted of simulations performed for nine combinations of temperatures and relative humidities, for all combinations of values of insulation thickness, exterior sheathing, and installed insulation moisture, resulting in 72 simulation runs. The simulations were calculated with a 1-hour time step, over a period of 313 hours (13 days). All simulation runs began at noon, to represent the completion of an insulation installation.

Defining Exterior Climate

Some of the key boundary conditions applied in the simulation are determined from the exterior climate. The climatic data typically used are taken either from the weather database built in to the software, or from weather data obtained form other sources.

Rather than using existing weather data for specific locations, a set of climatic data was created, to represent a range of temperature and relative humidity conditions that would be constant, except for defined daily fluctuations. The reasons for using this approach were:

- Assuming relatively constant mean temperatures and air moisture content should be applicable over the short period of time expected to be required for insulation drying.

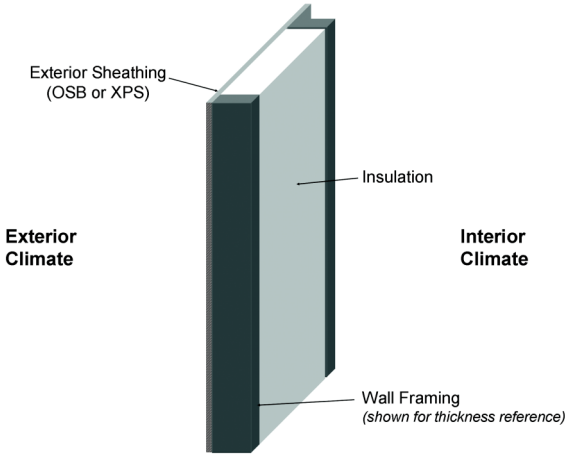

Figure 1 *Wall system used in the simulation studies.*

Table 1. Wall Parameters Used in Models

Model Parameters	Values
Insulation thickness	92 mm, 143 mm (3.625 in., 5.625 in.) (to represent nominal 2x4 and 2 × 6 framing)
Exterior sheathing material	Oriented strand board (OSB), extruded polystyrene (XPS), both 12.7 mm (0.5 in.) thick
Exterior mean temperature	0°C, 16°C, 30°C (32°F, 61°F, 90°F) Daily fluctuations = ±8°C (±15°F)
Exterior relative humidity (midpoint)	30%, 60%, 90%
Insulation density	56.8 kg/m (3.5 lb/ft)
Insulation installed moisture (by weight)	0%, 15%

- A given location does experience a broad range of temperature and humidity conditions over the portion of a calendar year when residential construction is likely to occur.

The exterior temperature was defined for each condition by

$$T_{ext} = T_{mean} + T_{range}\sin(\phi + t)\,, \tag{1}$$

where

T_{mean} = the mean exterior temperature, °C;

T_{range} = the temperature range, ± from the mean, °C;

ϕ = 0.1*π, the phase shift applied to the sine function to force one cycle to equal 24 hours, and to define the desired time for the daily high temperature, radians; and

t = the hour number of the simulation.

Relative humidity and humidity ratio are related through psychrometric relationships. The saturation vapor pressure over water can be estimated by

$$P_{ws} = 611.2 \cdot e^{\left(\frac{17.67 \cdot t}{t + 243.5}\right)}, \tag{2}$$

where

P_{ws} = the saturation vapor pressure, Pa; and

t = temperature, °C.

The vapor pressure of water in air is given by

$$P_w = \Phi \cdot P_{ws}\,, \tag{3}$$

where

P_{ws} = saturation vapor pressure of water in air, Pa; and

Φ = relative humidity, as a decimal fraction.

The humidity ratio, W, is defined as the weight fraction of water to dry air by

$$W = \frac{0.622 \cdot P_w}{P_t - P_w}\,. \tag{4}$$

Substituting Equation 3 for the P_w terms,

$$W = \frac{0.622 \cdot \Phi \cdot P_{ws}}{P_t - \Phi \cdot P_{ws}}\,, \tag{5}$$

where

P_t = total atmospheric pressure, Pa.

Equation 5 can be solved for relative humidity, Φ, in terms of W and P_{ws}, to allow Φ to be calculated as a function of P_{ws} (and hence only temperature) only, with a constant value of W.

$$\Phi = \frac{W \cdot P_t}{P_{ws}(0.622 - W)} \tag{6}$$

The form of the expression for relative humidity in Equation 6 allowed for a constant amount of water to be defined in the air (constant humidity ratio), while still allowing the relative humidity to vary with temperature, through the temperature dependence of P_{ws}, as shown in Equation 2. The humidity ratio was first calculated for the mean temperature and midpoint relative humidity for each climatic condition, and this constant value of W was used in Equation 6 to calculate the relative humidity in each simulation. Table 2 lists the humidity ratios used in Equation 6, calculated by Equation 5.

Defining Interior Climate

The remaining boundary conditions are dictated by the interior climate. Usually the interior climate is assumed to be controlled by the building's HVAC system, with the interior temperature relatively constant and the interior relative humidity based on the exterior climate, with a factor to account for interior humidity production. A building designated as "air conditioned" is simulated with a constant interior humidity. To more accurately represent the climate in a building under construction, a different approach was required.

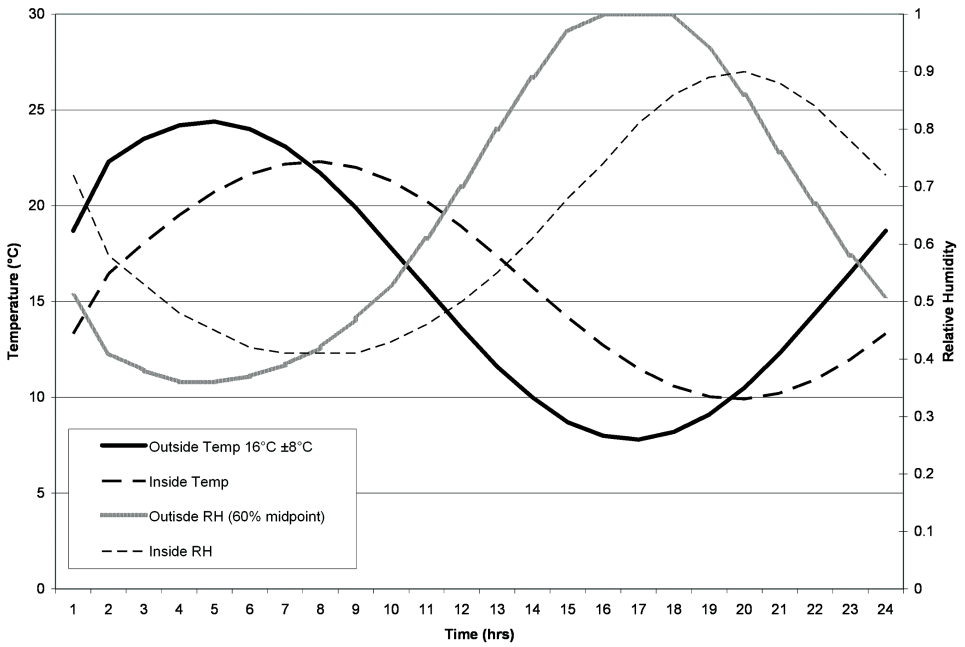

Figure 2 *Example of exterior and interior temperature and relative humidity values, showing a 24-hour cycle for the 16°C (61°F), 60% RH condition.*

Table 2. Humidity Ratios for Insulation Drying Simulations

Mean Temperature, °F (°C)	Relative Humidity Midpoint		
	30%	60%	90%
32 (0)	0.0013	0.0025	0.0038
61 (16)	0.0038	0.0076	0.0115
90 (32)	0.0101	0.0205	0.0313

The interior climates for this study were defined based on the exterior climate, with the same mean temperature and midpoint relative humidity as the exterior. To account for the time required for heat to flow through the building envelope, and for the thermal mass of air in the building to reach equilibrium, the temperature peaks were shifted two hours later than the exterior temperature peaks (high temperature at 5:00 PM). To further account for the effect of the envelope and thermal mass of the air inside the building, the range of interior temperature variation was defined to be ¾ of the range of exterior temperature variation, or ±6.2°C [±11.25°F]. The relative humidity in the interior was calculated using Equations 2 through 6, as was done for the exterior conditions, but using the interior temperature as the driving factor. Since the mean temperatures and the relative humidity midpoints were the same as for the exterior, the same humidity ratios presented in Table 2 were used for the interior relative humidity calculations. An example of the exterior and interior temperatures and relative humidities is shown in Figure 2.

Model Output

The simulation output collected was the moisture content, by weight, of the insulation for each hour. These data were then used for analysis of insulation drying. The moisture content was analyzed as a function of exterior climate, for each insulation thickness and exterior sheathing type. Figure 3 displays insulation moisture content for both installed moisture conditions, with an insulation thickness of 92 mm [3.625 in.], OSB exterior sheathing, and exposed to a 32°C, 90% RH [90°F, 90% RH] climate. The graph demonstrates the common behavior of the insulation moisture content in all the simulation runs. The insulation installed with 15% moisture dries over time, and the initially dry (0% installed moisture) insulation wets over time, both approaching an asymptotic limit at equilibrium with the local climate. Both the drying and wetting are affected by daily temperature and relative humidity fluctuations.

ANALYSIS

The analysis of the simulation data consisted of first defining drying criteria, evaluating the insulation moisture content against the criteria, and using the drying information and the installed moisture content to develop a drying guide for a specific type of spray-in fiber glass insulation.

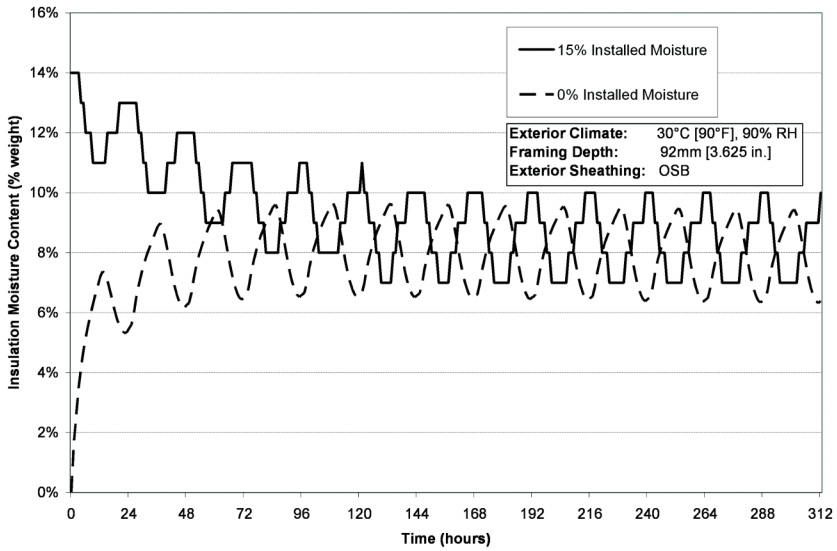

Figure 3 *Insulation moisture content versus time for 92 mm (3.625 in.) thick insulation over OSB sheathing in the 32°C (90°F), 90% RH climatic condition.*

"Dry" Criterion

In order to evaluate when the insulation material was dry, a criteria was developed based on common construction industry practice. Throughout North America, fiber glass batts and blankets are installed into buildings in nearly any climatic condition. This material is generally not conditioned in any way, except for allowing it to expand from its compressed packaging. Additionally, fiber glass batts are not considered to add any construction moisture to the assembly. In general, however, a fiber glass batt is not installed with 0% moisture, but is rather in moisture equilibrium with the surrounding climate. Analysis of the moisture content of the initially dry fiber glass (0% initial moisture content), in all of the study's climatic conditions and construction types, revealed that the highest equilibrium moisture content was approximately 10%. Since fiber glass is typically installed at this moisture content without resulting in any construction moisture related problems, 10% moisture content was chosen as the "dry" criterion for the modeled spray-in insulation.

Drying Time

An immediate consequence of the chosen drying criterion is that any insulation installed with less than 10% moisture would be considered initially "dry" and drying times were only determined for insulation installed at levels higher than 10% (15% moisture content in the present study). The drying time for insulation installed at a given moisture content, in a given exterior climate, was defined as the time, in hours, for the moisture content of the insulation to be less than or equal to the 10% moisture content. The insulation was considered dry at the first time period the criterion was met, even if the daily temperature and relative humidity fluctuations resulted in a temporary increase in the moisture content afterwards. Figure 4 graphically shows how drying time was determined, utilizing the same insulation moisture content curve for 15% initial moisture insulation shown in Figure 3.

The drying times for fiber glass insulation are presented below, in Tables 3 through 6. Tables 3 and 5 display drying times for insulation against OSB sheathing, while Tables 4 and 6 display drying times for insulation against XPS sheathing. It is interesting to note that the drying times in Tables 3 and 4, for equivalent climates, are almost identical for OSB and XPS sheathing materials. This suggests that, at or below approximately 60% R.H., the drying (and environmental wetting) of the insulation is not dependent on the water vapor permeance of the sheathing material. However, at high relative humidity (90%), the drying times for OSB sheathing systems are up to triple the drying times of XPS systems.

One possible explanation for the differences in drying times based on sheathing type could be additional wetting of the insulation, from the OSB sheathing, in the high humidity conditions. In the 90% RH climatic conditions, the relative humidity regularly reaches 100% during the coolest hours of the simulations, potentially resulting in condensation forming on the exterior surface of the sheathing materials. The OSB sheathing is water absorbent and water vapor permeable, and thus this material could absorb the condensed water, and release it as water vapor when the relative humidity lowers. However, the water vapor would likely flow to both the exterior climate, and to the insulation in the wall cavity. The vapor drive from the sheathing to the insulation during lower RH conditions would result in a re-wetting of the insulation material, and a lengthening of the overall drying time. Since XPS is not water absorbent, and is less water vapor permeable, this

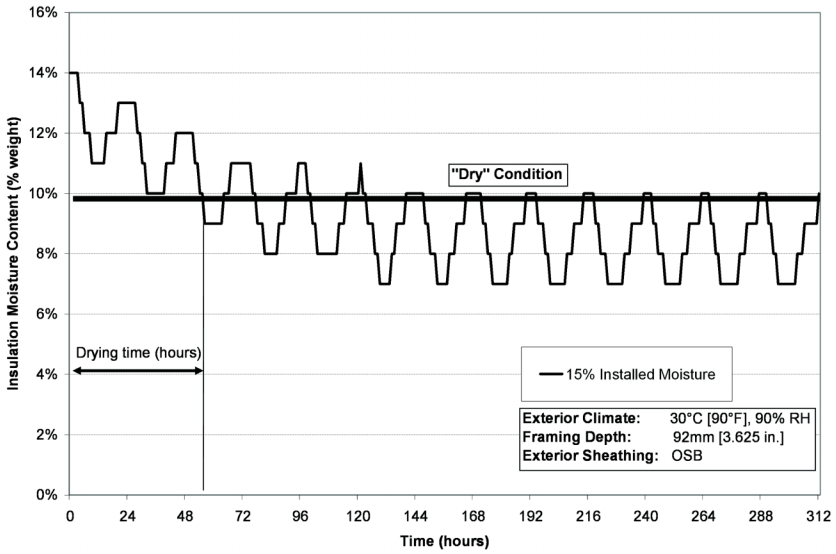

Figure 4 *Insulation moisture content versus time, as in Figure 3, graphically showing the determination of drying time.*

Table 3. Drying Time for Insulation with 15% Installed Moisture, 92 mm (3.625 in.) Thick, and Against OSB Sheathing, Hours

Mean Temperature, °C (°F)	Relative Humidity Midpoint		
	30%	60%	90%
0 (32)	10	27	105
16 (61)	6	8	56
30 (90)	4	6	33

Table 4. Drying Time for Insulation with 15% Installed Moisture, 92 mm (3.625 in.) Thick, and Against XPS Sheathing, Hours

Mean Temperature, °C (°F)	Relative Humidity Midpoint		
	30%	60%	90%
0 (32)	11	29	60
16 (61)	6	9	33
30 (90)	4	6	11

Table 5. Drying Time for Insulation with 15% Installed Moisture, 143 mm (5.625 in.) Thick, and Against OSB Sheathing, Hours

Mean Temperature, °C (°F)	Relative Humidity Midpoint		
	30%	60%	90%
0 (32)	31	56	298
16 (61)	10	28	154
30 (90)	6	9	105

Table 6. Drying Time for Insulation with 15% Installed Moisture, 143 mm (5.625 in.) Thick, and Against XPS Sheathing, Hours

Mean Temperature, °C (°F)	Relative Humidity Midpoint		
	30%	60%	90%
32 (0)	34	76	225
61 (16)	12	30	107
90 (32)	7	11	81

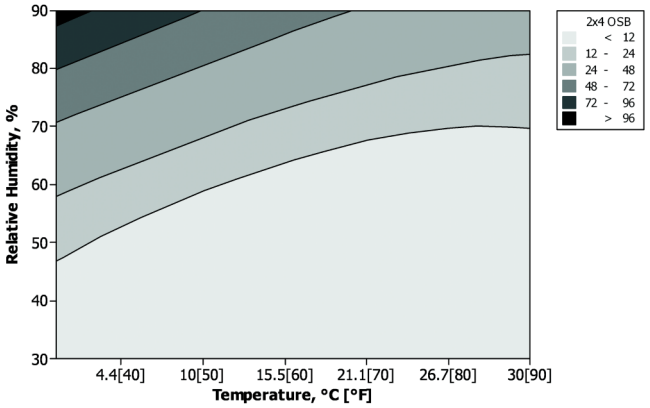

Figure 5 *Insulation drying time in a nominal 2 × 4 framed cavity over OSB sheathing. Legend values are in hours.*

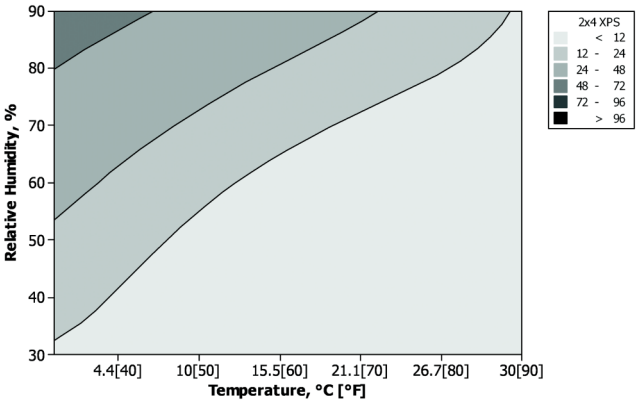

Figure 6 *Insulation drying time in a nominal 2 × 4 framed cavity over XPS sheathing. Legend values are in hours.*

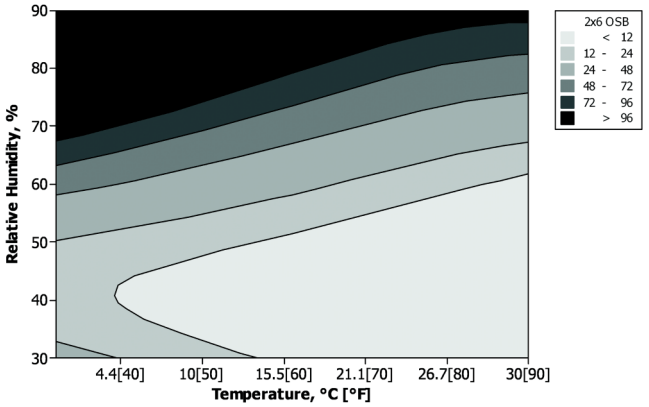

Figure 7 *Insulation drying time in a nominal 2 × 6 framed cavity over OSB sheathing. Legend values are in hours.*

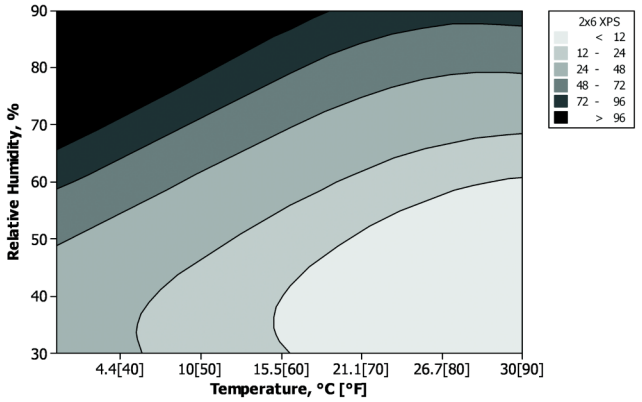

Figure 8 *Insulation drying time in a nominal 2 × 6 framed cavity over XPS sheathing. Legend values are in hours.*

re-wetting would not occur, and hence the overall drying time is shorter. A similar trend is present in Tables 5 and 6, for the 143 mm [5.625 in.] thick systems. A more detailed examination of the simulation runs is necessary to determine if this chain of events occurs during the 90% RH simulations.

The drying time data were also presented as contour plots, to be more useful as a guide to installers. This was done by analyzing the drying time values versus temperature and relative humidity with regression methods. The drying time contour plots are shown in Figures 5 through 8. The contour ranges were chosen to correspond to recommendations that would be meaningful to insulation installers, builders, and code officials.

Validation

The validity of the simulation approach used in this study was checked in two ways. Insulation moisture content from this study was compared to simulations utilizing climatic data from cities in the WUFI database as the exterior boundary conditions, and to insulation moisture content in laboratory measurements.

Simulation comparisons were performed utilizing the wall assembly consisting of 92 mm [3.625 in.] thick insulation, and OSB exterior sheathing. The climatic data selected for the comparisons is listed in Table 7. The cities and calendar periods were chosen so as to approximate the exterior climatic conditions used in the original study. Figures 9 through 13 present the comparisons of insulation moisture content versus time, for the first 160 simulation hours, for the five validation cases. As would be expected, the moisture content curves are similar for similar climates. Differences in the phase of the moisture content curves was likely due to the fact that the climate files from the WUFI database begin a midnight on the selected date, whereas the simulated climate files began at noon, to more closely represent when an actual insulation installation might be completed. Notable differences in moisture content were for comparisons in high-humidity climates: 32°C [90°F]- 90% R.H versus Houston, TX in July, and 0°C [32°F]- 90% R.H versus Vancouver, BC in February. In the 32°C [90°F]- 90% R.H compared to Houston, TX in July case (Figure 10), the climate was not as humid as the simulated climate. The resulting increased drying potential would partially explain why utilizing the Houston climatic data resulted in faster insulation drying. In the 0°C [32°F]- 90% R.H compared to Vancouver, BC in February case (Figure 13), the insulation moisture content actually increases from the initial condition, when exposed to the Vancouver database climate. This was due to precipitation events which introduced

Table 7. WUFI Database Cities for Comparison to Simulated Exterior Climatic Conditions

Simulated Environmental Condition (Midpoint)	WUFI Database			
	City	Dates	Mean Temperature, °C	Mean Relative Humidity
32°C, 30% RH	Salt Lake City, UT	July 1–14	24	29%
32°C, 90% RH	Houston, TX	July 1–14	28	78%
16°C, 60% RH	Pittsburgh, PA	April 1–14	6	68%
0°C, 30% RH	Billings, MT	February 1–14	4	47%
0°C, 90% RH	Vancouver, BC	February 1–14	3	89%

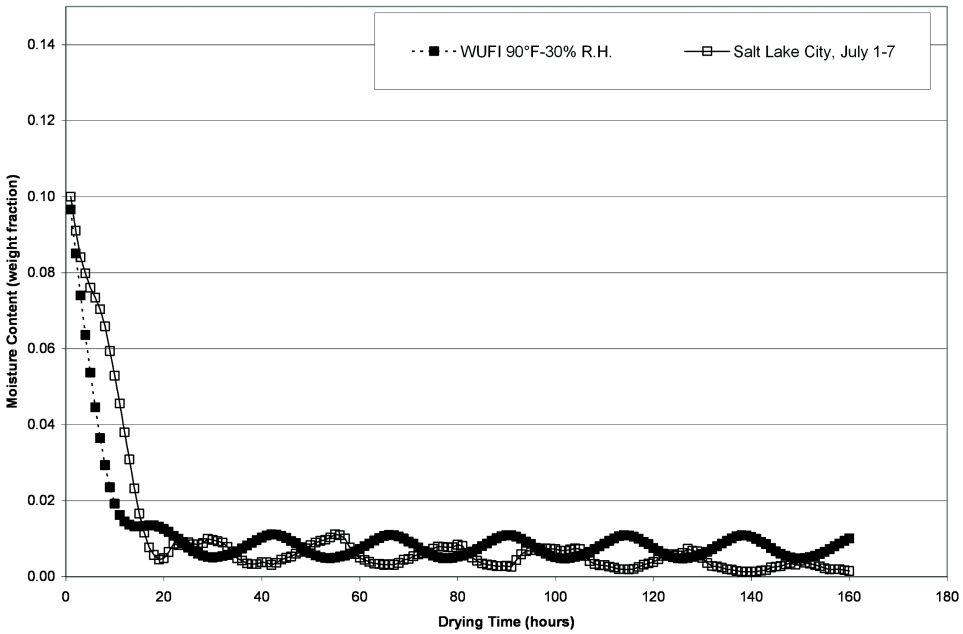

Figure 9 *Insulation moisture content versus time from WUFI simulations utilizing artificial and WUFI database exterior climates: comparison of 32°C, 30% RH condition and Salt Lake City, Utah, July 1–7.*

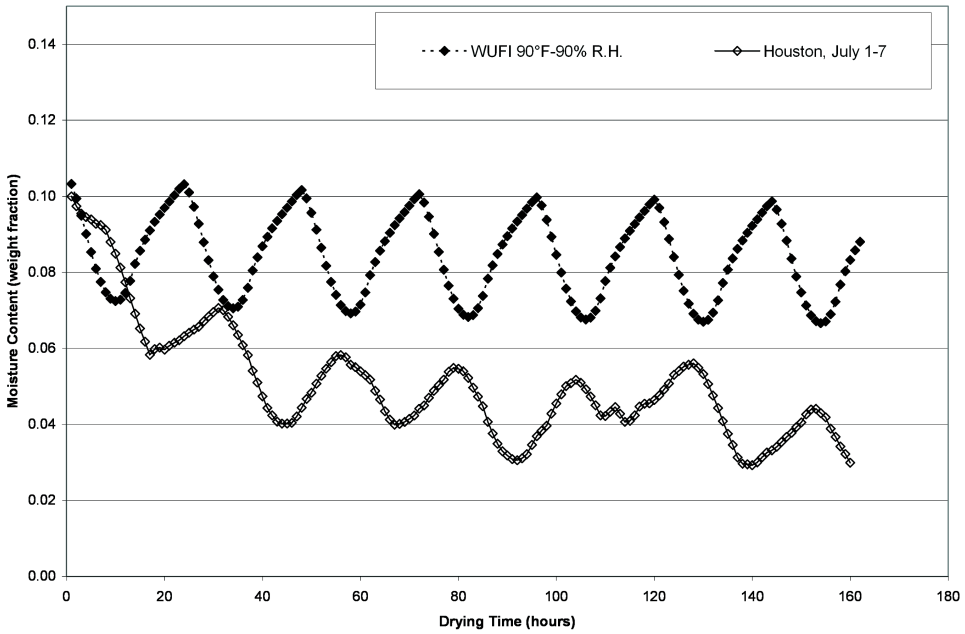

Figure 10 *Insulation moisture content versus time from WUFI simulations utilizing artificial and WUFI database exterior climates: comparison of 32°C, 90% RH condition and Houston, Texas, July 1–7.*

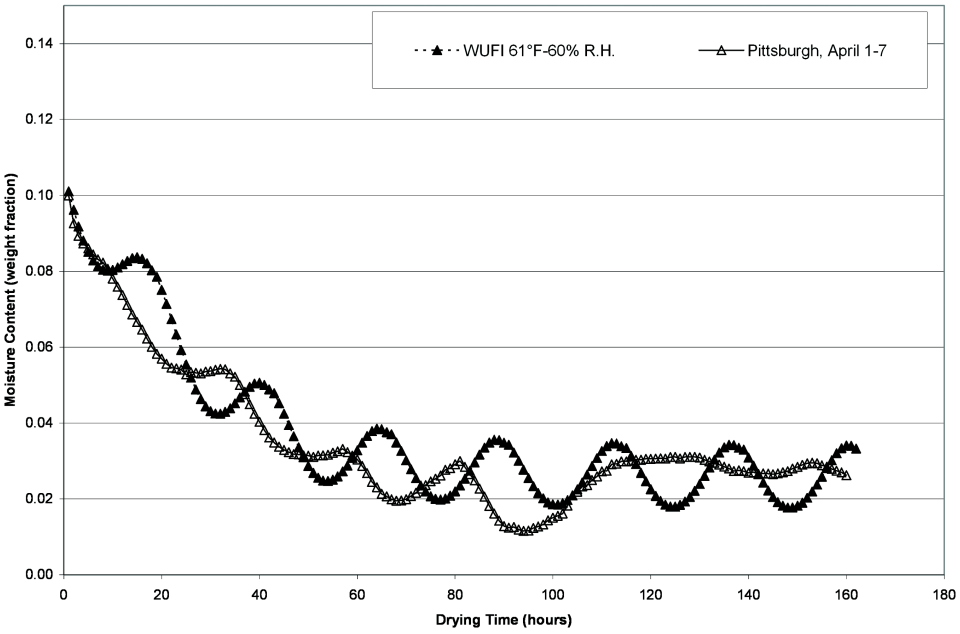

Figure 11 *Insulation moisture content versus time from WUFI simulations utilizing artificial and WUFI database exterior climates: comparison of 16°C, 60% RH condition and Pittsburgh, Pennsylvania, April 1–7.*

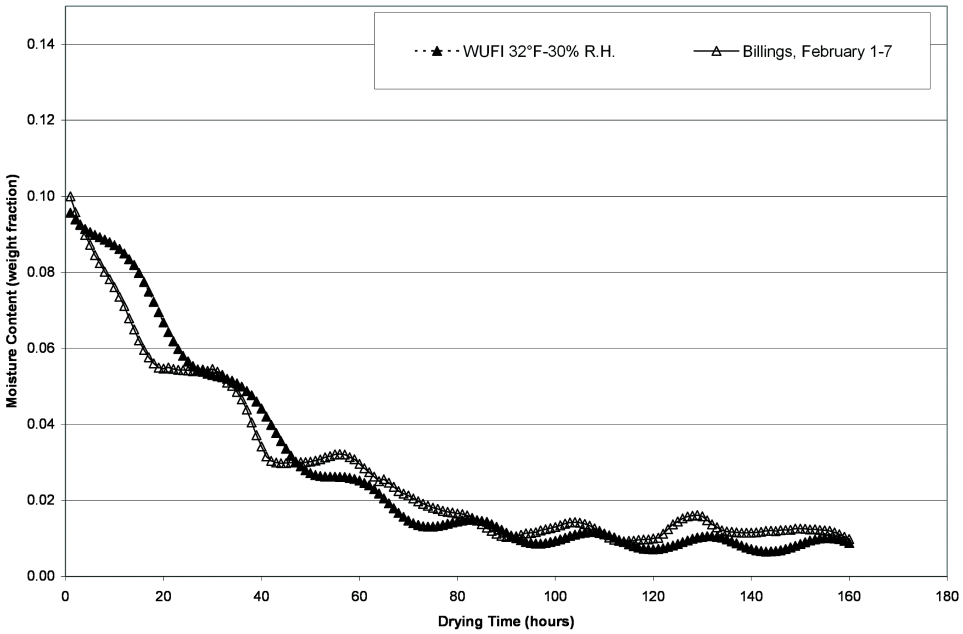

Figure 12 *Insulation moisture content versus time from WUFI simulations utilizing artificial and WUFI database exterior climates: comparison of 0°C, 30% RH condition and Billings, Montana, February 1–7.*

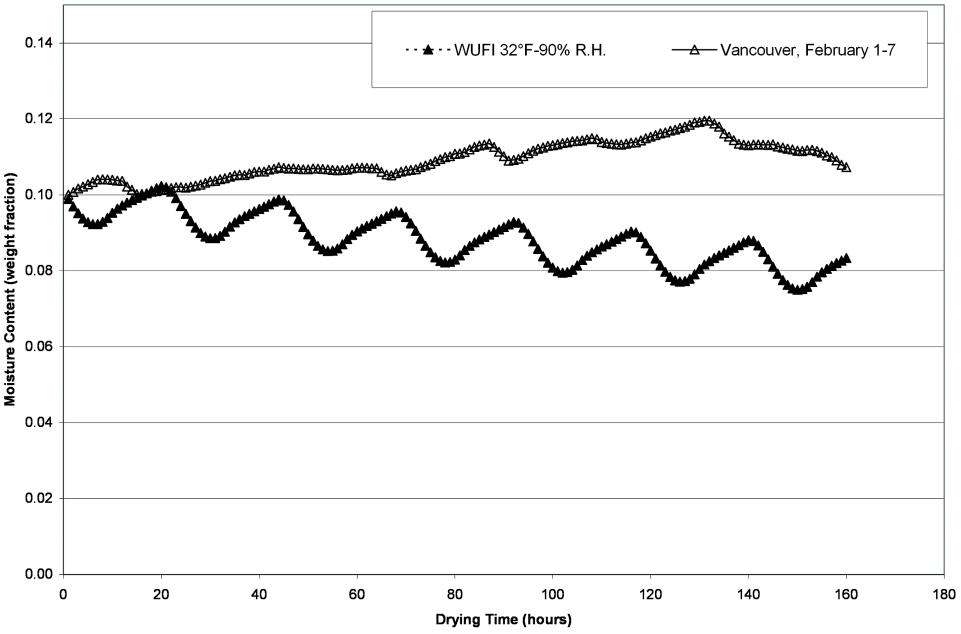

Figure 13 *Insulation moisture content versus time from WUFI simulations utilizing artificial and WUFI database exterior climates: comparison of 0°C, 90% RH condition and Vancouver, British Columbia, February 1–7.*

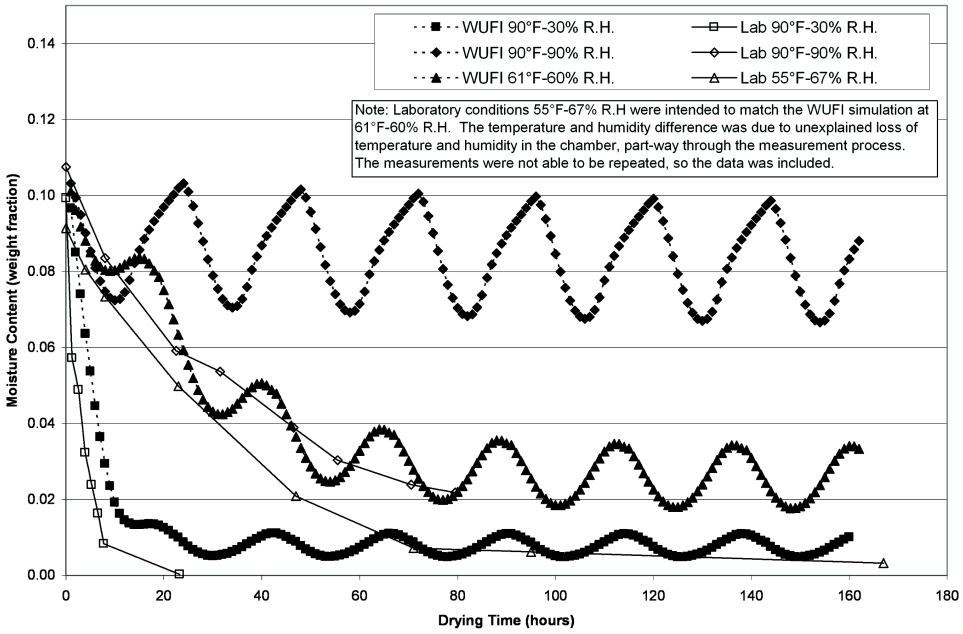

Figure 14 *Comparison of insulation moisture content versus time from USFI simulation and laboratory measurements: 92 mm (3.625 in.) thick insulation over OSB sheathing with 10% installed moisture content. Solid symbols represent the WUFI simulations, and the corresponding empty symbols represent the laboratory measured data.*

additional moisture into the system. These events, combined with reduced drying potential due to the cold temperatures and high humidities, may explain the considerable differences in insulation moisture content in Figure 13. The differences in simulation results for the 90% relative humidity conditions illustrate one of the areas for further work to develop an accurate, generalized simulation tool.

For laboratory validation, frames were constructed from polycarbonate panels, to create of a set of 305 mm [12 inch] square cells. Only 92 mm [3.625 in.] deep cells were tested in the laboratory. Two frames sets were constructed, each consisting of a 6x4 grid of sample cells, with OSB and extruded polystyrene each used to back one frame set, to represent a sheathing material. The cells were installed with spray-in fiber glass, at nominal 10% initial moisture content and at a density representing a thermal value of R-15. Both frame sets were then placed into controlled environmental conditions: 30°C [90°F] & 90% RH, 30°C [90°F] & 30% RH, and 13°C [55°F] & 67% RH. The laboratory test samples were installed into individual framed cells so that one cell could be completely removed for moisture content analysis with minimal disturbance to the remaining samples. The environmental chamber maintained a steady-state environment, rather than the cyclic environment of the WUFI simulations. Each measurement period, three (3) sample cells were emptied and individually measured for moisture content, by weight percent. Figure 14 displays comparisons of the drying curves for the laboratory samples installed with OSB sheathing with the corresponding simulations from the study. The overall shapes of the drying curves were comparable, though the laboratory measurements consistently demonstrated a faster drying rate than in the WUFI simulations. Comparisons between WUFI and laboratory measurements with XPS sheathing displayed similar behavior to the graphs in Figure 14. The increased drying rates in the laboratory conditions are likely due to convection and evaporation at the boundary, not accounted for by WUFI. To maintain relatively uniform temperature and humidity, fans are continually operating in the chamber, resulting in a noticeable air flow over the face of the samples. Measurements were not performed in this study to enable calculation of convective and evaporative moisture loss. However, the difference in the drying rates between the lab and simulations in Figure 14 suggest that the effect of convective and evaporative moisture removal can be considerable. This would especially be the case when environmental conditions are such that diffusion is not as effective, such as in high relative humidity.

CONCLUSIONS

This study demonstrated that transient hygrothermal modeling software can be used to predict the drying of spray-in, fibrous insulation materials in light residential construction. Furthermore, instead of using existing weather data to model a building in a specific location or climatic zone, artificial interior and exterior climatic data can be used to create a generic set of drying recommendations. These results show that the amount of time a spray-in insulation should be allowed to dry depends not only on the installed moisture content of the

insulation, but also on the climate, the construction type (framing depth), and even the type of exterior sheathing material used. The variability in this study's recommended drying times is contrary to the typical guidance provided to insulation installers or homebuilders by most insulation manufacturers, which is typically based only on the installed moisture content, and very general "rules of thumb." This is especially true in cold, damp climates, where the drying potential of any damp material is greatly reduced. For these climates, the simulations suggest that either the insulation could take many days to dry, or that space heaters may be needed to accelerate the insulation drying.

Risk factors of moisture-related building failures could be further reduced with the development of more comprehensive parametric studies, beyond those presented herein, evaluating the moisture added into the building from spray-in insulations, and how this moisture is removed in various construction scenarios.

While this study focused on damp sprayed-in fiber glass insulation, the approach described is applicable to any other spray-in insulation materials, so long as the hygrothermal properties required to perform the simulations are known. This approach could certainly be used to predict drying rates in a specific locale, using local weather data as the exterior boundary condition. However, an artificial interior boundary condition would still be needed, to reflect the probable lack of an operating HVAC system in the building. Potentially useful extensions of this study would be to explore insulation drying in very cold climates, with mean temperatures of -10°C or less, and to incorporate exterior climatic conditions that have been excluded from this study, such as solar radiation, wind, and precipitation striking the exterior sheathing. These additional factors would certainly be useful for predicting building assembly behavior at a specific locale, with a known climate and building orientation.

Field experiments could improve the understanding of the drying behavior of recently applied spray-in insulation in real applications.

REFERENCES

ASHRAE. 2005. *ASHRAE Handbook of Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Hall, C., W.D. Hoff, and M.R Nixon. 1984. Water movement in porous building materials—VI. Evaporation and drying in brick and block materials. *Building and Environment* 19(1):13–20.

Kuenzel, H.M., and K. Kiessl. 1997. Calculation of heat and moisture transfer in exposed building components. *Int. J. Heat Mass Transfer* 40(1)159–67.

Straube, J.F., and E.F.P. Burnett. 2005. *Building Science for Building Enclosures*. Westford, MA: Building Science Press. Westford.