Technical Paper #4

Hygrothermal Analyses of Ammonia Refrigeration Pipe Insulation Systems

Gordon H. Hart, P.E.
Artek Engineering, LLC

Christian Bludau, Dipl.-Ing.
Fraunhofer Institute for Building Physics

Introduction

Hygrothermal computer analyses can be used to model how much moisture accumulation, in the form of both condensed water and ice, is likely to occur in a refrigeration pipe insulation system. Hence, these analyses may be a valuable tool to estimate the useful life of a refrigeration pipe insulation system. Such analyses can also be used to model various insulation systems exposed to different environmental conditions. To determine how several thermal insulation systems on ammonia refrigeration pipes would perform over time, a study used a computer model to perform hygrothermal analyses, thereby predicting simultaneous heat and moisture transfer. This study modeled several variables, including one pipe temperature and pipe size, three different insulation materials both without and with a particular film type vapor retarder, and a certain number of years, and input standardized annual hourly weather data from three U.S. cities.

Background

A refrigeration pipe is typically thermally insulated for three reasons: to reduce energy use caused by heat gain, to transfer energy through pipes in a controlled fashion, and to limit surface water vapor condensation. The frequency of water vapor condensation at the outer insulation surface can be greatly reduced with an adequate insulation system design that combines insulation thermal conductivity, insulation thickness, and outer surface emittance (see [1] for further discussion). Water vapor condensation at the cold pipe surface and within the insulation itself is limited by having a low water vapor permeance, which is achieved with one of three methods: (1) a low permeance, sealed outer insulation jacket (which may or may not also be a protective jacket); (2) a low permeability, sealed insulation material; or (3) a combination of the two. Regardless of how low the system permeance is, some water vapor in the warmer ambient air, which has a higher vapor pressure, will migrate over time to a lower temperature surface with a lower vapor pressure, namely that at the surface of the cold, refrigerated pipe. If a zero permeance insulation system could be achieved (i.e., a perfect system, which cannot in practice be achieved), then no water vapor would migrate to the cold pipe over time.

A low-permeance insulation system increases the length of time required for a certain quantity of water vapor to reach the cold pipe and condense. As time passes, the increasing condensed water vapor, which may be in the form of ice or water, will fill voids within the insulation itself. As this happens, the insulation materials' thermal conductivity will increase as well, rendering it less effective. Hence, while a low but nonzero permeance increases the useful life of the pipe insulation system, it cannot ensure that the system will effectively do this forever. Water vapor pressure difference and time, together, are the two enemies of a refrigeration pipe insulation system.
A case study by Hart [2] shows that in the real world, failure of refrigerant pipe insulation can occur, resulting in cellular insulation that becomes ice-laden and/or soaked with water.

Mechanical design practice has relied on the specified low values of water vapor permeance to ensure the longevity of a refrigeration pipe insulation system. It has not been to perform hygrothermal analyses to predict the quantity of condensed water vapor in the insulation system over a particular time duration. Hence, this study, consisting of a series of hygrothermal analyses, is thought to be the first of its kind.

Methodology

The hygrothermal analyses were performed using WUFI, a computer program developed at the Fraunhofer Institute. This program allows two-dimensional, transient modeling of coupled heat and moisture transport in building components under real climate conditions [3]. In this study, the program was modified for a cylindrical shape using a one-dimensional, transient model with the one dimension being the radial component. Hence, the insulated pipes were assumed to be both axially symmetric and cylindrically symmetric. Input data included standardized hourly weather data, for dry bulb temperatures and percent relative humidity values, for three U.S. cities. The effects of wind and solar impingement were ignored. The reasons for ignoring wind are that it does not affect the ambient vapor pressure and it has only a small effect on the temperature profile in the insulation of a well-insulated refrigeration pipe. The reasons for ignoring solar impingement are to consider the more conservative case of no sunshine and because insolation also has no effect on ambient vapor pressure.

Input to the model

In addition to geometric information, several material properties for insulation and film vapor retarder are required as input for the analyses: density, porosity, specific heat, thermal conductivity as a function of mean temperature and % water content by volume, and water vapor permeability.

The computer modeling was conducted on a 75 mm (2.95 in.) diameter pipe operating at a constant temperature of -30°C (-22°F). Three different pipe insulation materials were considered: 115 mm (4.5 in.) thick polyethylene insulation (PEI), 115 mm (4.5 in.) thick extruded polystyrene insulation (XPS), and 76 mm (3.0 in.) thick polyisocyanurate insulation (PIR). The vapor retarder, when applied, consisted of 0.10 mm (0.004 in.) thick polyvinylidene chloride (PVDC) film. Thicker PVDC film is also commercially available with a thickness of 0.15 mm (0.006 in.); however, the thinner material was used in these analyses to be conservative because it has a greater value of water vapor permeance. Appendixes A and B provide the properties of these insulation materials in in.-lb units and Système International (SI) units, respectively. A constant surface heat transfer coefficient of 17 W/m^2K (3.0 $Btu/h\text{-}ft^2\text{-}°R$) was applied to the insulation outer surface. All simulations were started at time = 0, with 80% relative humidity (RH) and 20°C (68°F). Annual, hourly weather data were input for three U.S. cities: Raleigh, North Carolina; Houston, Texas; and Los Angeles, California; these data allowed the modeling of a single year. Ten years were modeled by running the same year 10 times in a row for the particular city, allowing condensed water vapor to accumulate inside or reevaluating from the pipe insulation system. Tables 1 and 2 summarize these input data.

The insulation material's thermal conductivity–mean temperature values were taken from manufacturer data given in Appendixes A and B. However, these values are only for dry insulation. For wet insulation, thermal conductivity was modeled to increase with increasing quantities of water. In the hygroscopic analyses, the computer program first calculated the amount of condensed water in several concentric layers within the insulation, allowing it to calculate the new thermal conductivity values as a function of mean temperature and water content in the layers. The calculations then determined the modeled distribution of condensed water vapor within the pipe insulation (i.e., within the concentric layers).

Figure 1 illustrates the geometric model of the insulated refrigeration pipe. Note the use of cylindrical units. Figures 2, 3, and 4 (with two graphs for each figure) show the variations of input dry bulb temperature and percent relative humidity (% RH) over the course of a year for the three geographic locations: Raleigh, NC; Los Angeles, CA; and Houston, TX, respectively. Note that units on the horizontal axis are given in quarters of a year. For 10 years, this input hourly dry bulb and % RH data were merely repeated 10 times.

Results of the modeling

The results of the hygrothermal computer modeling are given in Figures 5–23 and Table 3. The change of water content in the insulation materials is highest for all insulation systems in Houston. This is due to Houston having the highest annual mean temperature, 37.2°C (99.0°F), which also leads to the highest temperature and water vapor pressure gradient across the pipe insulation system. However, the differences among the three locations remain on a level that doesn't lead to a different evaluation of the systems under different climate conditions. A detailed description follows.

Polyethylene insulation systems

The polyethylene insulation material has very low vapor permeability; therefore the sealed system with or without vapor retarder accumulates very little moisture over 10 years, as shown. The computer analysis predicts a change in the water content over 10 years that is less than 1.0% by volume without the PVDC film vapor retarder and less than 0.5% by volume with the PVDC vapor retarder, regardless of geographic location, as shown in Figure 5 (PEI with no vapor retarder) and Figure 6 (PEI with a vapor retarder). Note that Houston, represented by the blue curve, has the greatest water accumulation, compared with Raleigh and LA, but the differences are not significant for this low-permeability insulation material, either with or without a PVDC film vapor retarder.

The profiles show that with the PEI insulation systems, the water content is distributed evenly over the insulation section. Close to the inner (cold) surface a peak occurs with predicted water content up to approximately 100 kg/m^3 directly at the pipe (see the two relative humidity graphs in Figure 7). Here some ice formation will occur, but as the pores are only approximately 10% filled no degradation of the pore structure is likely. As the moisture entry remains very low, the thermal conductivity of the material also is not affected—the design value of 0.036 W/m-°K is not exceeded in any case (see the polyethylene graphs in Figures 7, 8, and 9). That means that the polyethylene insulation, when sealed at all joints, can be used effectively as refrigeration pipe insulation under rather extreme temperature conditions without applying a separate film vapor barrier for a period of 10 years. This is because the insulation is predicted to remain mostly dry and hence its thermal conductivity is predicted to be stable over that 10-year time span.

XPS insulation systems

See Figures 10, 11, and 12 for graphs of water content over 25 years of time, both without and with a vapor retarder, on the XPS pipe insulation. In the XPS insulation system without vapor retarder, water content increases from 0% to 15% to 23% by volume over 10 years, depending on the geographic location (see the lower-left graphs for % water content with no vapor retarder in Figures 13, 14, and 15). Inside the insulation, the moisture migrates to the cold surface (i.e., the pipe surface) where ice formation occurs. With vapor retarder, the moisture accumulation is limited to the interface between insulation and cold pipe with values up to 300 kg/m^3 (90% by volume) in Houston (compare graphs for % water content without and with a vapor retarder in the figures cited above). Although the accumulation of water and/or ice within the pipe insulation is physically damaging to the insulation material, that subject is not within the scope of this paper.

Without the film vapor retarder, the predicted moisture conditions at the pipe are similar, but in addition the moisture level in the inner 80 mm (3.1 in.) of the insulation increases over time, thus increasing the thermal conductivity of the XPS insulation. During 10 years' operating life, the thermal conductivity is predicted to rise by 35 to 50% depending on the geographic location, as shown in the above figures for the XPS material.

PIR insulation systems

Water content increases rapidly in the PIR system without vapor retarder: after 10 years the insulation approaches maximum saturation with a moisture content of about 90% by volume. The water is predicted to freeze and presumably damage the pore structure. After a few years, condensation and freezing can even appear at the surface due to the lower temperature level resulting from increasing thermal conductivity in the humid PIR. Therefore this insulation system cannot effectively be used without an effective sealed film vapor retarder. For predicted changes in water content, see Figures 16, 17, and 18, and for predicted changes in thermal conductivity, see Figures 19, 20, and 21.

With the PVDC film vapor retarder, the water uptake after 10 years, which is about 2% by volume, is close to the value of the XPS system with the film vapor retarder. Again ice formation is possible only in the insulation close to the pipe. Although some local degradation of the pore structure cannot be excluded, it would have little relevance to the performance of the system. The thermal conductivity will hardly be affected when an effective film vapor retarder such as the PVDC film is used, as the above cited figures show for the PIR insulation with PVDC film in each of the three cities.

Comments

Figures 22, 23, 24, and 25 show the predicted values of insulation thermal conductivity for each of the six different insulation systems, for each of the three cities, over 25 years of time. Increases in thermal conductivity follow increases in condensed water content. To prevent this increase in thermal conductivity, manufacturers of both XPS and PIR pipe insulation typically recommend the use of sheet or film vapor retarders when their products are used on below-ambient pipes, such as refrigeration pipes. Therefore, performing hygrothermal analyses of these types of pipe insulation with and without a sheet or film vapor retarder may seem unnecessary and of no value. The authors, however, believe this modeling does have value because it conclusively shows the value of the sheet or film vapor retarder. The modeling also can be used to determine what the impact might be were that sheet or film damaged in such a way as to allow water vapor leakage. The results of the modeling suggest the effect would be catastrophic.

Summary and Conclusions

Based on a series of hygrothermal computer analyses, this study conclusively shows that over a simulated period of 10 years in three U.S. cities, PIR and XPS ammonia refrigeration pipe insulation systems are only effective if covered with a sealed, low-permeance sheet or film vapor retarder, such as the 0.1 mm (0.004 in.) thick PVDC film discussed in this paper. Fortunately, the manufacturers of XPS and PIR pipe insulation typically recommend the use of a sheet or film vapor retarder over their insulation products when used on ammonia refrigeration pipes.

This study also shows that a low-permeability polyethylene pipe insulation system, sealed at all joints, can effectively insulate the same ammonia refrigeration pipe for the same period of time and in the same U.S. cities, without the need for a film vapor retarder (note that this refrigeration pipe insulation system is no longer commercially available). To effectively insulate, the moisture content inside the insulation material should remain within 2% by volume of the insulation material over that 10-year time.

This study was performed on an ammonia refrigeration pipe of one size (75 mm (29.5 in.) diameter) and at one operating temperature (-30°C) that was insulated with three insulation materials: PEI, XPS, and PIR, with and without a particular film vapor retarder (0.1 mm (0.004 in.) thick PVDC film), over an assumed 10-year duration. However, other insulation materials and sheet or film vapor retarders may also be as effective, depending on the particular material's performance characteristics. Hence, it is recommended that this study be extended to include other insulation materials, namely flexible elastomeric insulation, cellular glass insulation, expanded polystyrene insulation, and other commercially available types of film or sheet vapor retarders. It is also recommended that analyses be performed both for longer periods than 10 years and for pipes with changing temperature over time, which could give valuable information because the rate of ice formation will vary.

Outer surface	
Climatic locations	Raleigh, NC—American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) year 3 Los Angeles, CA—Oak Ridge National Laboratory (ORNL) warm year Houston, TX—ORNL warm year
Heat transfer coefficient	17 W/m^2-°K (3.0 Btu/hr-ft^2-°R)
Radiation	Not used
Inner surface	
Temperature	-30°C (-22°F)
Relative humidity	60% RH (no influence)
Heat transfer coefficient	100,000 W/m^2-°K (17,606 Btu/hr-ft^2-°R)
Miscellaneous	
Type of calculation	Radial geometry
Initial conditions	Equilibrium moisture at 80% RH
Time of calculation	10 years
Start of calculation	1st of January

Table 1. Boundary conditions and settings used for the hygrothermal simulations.

No.	Construction	Location		

1	Pipe r = 75 mm (2.95 in.) T = -30°C (-22°F)	PEI 115 mm (4.5 in.)		Raleigh, NC
2		PEI 115 mm (4.5 in.)	vapor retarder	
3		PEI 115 mm (4.5 in.)		Los Angeles, CA
4		PEI 115 mm (4.5 in.)	vapor retarder	
5		PEI 115 mm (4.5 in.)		Houston, TX
6		PEI 115 mm (4.5 in.)	vapor retarder	
7		PIR 76 mm (3.0 in.)		Raleigh, NC
8		PIR 76 mm (3.0 in.)	vapor retarder	
9		PIR 76 mm (3.0 in.)		Los Angeles, CA
10		PIR 76 mm (3.0 in.)	vapor retarder	
11		PIR 76 mm (3.0 in.)		Houston, TX
12		PIR 76 mm (3.0 in.)	vapor retarder	
13		XPS 115 mm (4.5 in.)		Raleigh, NC
14		XPS 115 mm (4.5 in.)	vapor retarder	
15		XPS 115 mm (4.5 in.)		Los Angeles, CA
16		XPS 115 mm (4.5 in.)	vapor retarder	
17		XPS 115 mm (4.5 in.)		Houston, TX
18		XPS 115 mm (4.5 in.)	vapor retarder	

Table 2. Listing of all systems calculated in the study.

Insulation system	Calculated water content of insulation after 10 years (kg/m³, % by volume)		
	Raleigh, NC	Los Angeles, CA	Houston, TX
PEI without vapor retarder	6.7 (0.7)	6.4 (0.6)	8.2 (0.8)
PEI with vapor retarder	4.3 (0.4)	4.4 (0.4)	5.4 (0.5)
XPS without vapor retarder	150.7 (15.1)	148.9 (14.9)	217.5 (21.8)
XPS with vapor retarder	12.0 (1.2)	12.5 (1.3)	16.0 (1.6)
PIR without vapor retarder	829.0 (82.9)	835.5 (83.6)	874.5 (87.5)
PIR with vapor retarder	14.1 (1.4)	14.9 (1.5)	19.4 (1.9)

Table 3. Comparison of the calculated water content in the insulation after use on the -30°C (-22°F) pipe for 10 years.

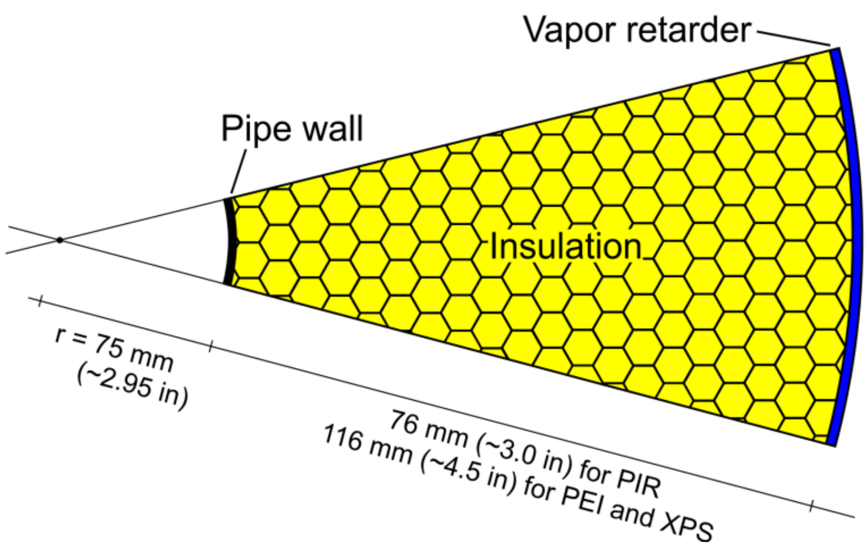

Figure 1. Schematic drawing of a cross section of the pipe insulation system.

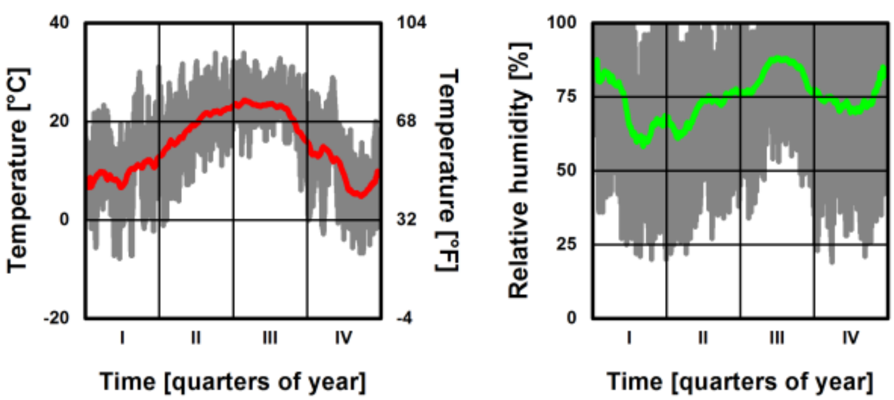

Figure 2. Temperature and relative humidity for Raleigh, NC. The gray area shows hourly values, the colored line the flowing monthly mean value.

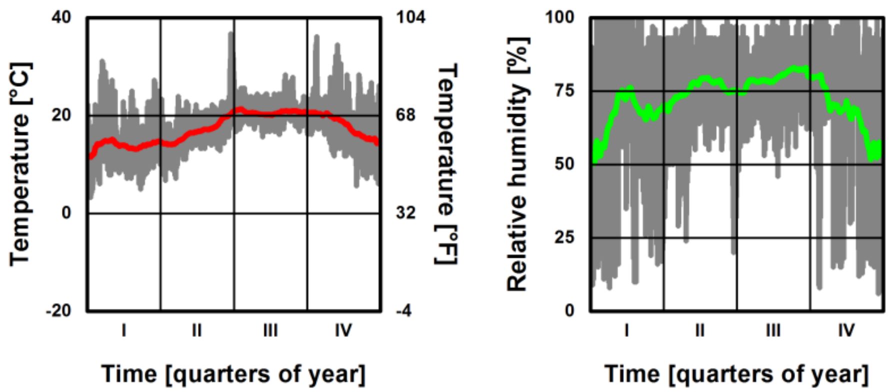

Figure 3. Temperature and relative humidity for Los Angeles, CA. The gray area shows hourly values, the colored line the flowing monthly mean value.

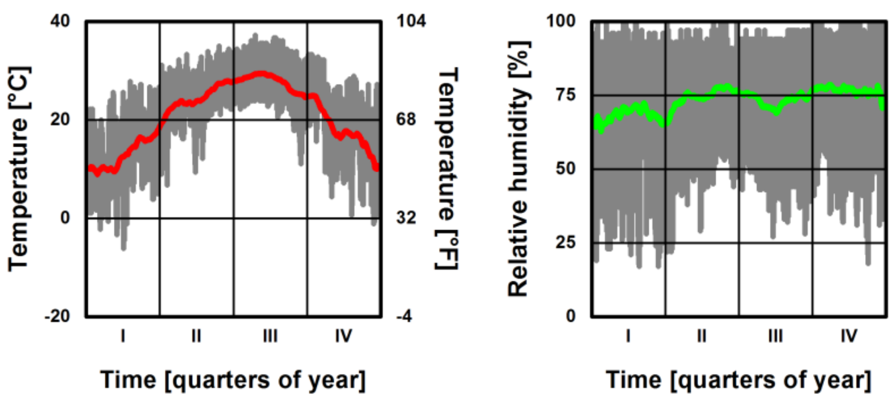

Figure 4. Temperature and relative humidity for Houston, TX. The gray area shows hourly values, the colored line the flowing monthly mean value.

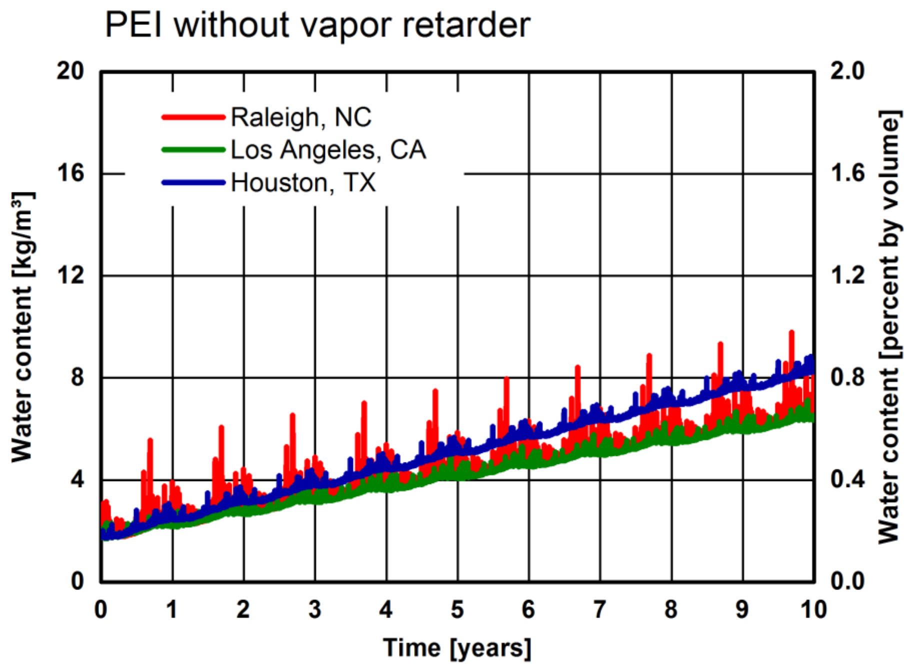

Figure 5. Insulation system: PEI without vapor retarder. Simulated total water content in the insulation layer over 10 years for Raleigh, Los Angeles, and Houston.

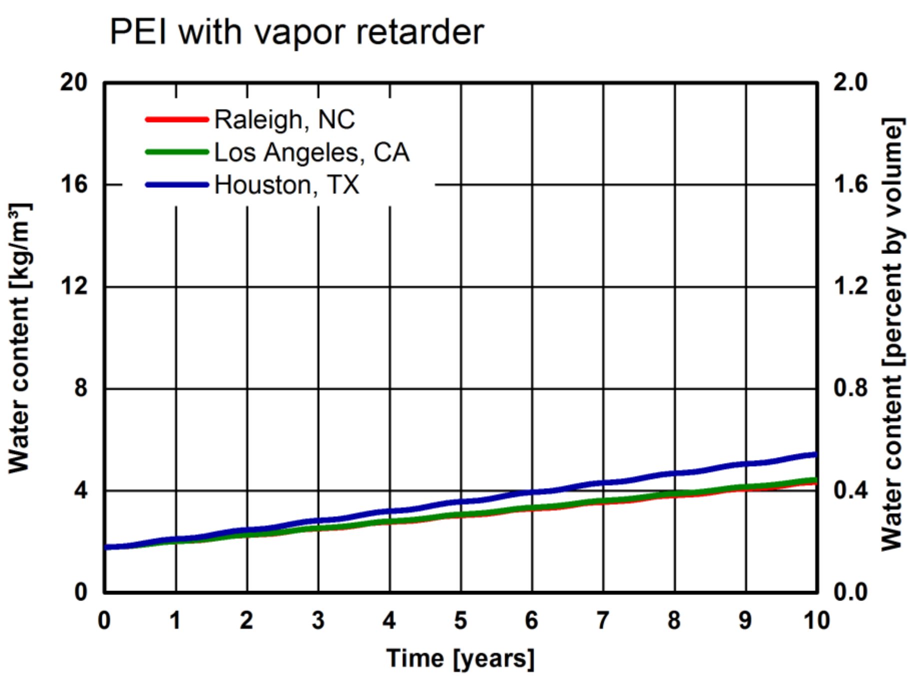

Figure 6. Insulation system: PEI with vapor retarder. Simulated total water content in the insulation layer over 10 years for Raleigh, Los Angeles, and Houston.

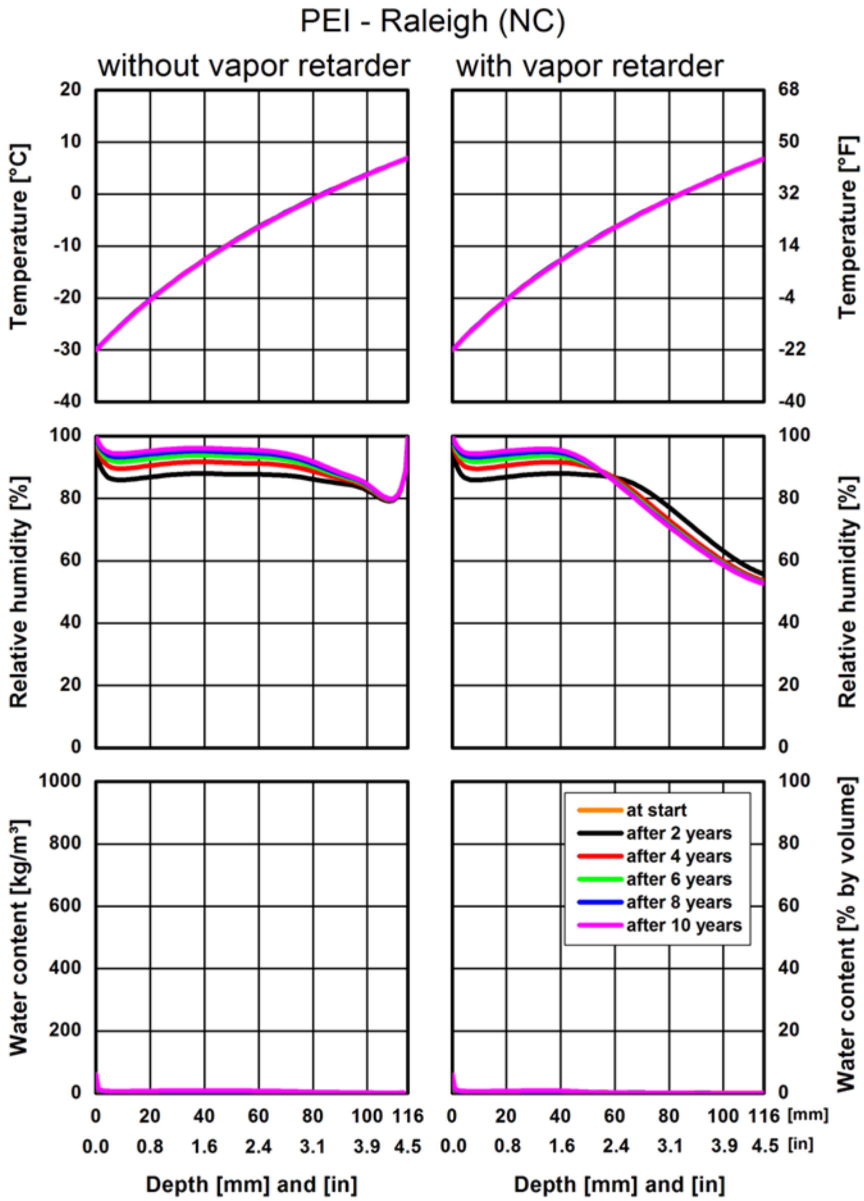

Figure 7. PEI, Raleigh (NC). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only

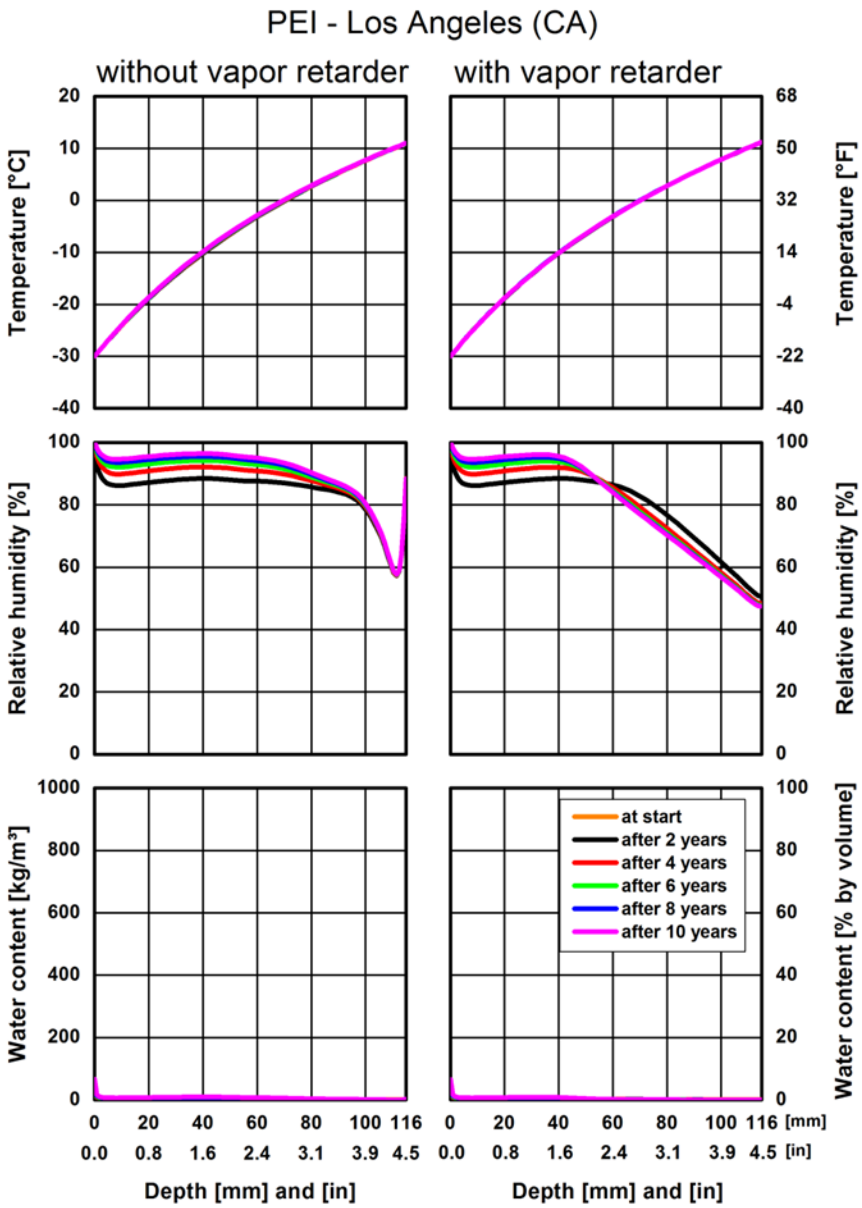

Figure 8. PEI, Los Angeles (CA). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

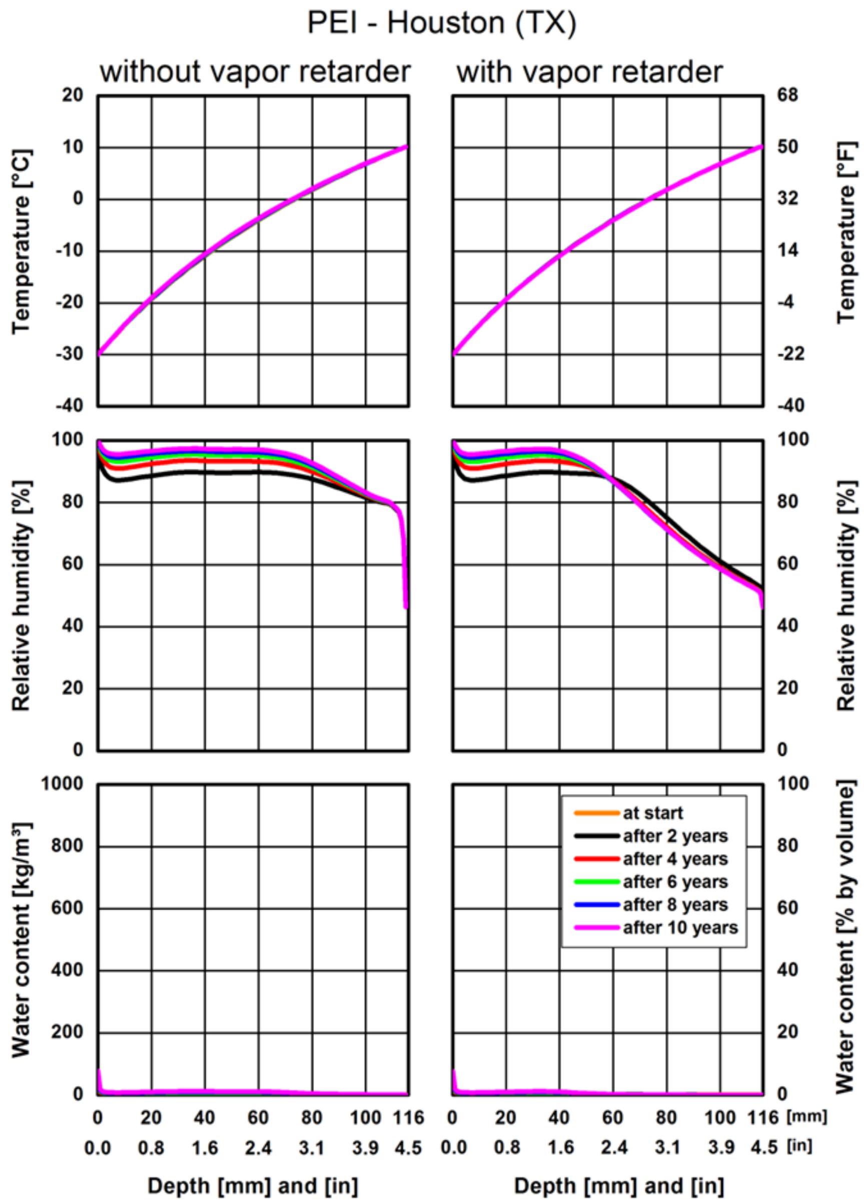

Figure 9. PEI, Houston (TX). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

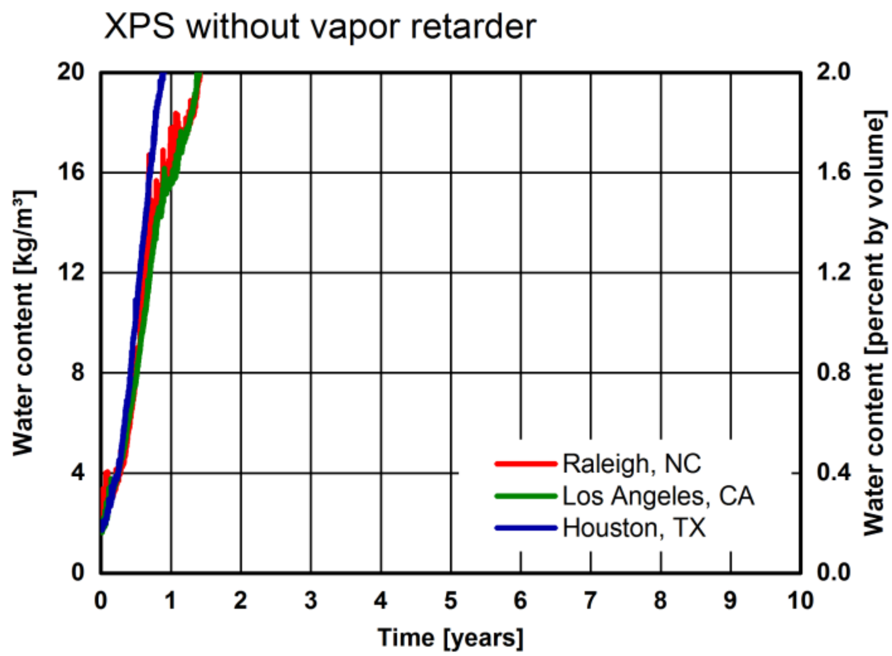

Figure 10. Insulation system: XPS without vapor retarder. Course of the water content over 10 years for Raleigh, Los Angeles, and Houston. For better comparison the scale is limited to 20 kg/m³; the whole course is displayed in Figure 8.

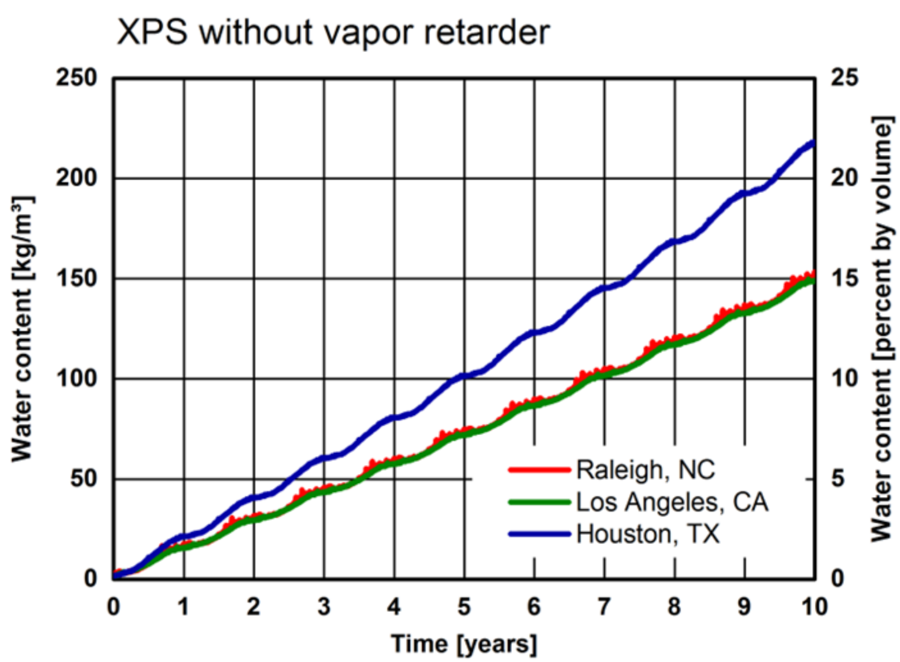

Figure 11. Insulation system: XPS without vapor retarder, complete course of Figure 7. Simulated total water content in the insulation layer over 10 years for Raleigh, Los Angeles, and Houston.

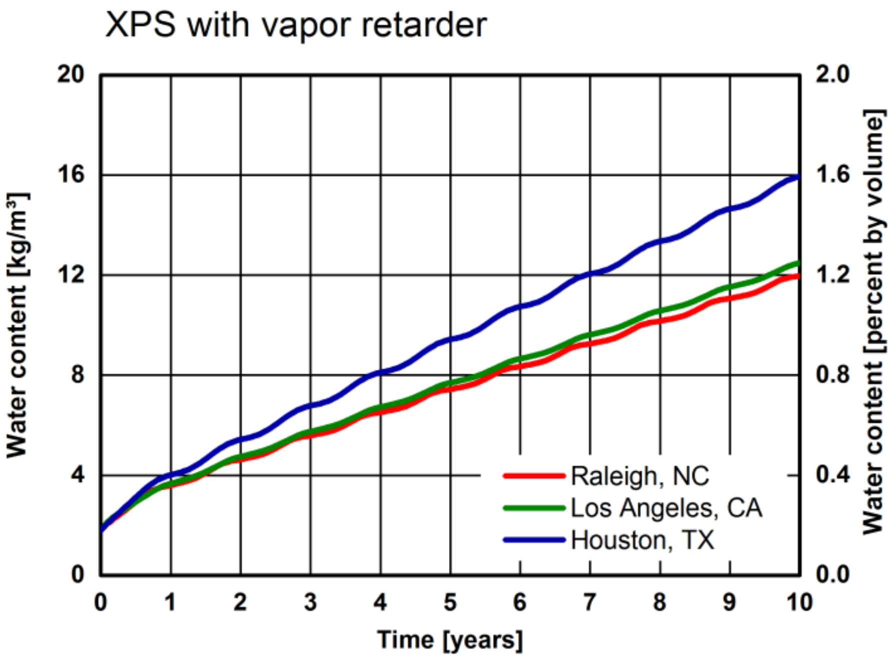

Figure 12. Insulation system: XPS with vapor retarder. Simulated total water content in the insulation layer over 10 years for Raleigh, Los Angeles, and Houston.

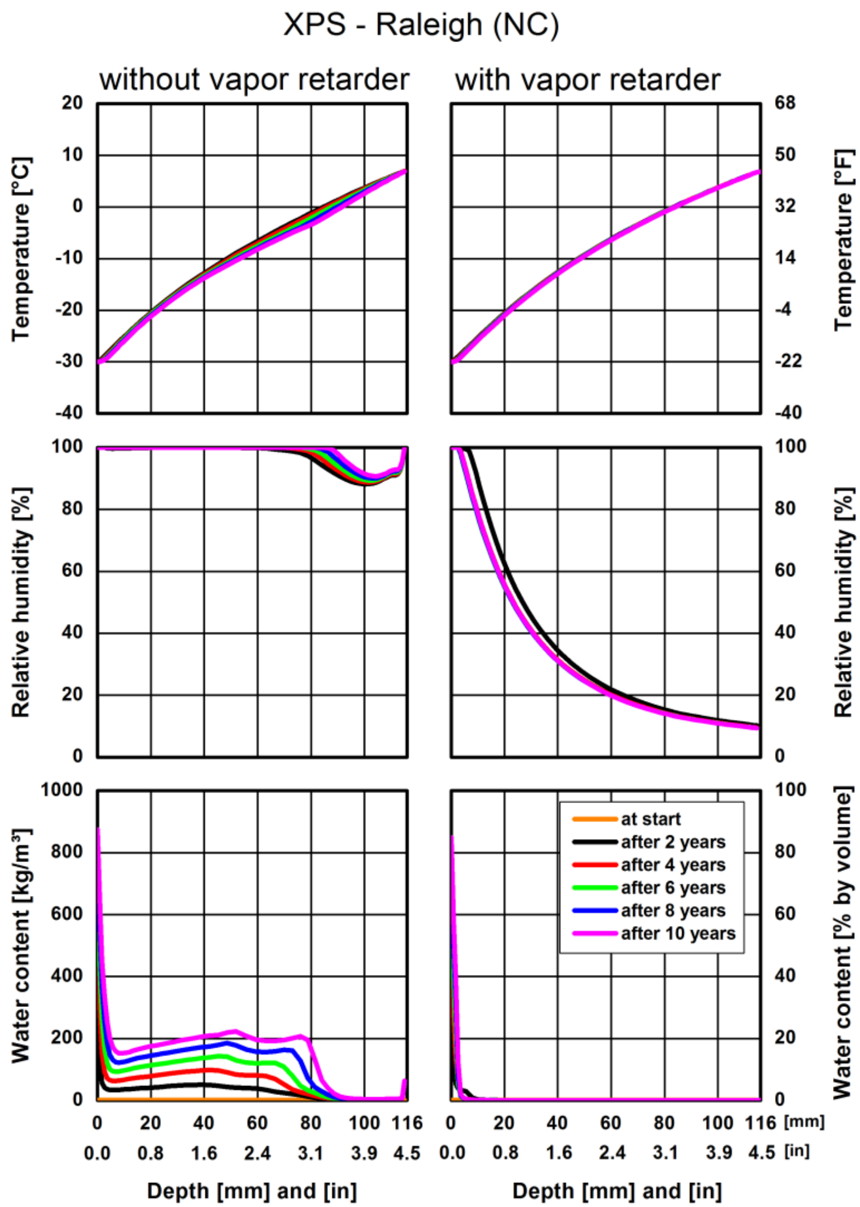

Figure 13. XPS, Raleigh (NC). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

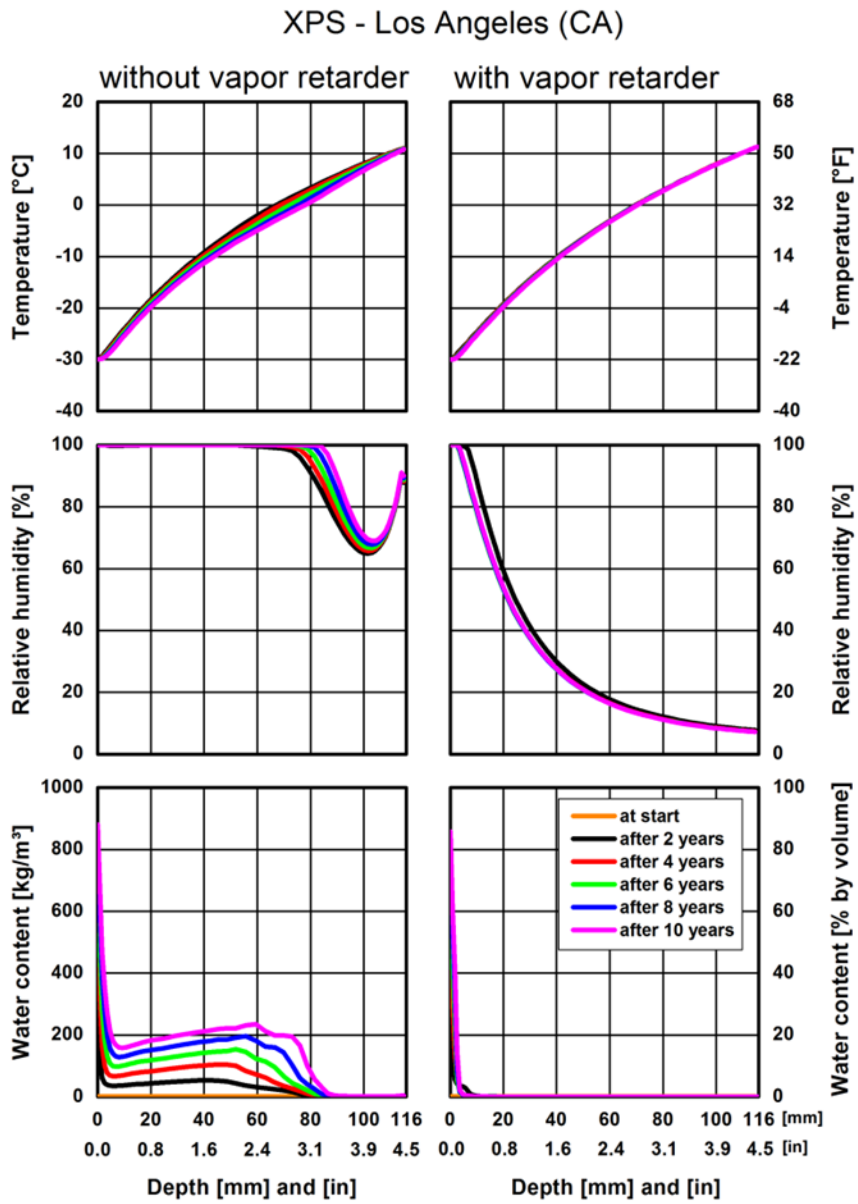

Figure 14. XPS, Los Angeles (CA). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

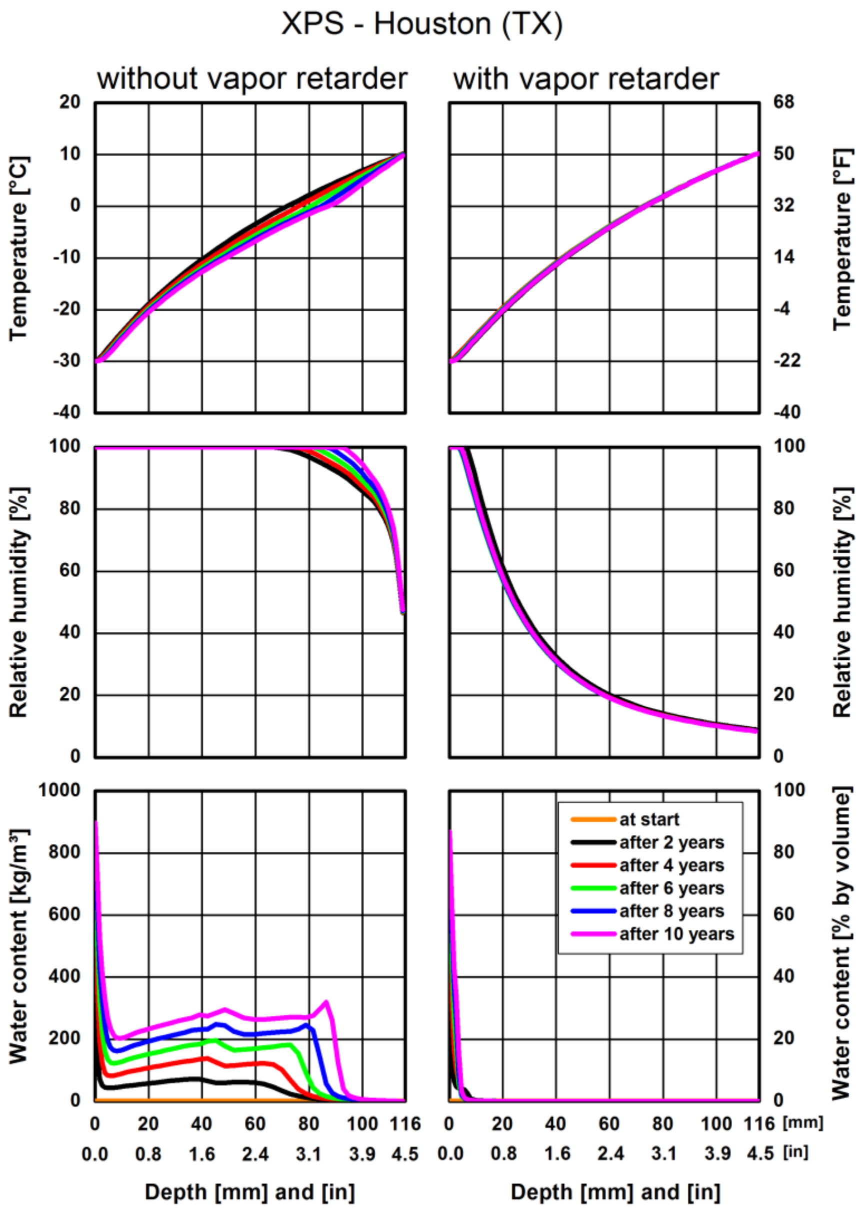

Figure 15. XPS, Houston (TX). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are only displayed for the water content.

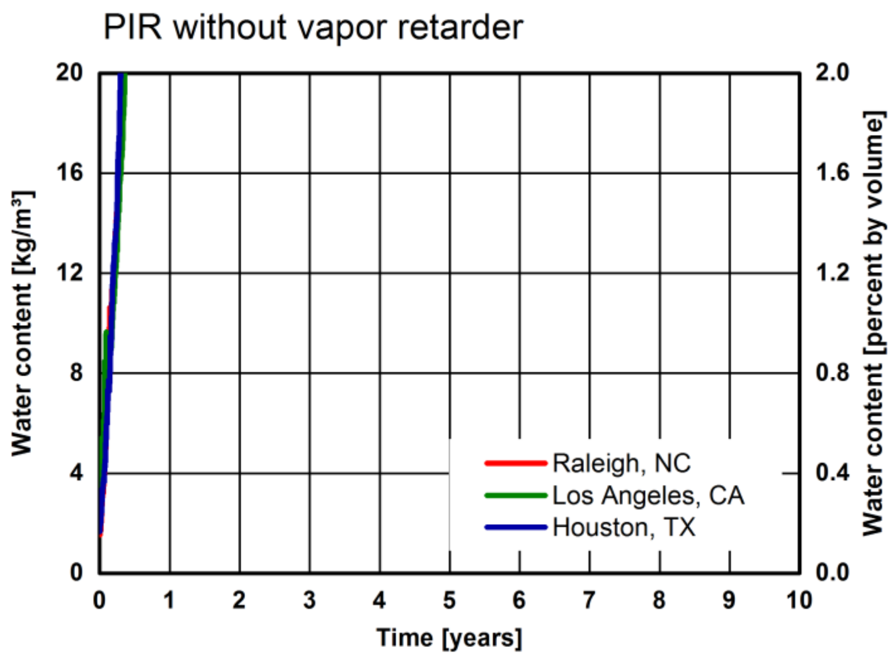

Figure 16. Insulation system: PIR without vapor retarder. Course of the water content over 10 years for Raleigh, Los Angeles, and Houston. For better comparison the scale is limited to 20 kg/m³; the whole course is displayed in Figure 11.

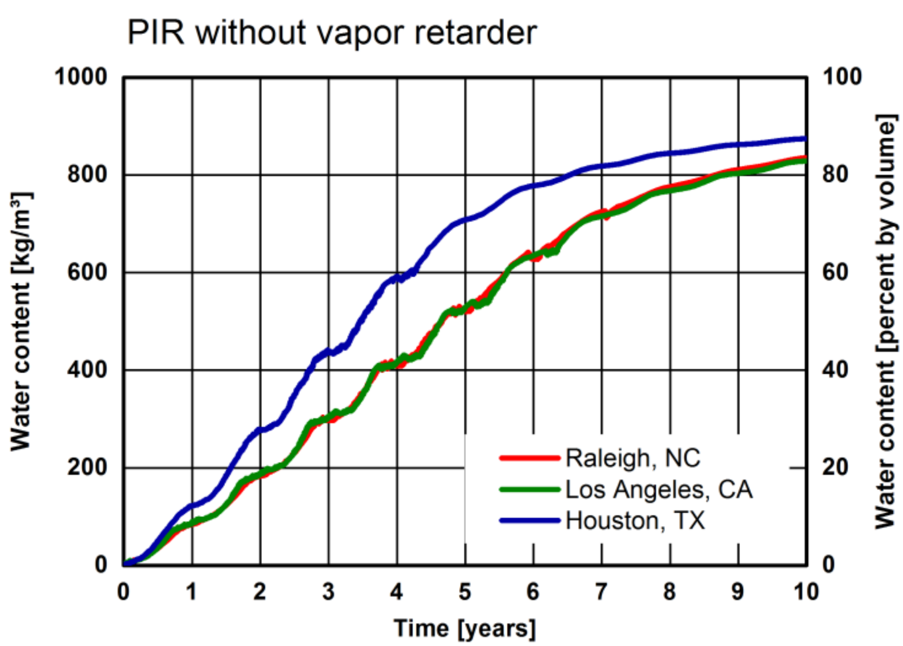

Figure 17. Insulation system: PIR without vapor retarder, complete course of Figure 10. Simulated total water content in the insulation layer over 10 years for Raleigh, Los Angeles, and Houston.

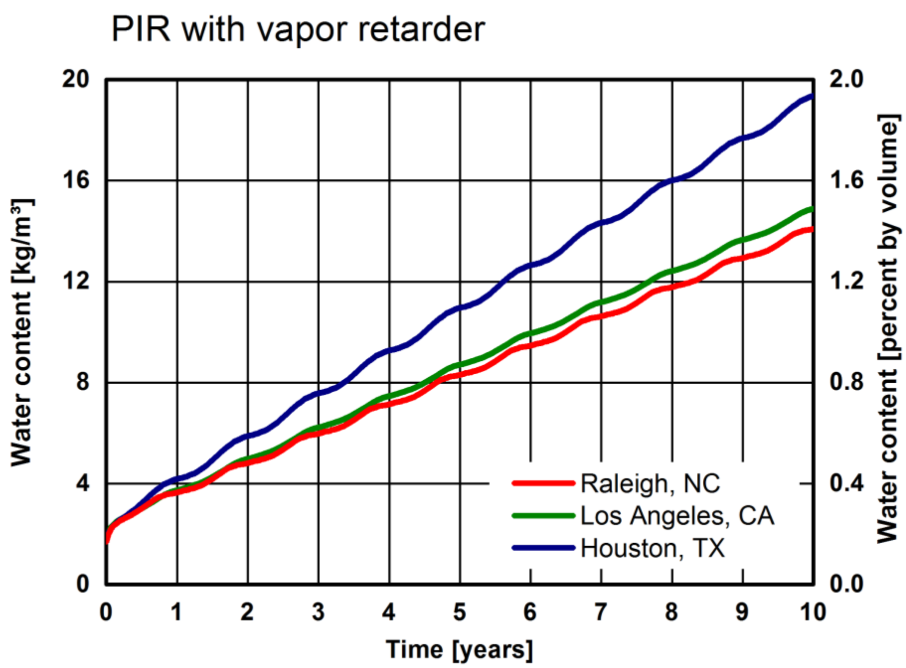

Figure 18. Insulation system: PIR with vapor retarder. Simulated total water content in the insulation layer over 10 years for Raleigh, Los Angeles, and Houston.

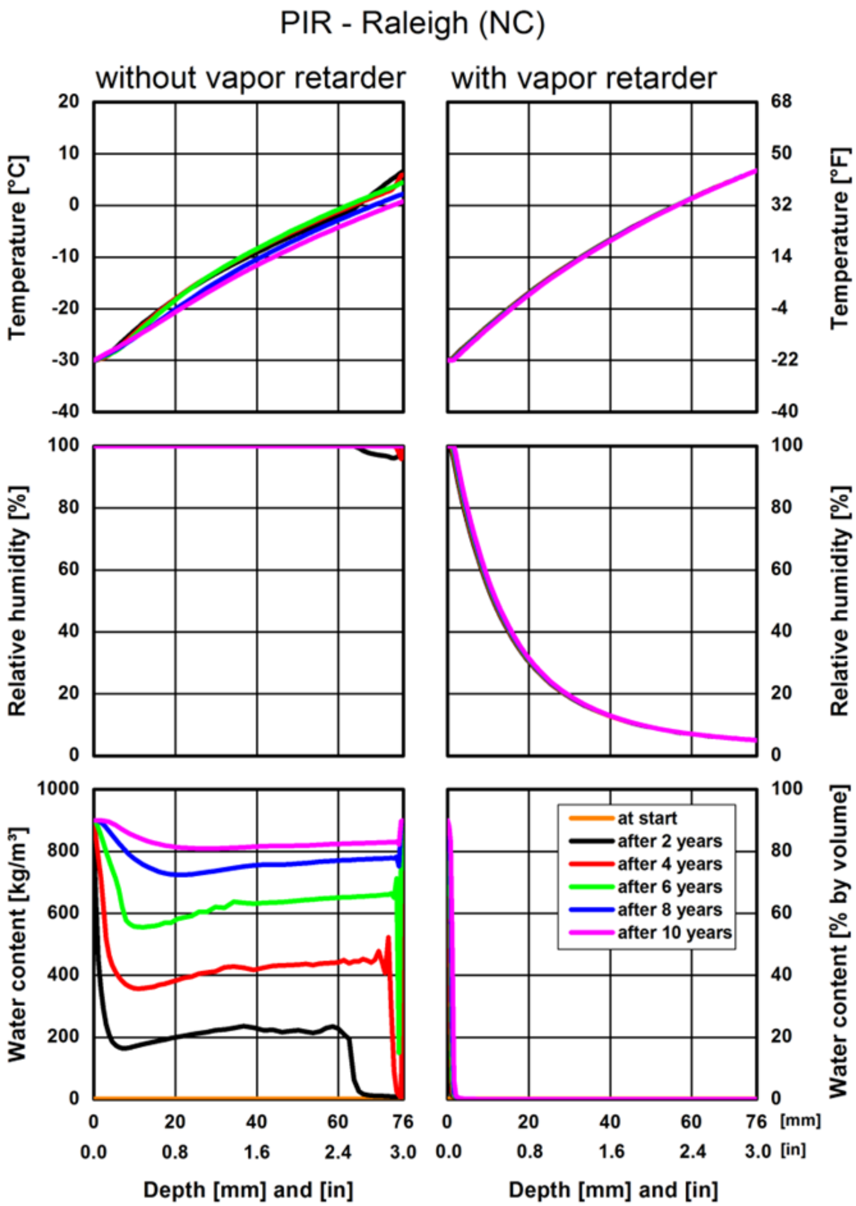

Figure 19. PIR, Raleigh (NC). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

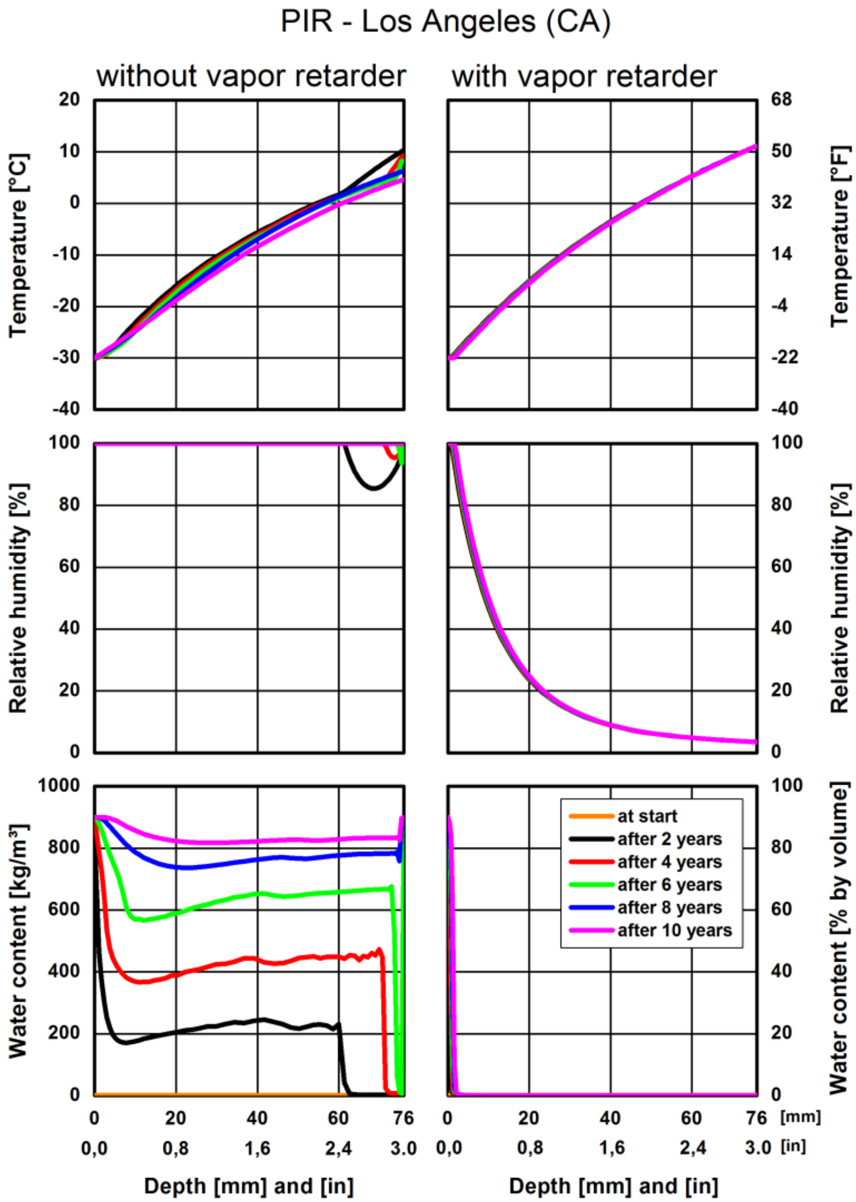

Figure 20. PIR, Los Angeles (CA). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

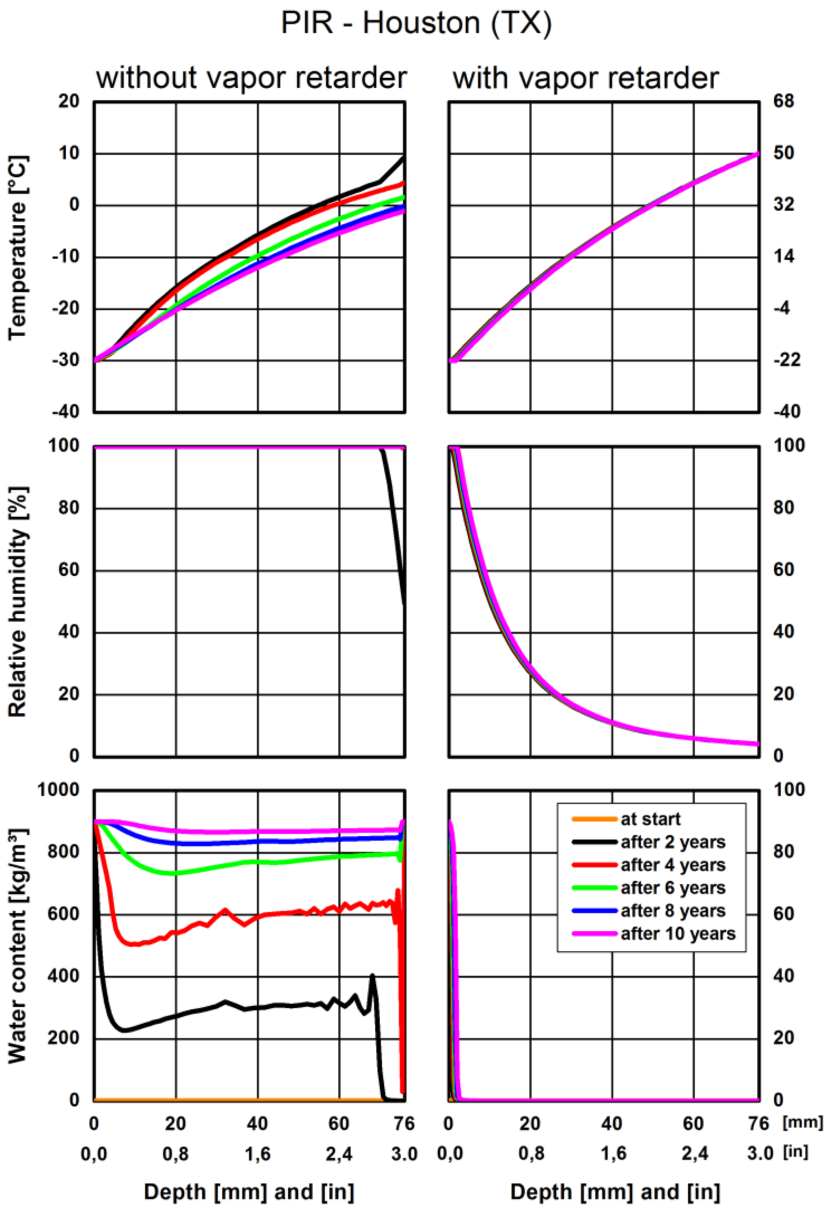

Figure 21. PIR, Houston (TX). Profiles for temperature, relative humidity, and water content after two, four, six, eight, and 10 years. The conditions at start are displayed for the water content only.

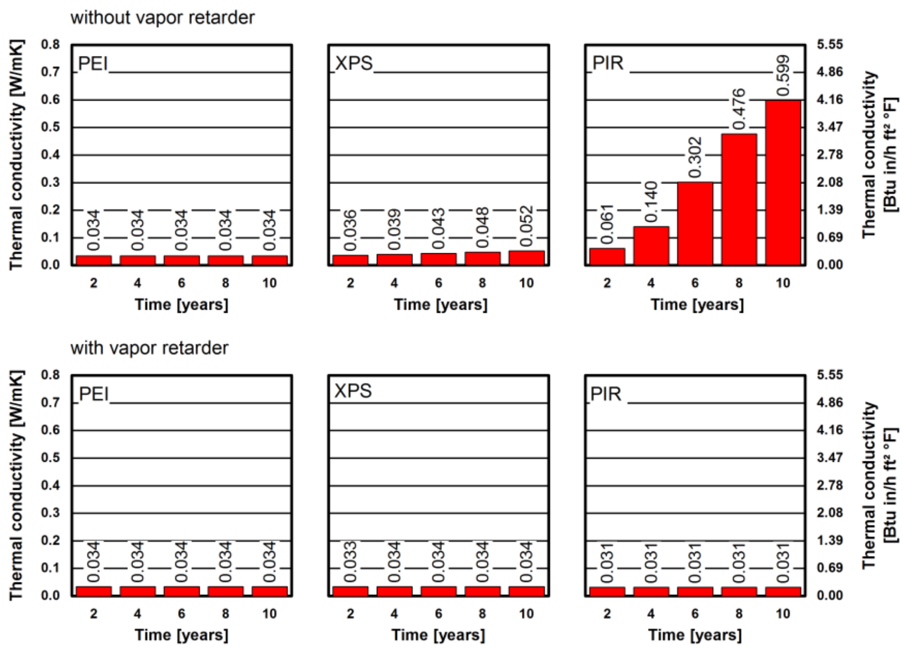

Figure 22. Raleigh (NC). Thermal conductivity of the three insulation systems without and with vapor retarder after two, four, six, eight, and 10 years.

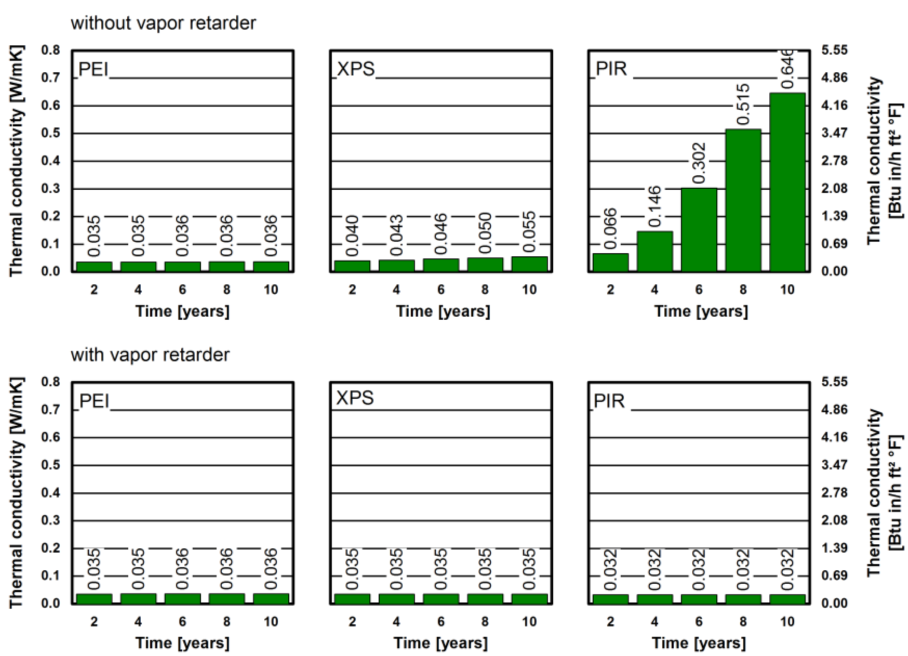

Figure 23. Los Angeles (CA). Thermal conductivity of the three insulation systems without and with vapor retarder after two, four, six, eight, and 10 years.

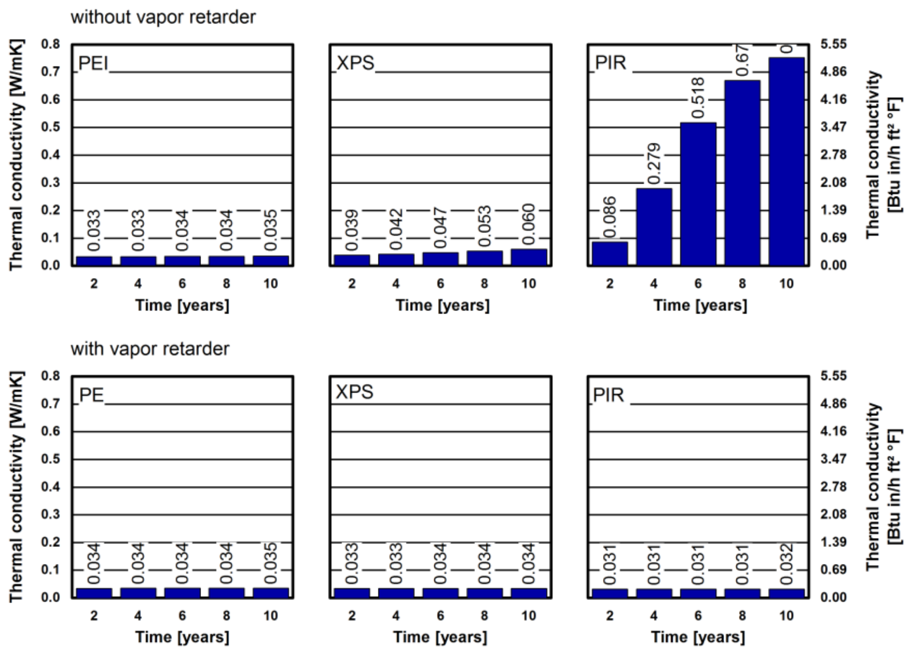

Figure 24. Houston (TX). Thermal conductivity of the three insulation systems without and with vapor retarder after two, four, six, eight, and 10 years.

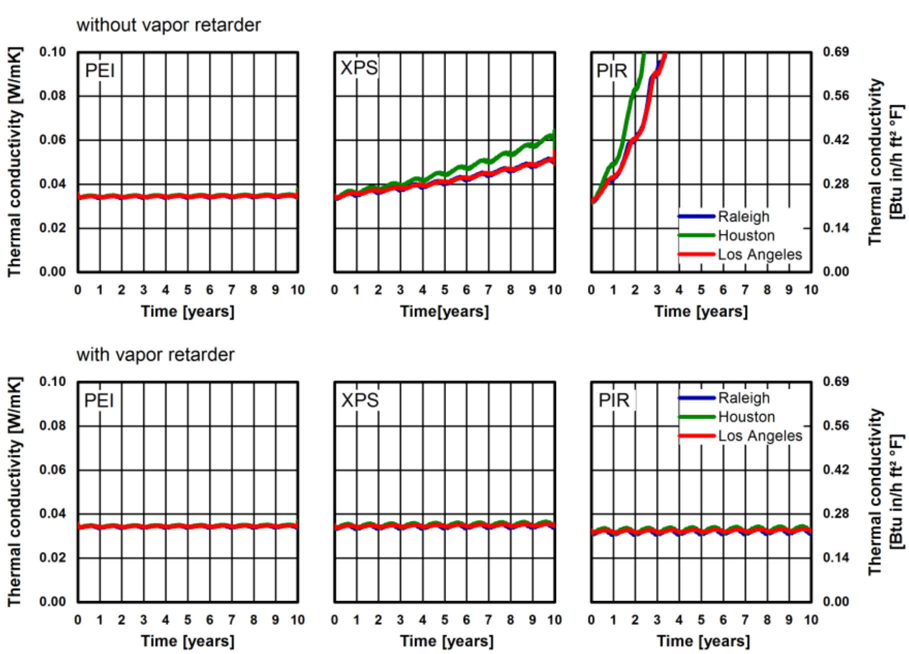

Figure 25. Thermal conductivity over 10 years for the three insulation systems without and with vapor retarder at all three locations (floating monthly mean values).

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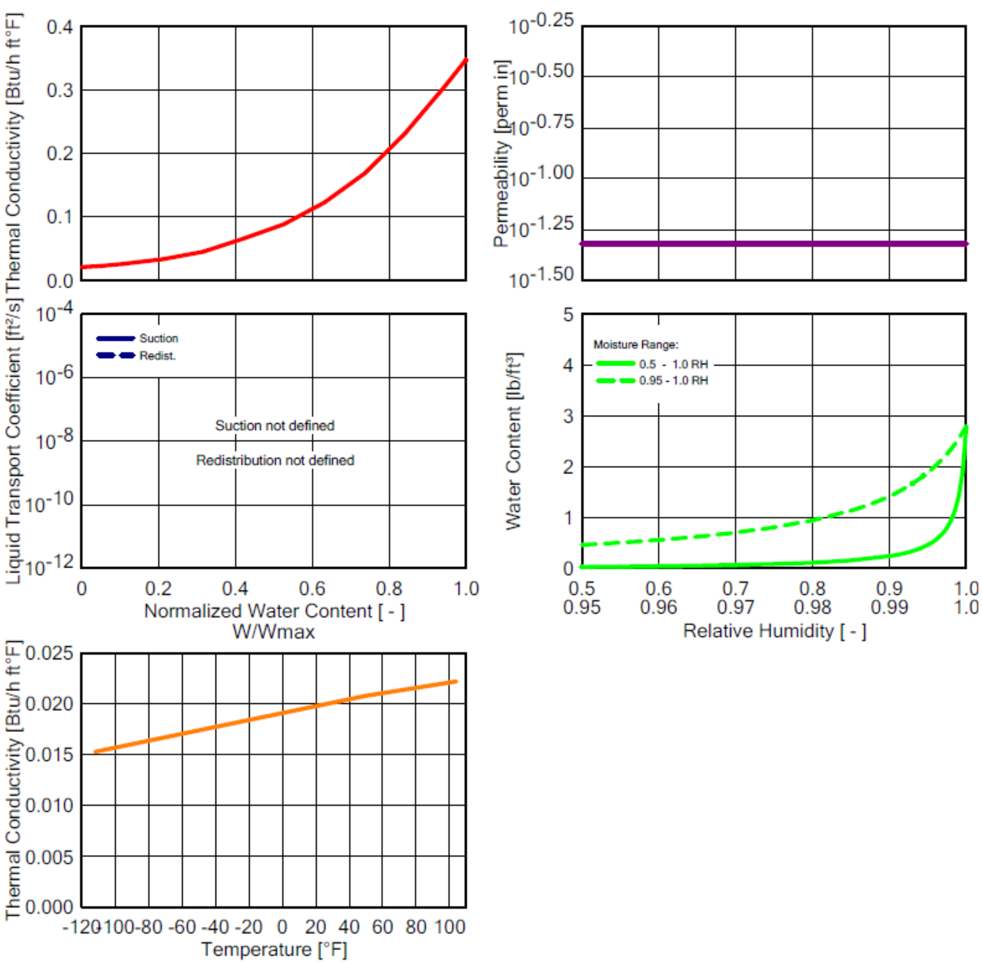
[6] Scientific-Technical Association for Building Maintenance and Preservation (WTA).(2001a). "Leitfaden für Hygrothermische Simulationsberechnung." *WTA-Merkblatt 6-1-01/D*. Stuttgart, Germany: WTA Publications, Fraunhofer IRB Verlag.

[7] Scientific-Technical Association for Building Maintenance and Preservation (WTA). (2001b). "Simulation of Heat and Moisture Transfer." *WTA-Guideline 6-2-01/E*. Stuttgart, Germany: WTA Publications, Fraunhofer IRB Verlag.

Appendix A. Material properties for hygrothermal computer analyses (in in.-lb units) (Note: these are assumed based on manufacturer's data)

Material: Polyethylene insulation (PEI) (in.-lb units)

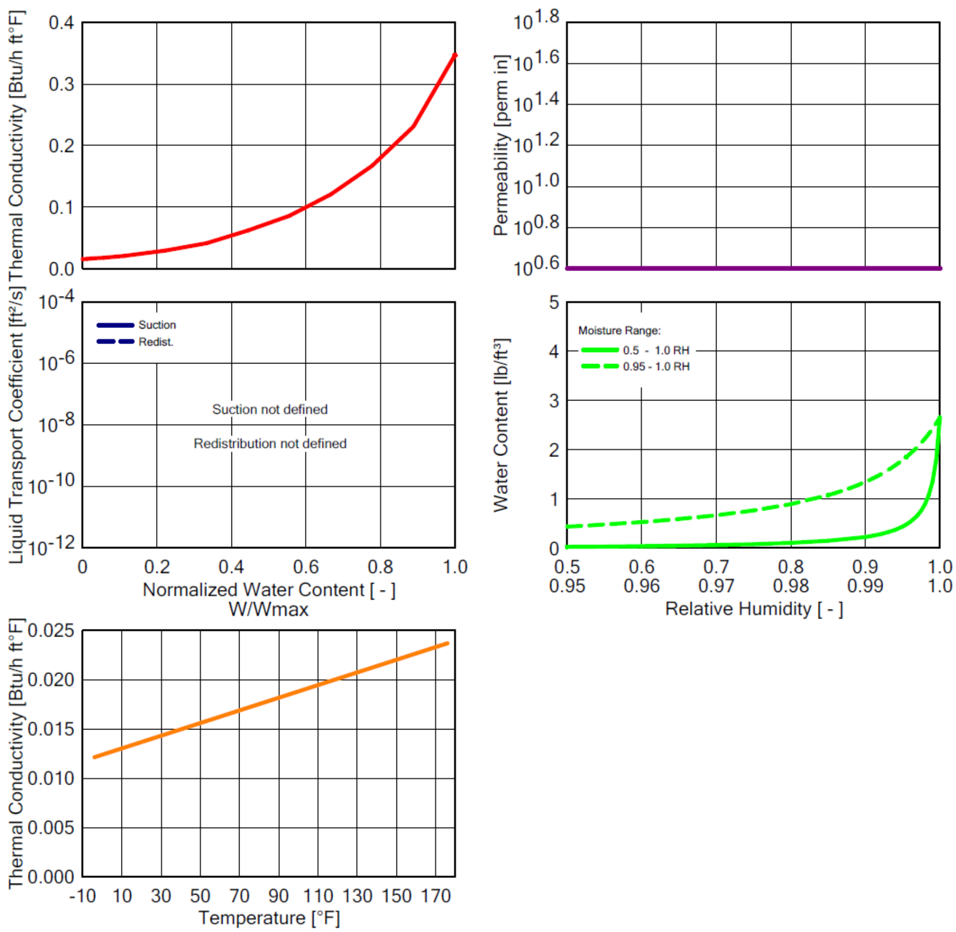
Property	Unit	Value
Bulk density	[lb/ft³]	1,9353
Porosity	[ft³/ft³]	0,95
Specific Heat Capacity, Dry	[Btu/lb°F]	0,3583
Thermal Conductivity, Dry, 50°F	[Btu/h ft°F]	0,0208
Permeability	[perm in]	0,0479



Material: PIR insulation (in.-lb units)

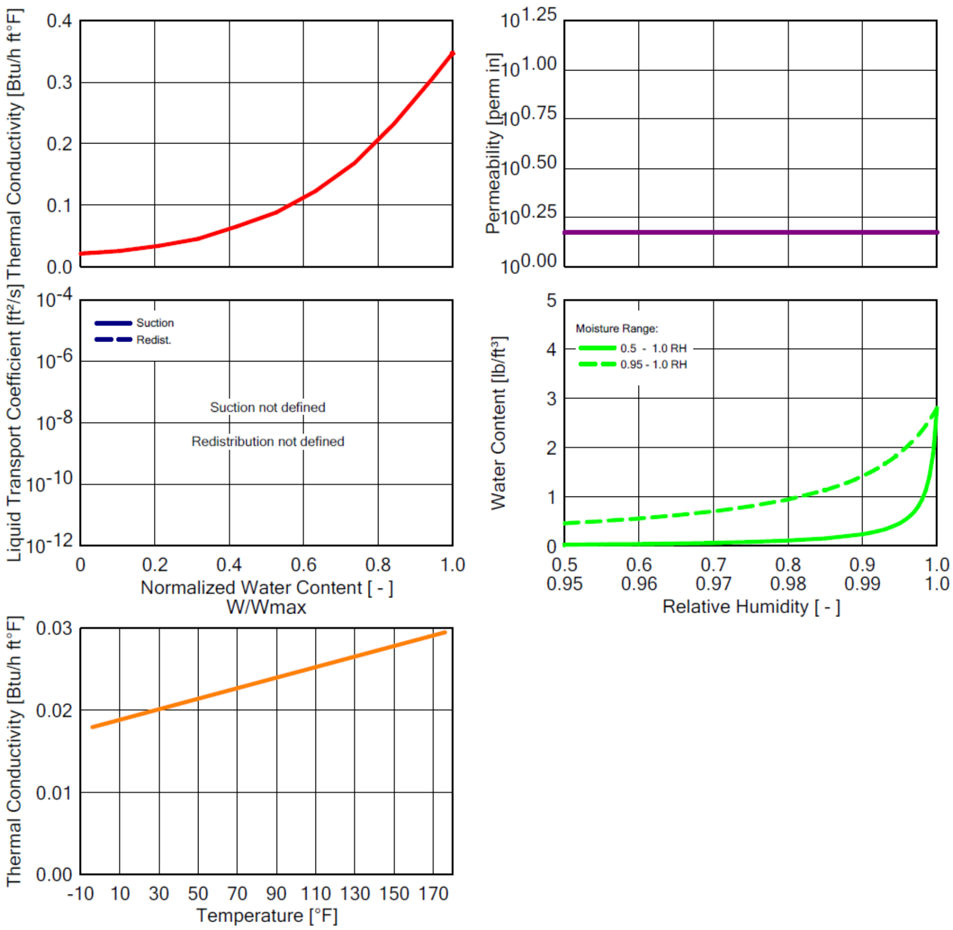
(Note: these are assumed based on manufacturer's data)

Property	Unit	Value
Bulk density	[lb/ft³]	1,7979
Porosity	[ft³/ft³]	0,9
Specific Heat Capacity, Dry	[Btu/lb°F]	0,3583
Thermal Conductivity, Dry ,10°C	[Btu/h ft°F]	0,0156
Permeability	[perm in]	3,9938
Temp-dep. Thermal Cond. Supplement	[Btu/h ft°F²]	0,0000642



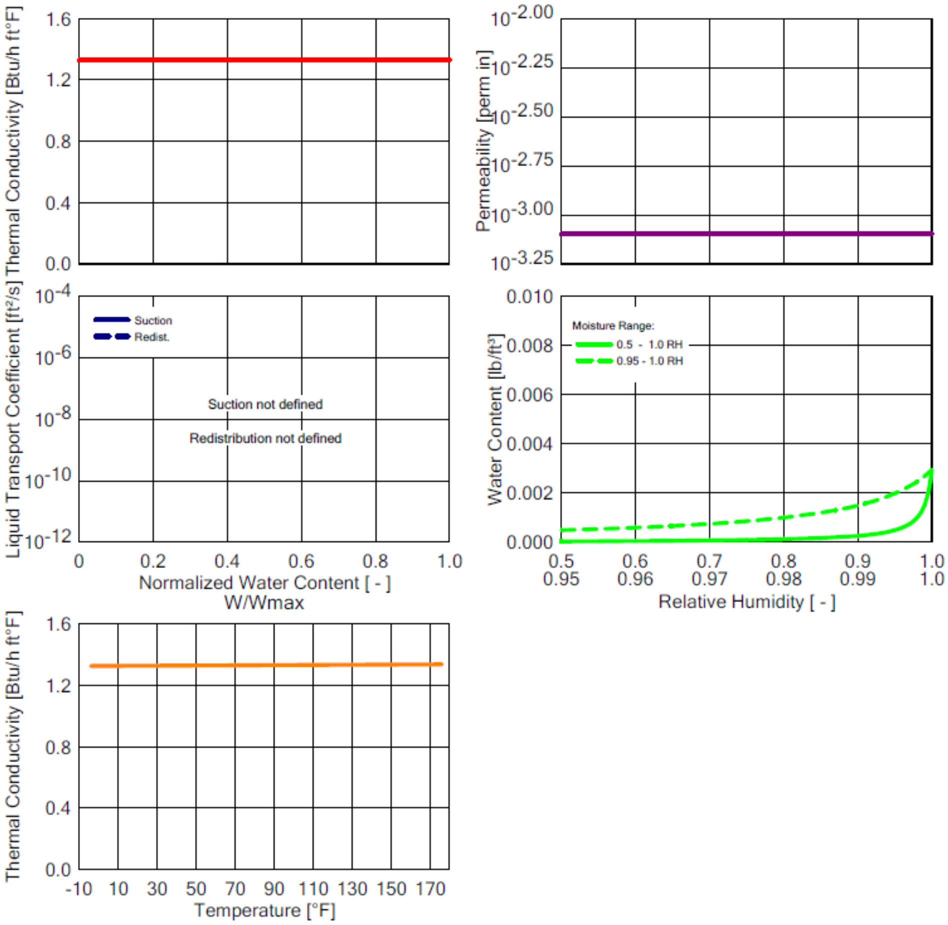
Material: XPS insulation (in.-lb units)
(Note: these are assumed based on manufacturer's data)

Property	Unit	Value
Bulk density	[lb/ft^3]	1,6231
Porosity	[ft^3/ft^3]	0,95
Specific Heat Capacity, Dry	[Btu/lb°F]	0,3583
Thermal Conductivity, Dry ,10°C	[Btu/h ft°F]	0,0214
Permeability	[perm in]	1,4977
Temp-dep. Thermal Cond. Supplement	[Btu/h ft°F^2]	0,0000642



Material properties: PVDC film (in.-lb units)
(Note: these are assumed based on manufacturer's data)

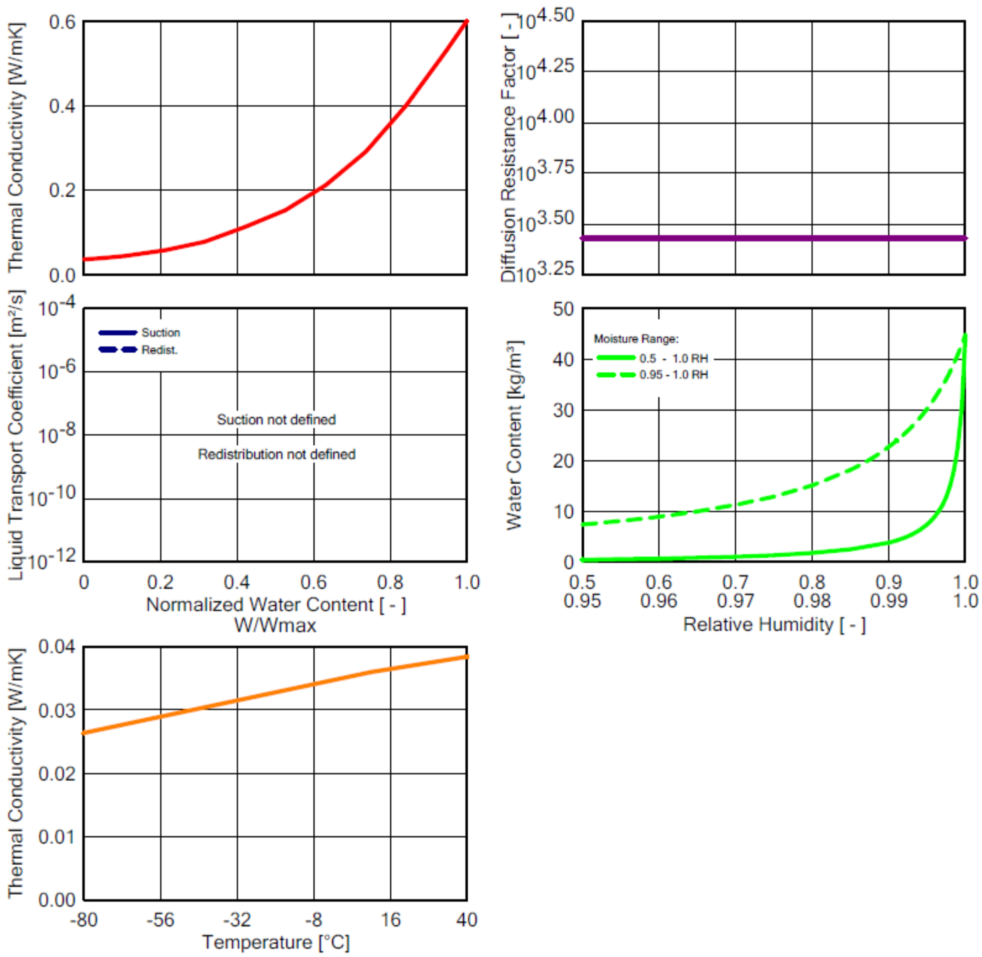
Property	Unit	Value
Bulk density	[lb/ft³]	8,1156
Porosity	[ft³/ft³]	0,001
Specific Heat Capacity, Dry	[Btu/lb°F]	0,5493
Thermal Conductivity, Dry ,10°C	[Btu/h ft°F]	1,3289
Permeability	[perm in]	0,0008
Temp-dep. Thermal Cond. Supplement	[Btu/h ft°F²]	0,0000642



Appendix B. Material properties for hygrothermal computer analyses (in SI units) (Note: these are assumed based on manufacturer's data)

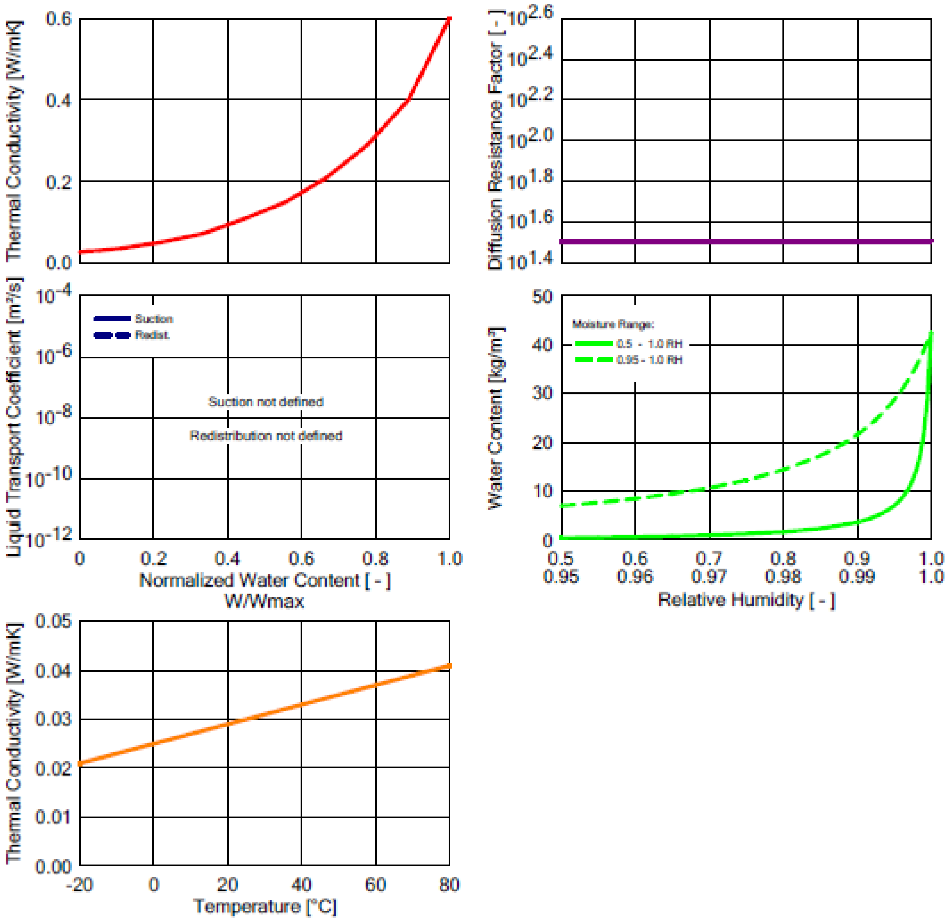
Material: Polyethylene insulation (PEI) (SI units)

Property	Unit	Value
Bulk density	[kg/m³]	31,0
Porosity	[m³/m³]	0,95
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry, 10°C	[W/mK]	0,036
Water Vapour Diffusion Resistance Factor	[-]	2687,5



Material: PIR insulation (SI units)
(Note: these are assumed based on manufacturer's data)

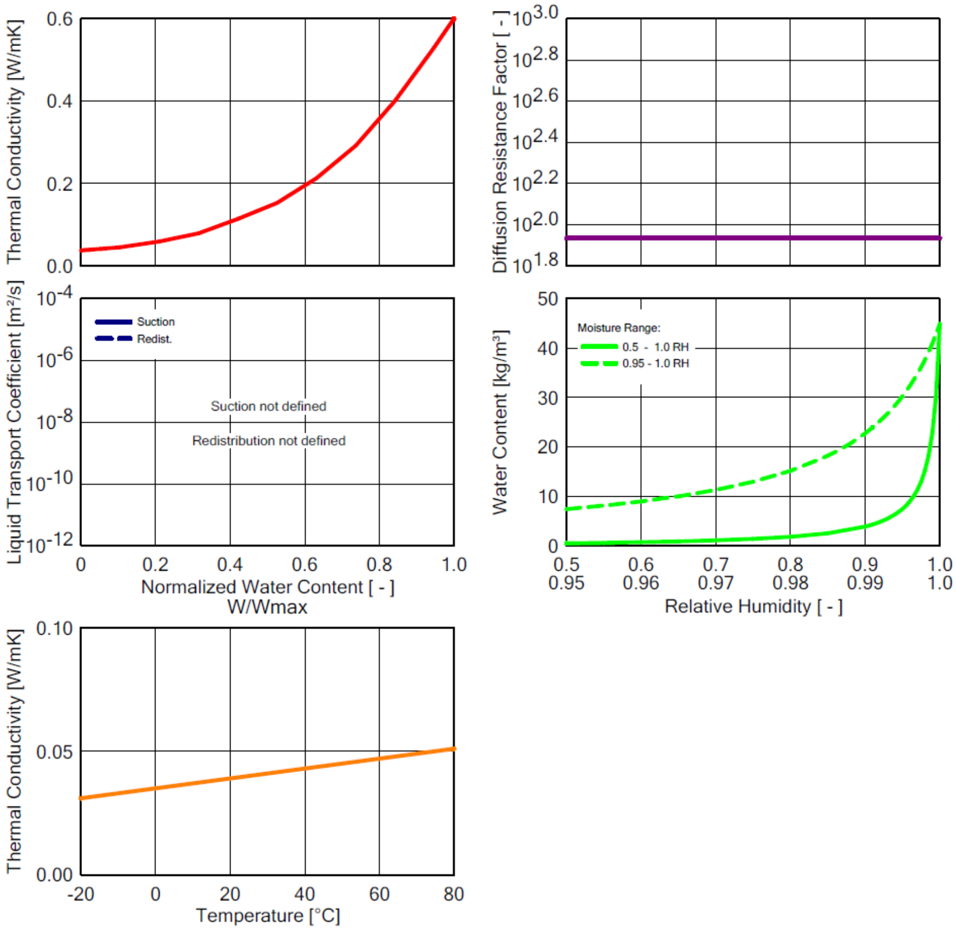
Property	Unit	Value
Bulk density	[kg/m³]	28,8
Porosity	[m³/m³]	0,9
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry ,10°C	[W/mK]	0,027
Water Vapour Diffusion Resistance Factor	[-]	32,25
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002



Material: XPS insulation (SI units)

(Note: these are assumed based on manufacturer's data)

Property	Unit	Value
Bulk density	[kg/m³]	26,0
Porosity	[m³/m³]	0,95
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry ,10°C	[W/mK]	0,037
Water Vapour Diffusion Resistance Factor	[-]	86,0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002



Material properties: PVDC film (SI units)
(Note: these are assumed based on manufacturer's data)

Property	Unit	Value
Bulk density	[kg/m³]	130,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	2300,0
Thermal Conductivity, Dry ,10°C	[W/mK]	2,3
Water Vapour Diffusion Resistance Factor	[-]	164000,0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002