Moisture Performance of Leaky Exterior Walls With Added Insulation

Guylaine Desmarais **Dominique Derome, Ph.D.** **Paul Fazio, Ph.D.**
Member ASHRAE

ABSTRACT

Adding insulation to existing exterior walls has the potential to create moisture-related problems as moisture from indoors gets into moderately leaky building envelopes. A test was designed to investigate the behavior of exterior walls with and without added insulation and having different leakage characteristics.

Nine wall assemblies included within a full-scale test hut were consecutively subjected to winter and late spring weather conditions. All specimens had glass-fiber batt insulation between the studs. Extruded polystyrene boards were added on the cold side of the assembly in three of the specimens, and on the warm side in two of them. These three compositions were studied with various air leakage paths—a long path, a concentrated path, and a uniformly distributed exfiltration path.

Moisture content in the fiberboard sheathing and wood studs measured throughout the test is compared to demonstrate the influence of location of insulation and geometry of air leakage. The results show that walls having the same R-value but a different composition do not necessarily behave the same way. Depending on the position of the added insulation and its properties, the sensitivity to air leakage will vary. It is also shown that air leakage should be taken into account before increasing the thermal resistance of existing exterior walls.

INTRODUCTION

Research and practice have shown that adding thermal insulation in the envelope of residential buildings is one of the most effective measures to decrease energy use for heating and cooling (Hens 1996). In addition, the benefits of additional insulation on energy consumption are easy to evaluate because many simple calculation methods exist (Jones 1995). However, other consequences of adding insulation, such as the potential for condensation due to moisture and air movement through the exterior wall assembly, are not often taken into account.

For a long time, moisture has been acknowledged to be an important agent of deterioration for exterior wall assemblies (Latta and Beach 1964). Furthermore, moisture poses the most serious threat to the integrity and durability of the envelope by accounting for up to 80% of damage in building envelopes (Bomberg and Brown 1993). Exfiltration is the main transfer mode of indoor moisture into the exterior wall assemblies in cold climates. Moisture transfer by exfiltration is likely to occur since the exterior walls of most existing residential buildings are not airtight, as demonstrated in a survey by Hamlin and Gusdorf (1997). This suggests that the initial air leakage characteristics of the assembly should be considered when adding insulation to leaky exterior wall assemblies. Knowing this, the questions are: How can insulation be added with moisture accumulation being avoided? What effect do the initial air leakage characteristics have on moisture accumulation? Where in the assembly should the insulation be added to minimize the likelihood of moisture-related problems?

To answer these questions, nine wall assemblies, all included within a full-scale test hut built inside an environmental chamber, were consecutively subjected to winter and late spring weather conditions. All specimens had glass-fiber

Guylaine Desmarais is an architect with the Building Science Group Air-Ins Inc. in Montreal, Quebec. **Dominique Derome** is an assistant professor and **Paul Fazio** is a professor a the Centre for Building Studies of the Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec.

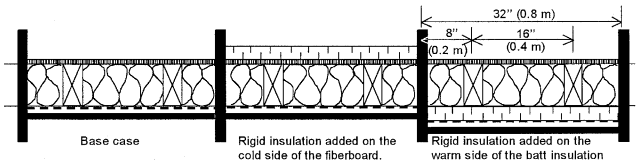

Figure 1 *Composition of wall assemblies (horizontal section across assemblies).*

batt insulation between the studs. Rigid extruded polystyrene insulation was added on the cold side of the assembly in three specimens, and it was added on the warm side of the assembly in two specimens. To represent field conditions, the specimens were studied with air leakage—three sections had a long leakage path, two sections had a concentrated leakage path, and two sections had a uniformly distributed leakage path. One specimen with no insulation added was made airtight to serve as reference. The objective was to evaluate the performance of moderately leaky exterior wall assemblies (with an exfiltration area equivalent to ACH50 of around four), with and without added insulation in two locations, in terms of the moisture content of the fiberboard sheathing and the wood studs. Comparison of gravimetric results measured throughout the test for each section shows the influence of the parameters (overall R-value, location of added insulation, and geometry of air leakage) on the moisture content levels reached for the type of assemblies and conditions that were studied.

EXPERIMENTAL PROTOCOL

Built within an environmental chamber (Fazio et al. 1997), the test hut measured 13.75 ft long by 8.33 ft wide by 10 ft high (4.2 by 2.5 by 3 m). The long walls were divided into nine sample sections, 2.67 ft wide by 8 ft high (0.8 by 2.4-m), consisting of one full stud space in the center flanked by half a stud space on each side to act as hygrothermal buffers. The sample sections did not include the exterior veneer. The base-case wall composition was typical of single-family residential construction in Quebec before the 1982 provincial regulation for energy efficiency (Regulation 1992). From outdoor to indoor, the materials of this base case were spun-bonded polyolefin membrane, 0.375 in. (10 mm) asphalt impregnated fiberboard, 2-by-4-in. at 16 in. o.c. (38-by-89-mm at 400 mm o.c.) wood studs, 3.5 in. (89 mm) glass-fiber batt insulation, 6 mil polyethylene air/vapor barrier, 1-by-3-in. at 16 in. o.c. (19-by-64-mm at 400 mm o.c.) horizontal wood strapping, 0.5 in. (13 mm) gypsum board, and standard latex paint (two coats). To represent the case where enough insulation is added to meet the requirements of the new regulation for energy efficiency (i.e., increase the thermal resistance from R14 [2.45 $m^2 \cdot °C/W$] to R 24 [4.81 $m^2 \cdot °C/W$]), 38 mm of rigid insulation was added to some of the sample sections

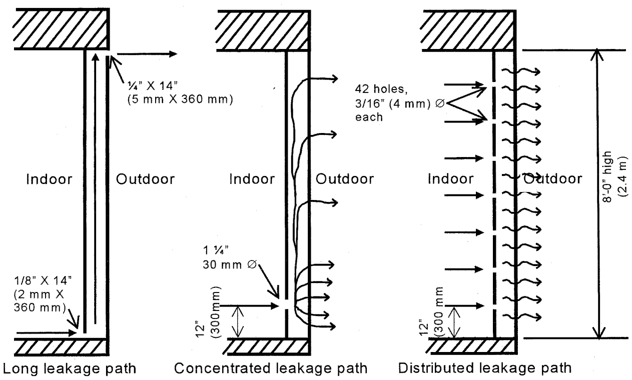

Figure 2 *Illustration of air leakage paths (vertical section across assemblies).*

TABLE 1
Summary of Sample Section Configurations

Section number		89 mm glass fiber only	38 mm polystyrene added on exterior side	38 mm polystyrene added on interior side
1	**Long** leakage path			
2	**Concentrated** leakage path			
3	**Distributed** leakage path			
4	**Long** leakage path			
5	**Concentrated** leakage path			
6	**Distributed** leakage path			
7	**Long** leakage path			
8	**Concentrated** leakage path			
9	Airtight			

(on the outdoor side, over the fiberboard sheathing, for three sections and on the indoor side, on the warm side of the glass-fiber batt insulation, for two sample sections). No insulation was added to the other four sections. The three wall compositions studied are illustrated in Figure 1. Table 1 lists a summary of sample section configurations. To assess the impact of different types of air leakage paths on moisture content levels and distribution patterns, intentional openings were made in the interior finish of the sample sections. Three different air leakage paths, as shown in Figure 2, were applied to the three wall compositions described above:

1. A long air leakage path, where air enters through a narrow crack in the interior finish at the bottom of the wall and exits

TABLE 2
Gravimetry Monitoring Schedule

Wetting period (day into test)								
0	7	15	22	31	37	45	59	72
12-May	19-May	27-May	3-June	12-June	18-June	26-June	10-July	23-July
Drying period (day into test)								
73	80	87	97	104	113	119	73	80
24-July	31-July	7-Aug	17-Aug	24-Aug	2-Sept	8-Sept	24-July	31-July

at the top of the exterior sheathing panel, which would represent the case where the interior finish/floor junction is not sealed;

2. a concentrated air leakage path, where air enters through one circular opening in the interior finish and flows out through the whole surface and cracks of the exterior sheathing, as may occur with electrical outlets; and
3. a distributed air leakage path, consisting of a series of small holes uniformly distributed across the surface of the interior finish, which should provide a uniform air leakage rate over the surface of the envelope, such as is often the input for computer models.

The total area of intentional openings is the same in the sections with the long or concentrated paths, namely 7.0 cm^2 per section. This total area is based on air leakage data from a survey performed on houses across Canada by Hamlin and Gusdorf (1997). The total area of intentional openings for the sections with the distributed leakage path[1] is 5.3 cm^2. In all sections, possible paths other than those intended were sealed. One section was made airtight to serve as reference.

Moisture content levels in the fiberboard and outdoor edge of wood studs, as well as temperatures on the cold and warm sides of the batt insulation, were monitored according to a grid determined by the leakage path of the sample section. In the vertical direction, the grid was tighter (6 in. [150 mm]) around indoor air entry points and looser (12 to 24 in. [300 to 600 mm]) for the rest of the section. In the horizontal direction, the distance was constant at 6 in. (150 mm). The monitoring grids were devised with the intent of producing maps from the data. Figure 3 shows the temperature and moisture content monitoring grid for the air exfiltration paths studied.

Moisture content levels in the fiberboard sheathing were monitored, using a total of 144 removable gravimetric samples (1.5 in. [38 mm] in diameter) and, in the wood, using 48 1.5-by-0.5-by-0.5-in. (38-by-12-by-12-mm) samples. Precautions were taken to minimize the impact of the presence of samples on the behavior of the assemblies, such as avoiding air leakage at their perimeter. The gravimetric samples were

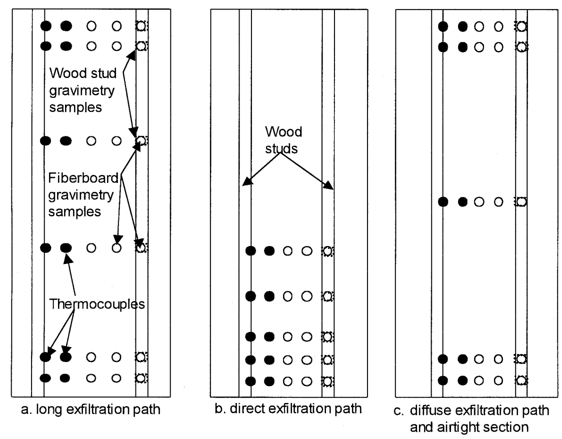

Figure 3 *Temperature and moisture content monitoring grid (elevation view of sample sections).*

weighed nine times during the wetting period and seven times during the drying period. Table 2 shows the actual gravimetric weighing schedule for both climatic periods. The first row gives the number of days into the test and the second row gives the actual date of the data collection. The data in Tables 4 and 5, as well as the moisture content maps presented in Figure 5, correspond to the moisture content data measured on day 59 into the test (indicated in bold in Table 2).

Weather data collected for Montreal over the last 12 years were used to determine the actual conditions in the climatic chamber, while the conditions inside the test hut were based on *ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy* (refer to Desmarais et al. [1998, 2000] for details on the selection of the climatic conditions). To study moisture accumulation and evacuation, the experiment was divided into a wetting period and a drying period. The conditions of each period are listed in Table 3 and the conditions that were achieved are presented in Figure 4.

MOISTURE PERFORMANCE OF ASSEMBLIES TESTED

The results presented in this paper focus on the moisture performance of the assemblies. Other results, including temperature maps, have been presented elsewhere (Desmarais et al. 1998, 2000). To provide a global idea of the moisture performance, average results are tabulated and moisture

1. The number of holes was limited by the presence of wood strapping and thermocouples on the warm side of the batt insulation. Holes were also to be as small and distributed as possible, explaining the smaller area of openings.

TABLE 3
Conditions for Each Climatic Period

Period	Outdoor temperature (°F [°C])	Indoor temperature (°F [°C])	Indoor relative humidity (%)	Air pressure differential (Pa)	Duration (Days)
Wetting	17 (-8.5)	72 (22)	50	4	72
Drying	63 (17)	73.5 (23)	45	1	47

TABLE 4
Average Fiberboard Gravimetric Moisture Content Values, Day 59 (July 10)*

	Long path	Concentrated path	Distributed path	Airtight	Average
Base case	17%	20%	19%	13%	17%
Cold side insulated	22%	27%	20%		23%
Warm side insulated	13%	15%			14%
Average	17%	21%	20%	13%	

* The area of openings in the interior finish for the distributed air leakage path is smaller than the area of openings for the long and concentrated air leakage paths (5.3 cm^2 compared to 7.1 cm^2).
Data presented in the tables, the charts, as well as in the maps for the base case, airtight section and the section with insulation added on the cold side and distributed path, were corrected to eliminate the effect of two manipulation errors made for these two sections by using data from neighboring samples to extrapolate values.

content maps for all assemblies are presented. Then, the analysis focuses on the moisture content variations versus time for the long air leakage path assemblies where graphs and maps are presented.

The moisture content measurements taken on Day 59 of the test on all gravimetric fiberboard samples are averaged for each sample section. As presented in Table 4, the sections with rigid insulation added on the cold side of the glass-fiber batt insulation have the highest average moisture contents at 23%. Those with rigid insulation added on the warm side have average moisture contents lower than the base case assemblies. The sections with the lowest average moisture contents are the airtight section and the section with the long air leakage path and insulation added on the warm side of the glass-fiber batt insulation—both at 13%. The sections with the concentrated and distributed air leakage paths have higher average moisture contents than those with the long air leakage path or the airtight section.

The maximum moisture content values measured in the fiberboard for each section on Day 59 are also presented in Table 5. When comparing the two tables, Table 4 shows lower numbers and a variation of 14% between the lowest and the highest moisture content averages, while Table 5 shows significantly higher numbers and a variation of 45% between the lowest and the highest maximum moisture content values. The fiberboard in the three sections with rigid insulation added on the cold side of the glass-fiber batt insulation reached the highest moisture content—particularly those with the long and concentrated air leakage paths (61% and 53% maximum moisture content, respectively). Fungus can grow in wood from a moisture content of 19% and both grow and germinate at moisture content above 28%, i.e., above the fiber saturation point of the wood (CMHC 1999). The high maximum moisture content values presented in Table 5, therefore, constitute a warning that, although the average moisture content did not rise above 27% for any of the sample sections studied, potential local problem areas may still exist. These problem areas are generally linked to the indoor air entry point into the assembly.

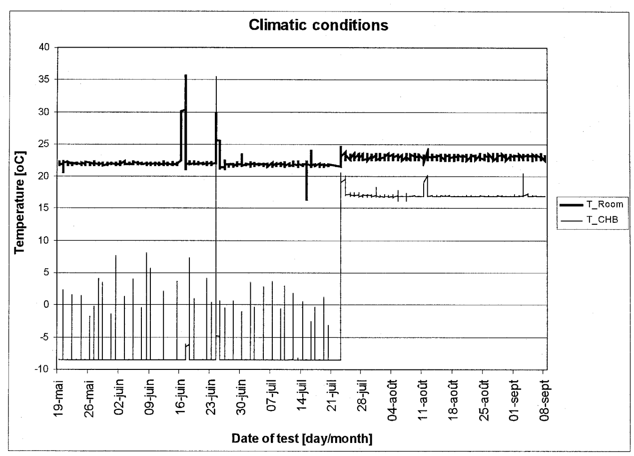

Figure 4 *Temperature conditions achieved during the experiment.*

To illustrate the moisture accumulation patterns for all walls, the gravimetric data collected for the fiberboard sheathing on Day 59 was also used to produce contour lines of equal moisture content, called *isohygrons*, presented in Figure 5. The same scale is used for all nine assemblies—from 10% to

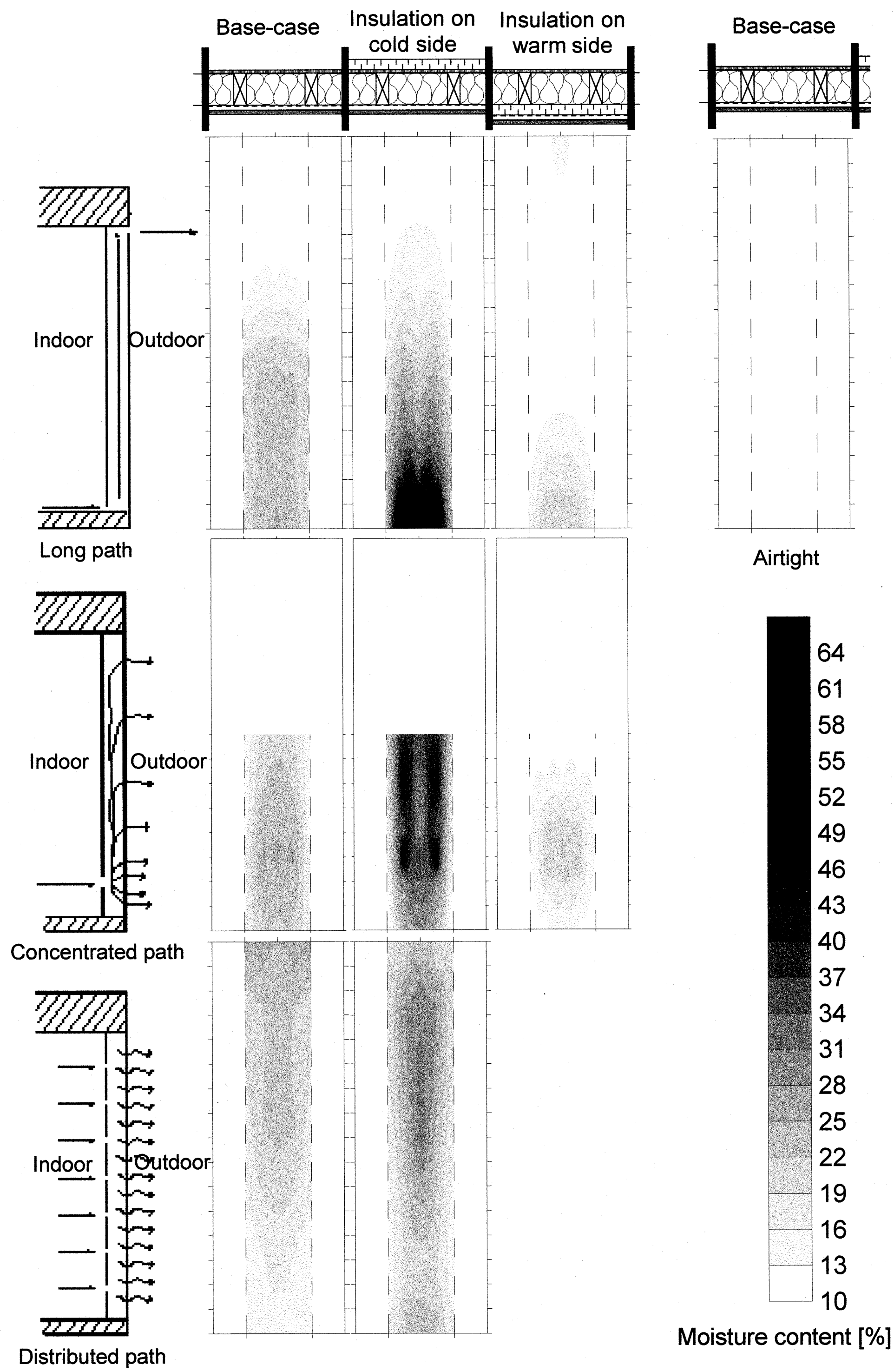

Figure 5 *Moisture content maps for Day 59 (July 10th) into the wetting period.*

TABLE 5
Maximum Fiberboard Gravimetric Moisture Content Values, Day 59

	Long path	Concentrated path	Distributed path	Airtight	Average of maximum
Base case	25%	26%	26%	16%	23%
Cold side insulated	61%	53%	32%		49%
Warm side insulated	21%	23%			22%
Average of maximum	36%	34%	29%	16%	

64% moisture content per dry weight in the fiberboard sheathing—allowing comparison of the moisture contents and of their distribution patterns among the sections. Between adjacent curves, there is a 3% moisture content difference.

The airtight section (top right corner of Figure 5) shows no curves because moisture content values are very low and do not vary by more than 3% across the whole section. The sections with added insulation on the cold side have areas with lower moisture content, but other areas reach the top of the scale. These sections also have the highest number of curves, corresponding to the largest variation in moisture content across the area of sample sections. The base-case assemblies and the sections with insulation added on the warm side all have moisture content toward the low end of the scale and fewer lines of moisture content change.

From Tables 4 and 5 and the maps of Figure 5, it can be concluded that the insulation strategy had more impact on moisture content levels reached than the type of air leakage. But the absence of air leakage had an even bigger impact, as the airtight section reached moisture content values too low to be registered on the scale that was used. The curves also confirm that the moisture accumulation pattern is related to the air entry path—the bottom of the wall has a higher moisture content for the sections with the long exfiltration, while higher moisture content levels are mostly found around the circular opening for the sections with the concentrated path.

In the results presented, the insulation strategy has more impact than the geometry of the air entry point on the moisture performance of the wall. Therefore, the impact of the insulation strategy is further discussed for one case of air leakage. The three sections with the long air leakage path are compared to the base case airtight section in terms of moisture content vs. time plots and isohygrons maps.

The moisture content levels for nine gravimetric samples in those four sections are plotted over time and presented in Figures 6 through 9. The following samples are presented:

1. The top, 1/3 down, and bottom samples located midway between the studs;
2. The top, 1/3 down, and bottom fiberboard samples in front of the studs;
3. The top, 1/3 down, and bottom wood samples located on the outer flange of the studs.

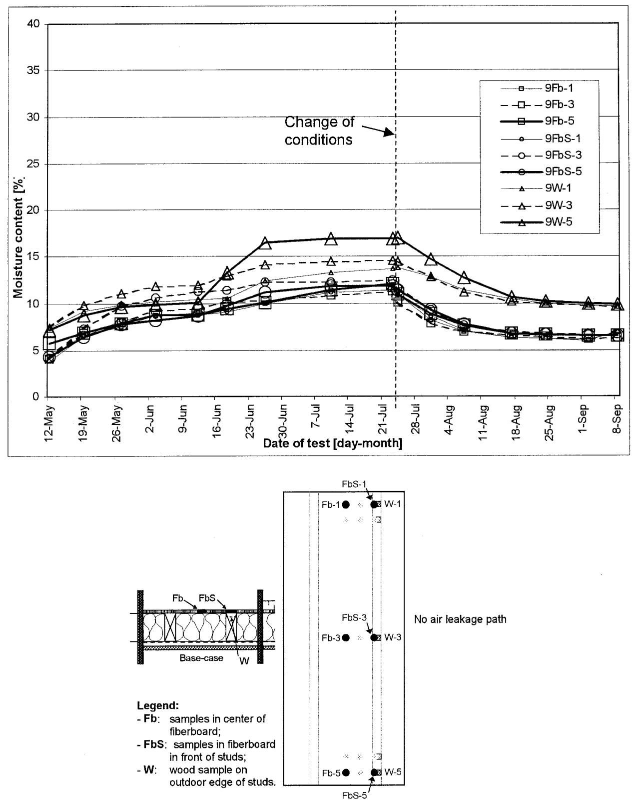

Figure 6 Gravimetry results, base-case assemblies, airtight.

A scale of 0% to 40% moisture content per dry weight was used in three cases. However, for the section with insulation added on the cold side and long leakage path (Figure 8), a scale of 0% to 75% was necessary. The moisture content axis is located at Day 72 (July 23), corresponding to the last day of the simulated winter conditions. The thinnest line shows data for the samples at the top, the dotted line shows data for the samples one-third down, and the thick line shows data for those at the bottom of the sample section. The squares are used to represent the fiberboard samples located between the studs, the circles represent the samples in front of the studs, and the triangles represent the wood samples from the outdoor flange of the studs. The samples presented on these graphs are identified and are darker on the sketches accompanying the charts.

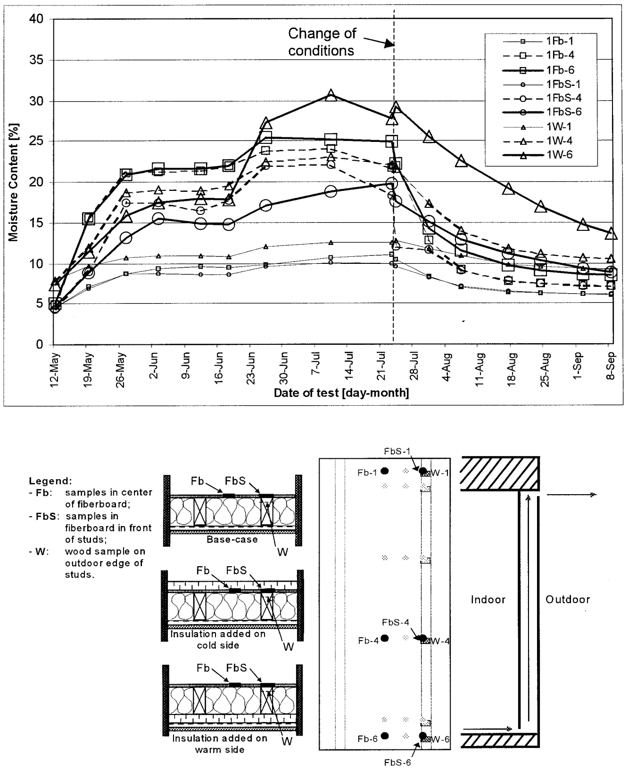

Figure 7 Gravimetry results, base-case assembly, long path (bottom sketch also applies to Figure 8 and Figure 9).

The section with the least moisture accumulation over the wetting period of the test is the airtight, base-case assembly (Figure 6). This section also had the slowest moisture accumulation rate and the least variation between moisture content levels at different locations (i.e., 5%). The moisture content in the wood studs (triangular markers) and in the fiberboard in front of the wood studs (circular markers) increased slightly more than those in the fiberboard between the studs (Figure 6). After the drying period was completed, the moisture contents of all samples—fiberboard and wood—were close to the original value, being 2% higher on average. All wood samples had reached the same moisture content per dry weight at the end of the drying period, indicating that equilibrium had likely been reached. The same applied for the fiberboard samples of this sample section.

For the section with the same base-case composition but also with a long leakage path (Figure 7), higher moisture content levels were reached in the fiberboard and wood studs for the 1/3 down and lower samples. All top samples remained below 15% for the whole duration of the test. Other samples remained below 25% except for the lowest wood samples, which reached 30%. Contrary to the section with no leakage, some samples were still drying and not all gravimetric samples had reached equilibrium at the end of the test. For a given height, the fiberboard samples taken between the wood studs had a higher moisture content than those in front of the wood studs.

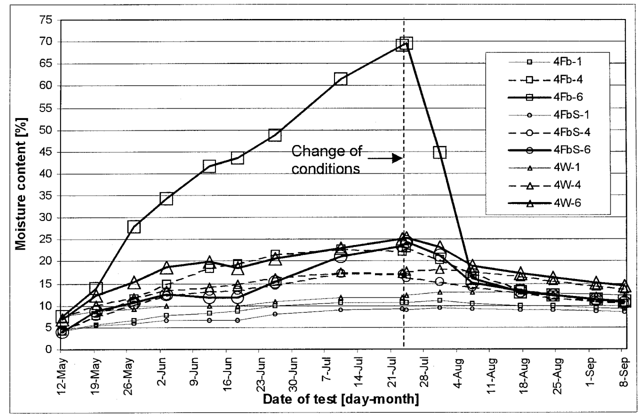

Figure 8 Gravimetry results, insulation added on cold side, long path.

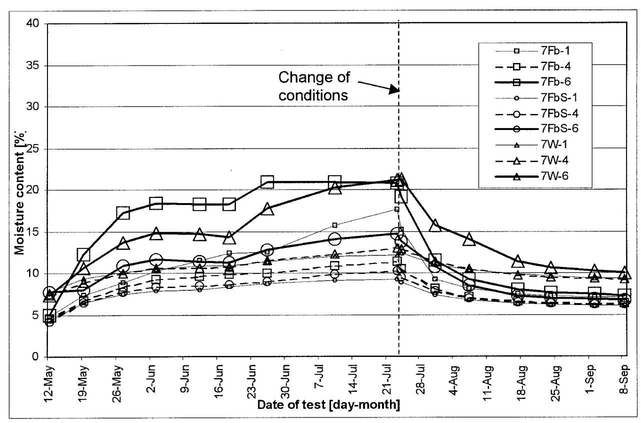

Figure 9 Gravimetry results, insulation added on warm side, long path.

For the section with insulation added on the cold side and the long leakage path, moisture content as high as 70% was reached in the fiberboard. At the end of the drying period, moisture content levels remained 5% to 7% higher than before the test started, suggesting that their drying is slightly lower than that of the base-case section and of the section with insulation added on the warm side. As for the other sections with the long air leakage path, lower samples, which are closer to the indoor air entry point, tend to have higher moisture contents than those at higher locations.

Moisture content levels in the section with rigid insulation added on the warm side and long leakage paths did not rise above 23%. A vertical moisture content stratification is also observed for this section.

During the experiment, frost was observed on the exterior surface of the fiberboard sheathing of the sections with rigid insulation added on the warm side and of the base-case assemblies. At the change of temperature, this frost melted and moderately increased the moisture content in some gravimetric samples. By the next weighing, moisture content had significantly lowered.

The initial moisture content for all sample sections considered is below 10% moisture content per dry weight. By the end of the test, most moisture content measurements were at or below this level except for the section with insulation added on the cold side. In this section, a large area of the fiberboard remained at a moisture content between 10% and 15% at the end of the test. This section also showed a faster moisture accumulation rate and higher moisture content levels were reached in the fiberboard. The section with the slowest and lowest moisture accumulation is the base-case, airtight section. The sections with the long leakage path, with no insulation added and with insulation added on the warm side, had a similar performance in terms of moisture accumulation according to these maps, with the latter performing slightly better.

A critical aspect to assess the moisture performance of walls is the amount of time that wood-based materials within assemblies spend at moisture content levels above 19% moisture content per dry weight. Moisture content levels in the airtight assembly never reached that level. In the section with insulation added on the warm side, a very small portion at the bottom did for about 30 days. Significant portions of the leaky base-case section remained above 19% for a period of 12 weeks but at a time when temperature conditions at the fiberboard plane were too cold to sustain fungi activity (below freezing). During the same period, significant zones of the section with insulation added on the cold side were also above 19% moisture content per dry weight. In this case, the temperature at the plane of the fiberboard was 32ºF (11ºC), which is warm enough to sustain fungal activity.

The only section showing regions with moisture content levels above 28% is the section with insulation added on the cold side and long leakage path. These levels were reached during a nine-week period. The moisture accumulation is concentrated at the bottom, close to the indoor air entry point into the assembly. This indicates that entry of moist indoor air in this assembly poses a risk of moisture-related problems, as the temperature conditions at the fiberboard plane are favorable to mold growth for this section.

DISCUSSION AND CONCLUSIONS

The moisture content results are used to assess the impact of adding extruded rigid polystyrene insulation on the hygrothermal behavior of existing, leaky exterior wall assemblies. When insulation was added on the warm side of leaky assemblies, moisture content measurements did not rise above 25%, while they increased to 70% when insulation was added on the cold side. On the other hand, the airtight section with no insulation added showed the lowest moisture accumulation. Even though the thermal performance of the base-case airtight section is lower, it performed best in terms of overall hygrothermal performance. The high moisture contents for the sections with insulation added on the cold side may be explained by the fact that the temperature at the interface between the fiberboard sheathing and the rigid insulation was above freezing but below the dew point of the indoor air at 58ºF (14.5ºC). For this type of assembly, when moisture, transported by exfiltrating air, reached this point, it condensed on the indoor surface of the rigid insulation and was absorbed by the fiberboard and the wood. During the wetting period, when a piece of rigid insulation was removed from the cold side to access the gravimetric samples, water was observed on its indoor surface. In addition, the vapor-tight insulation seems to have impeded drying to the exterior when conditions were changed from wetting to drying. The sections with insulation added on the warm side showed moisture accumulation, but to a lesser degree. In this type of assembly, the rigid insulation seems to have reduced convection within the assembly, as well as to have slightly improved the drying ability compared to the sections with insulation added on the cold side.

Adding 1.5 in. (38 mm) of rigid insulation to the cold or warm side of existing assemblies increases the thermal performance by 55% (from R14 (2.45 $m^2 \cdot$ºC)/W to R24 (4.81 $m^2 \cdot$ºC/W). The total R-value for the assemblies is the same whether rigid insulation is added on the cold side or on the warm side of the base-case assembly (insulated with glass-fiber batt insulation). In addition, dew point calculations indicate that there would be no significant moisture accumulation for airtight assemblies with insulation added either on the cold side or on the warm side of the batt insulation. However, when tested, these two assemblies demonstrated moisture accumulation, which was due to the exfiltration of moist indoor air through the assembly. Improvements in the thermal performance should therefore be examined in conjunction with air transfer as well as moisture transfer. Air leakage through the envelope has a major impact on moisture accumulation and should be minimized to avoid moisture problems. Results also indicate that exterior wall assemblies with a vapor-tight insulating material on the outside may be more sensitive to air leakage, especially if conditions are such that temperature conditions on its indoor face are above the freezing point of water but below the dew point of the indoor air, as was the case here.

Some conclusions concerning the execution of the type of retrofit work studied arise from the analysis of the data. The first one is that increasing the level of airtightness of the building envelope should be considered before adding insulation to existing exterior wall assemblies. This would help in reducing convective heat losses and in lowering the risk for moisture accumulation related problems. Allowing uncontrolled air leaks through the envelope greatly increases the probability for moisture-related problems, which tend to be concentrated around air entry points. When adding insulation, it has been found that adding 1.5 in. (38 mm) of rigid extruded polystyrene on the cold side of the assembly increases the risk of moisture accumulation-related problems because of its low vapor and water permeability and of the temperature conditions at its indoor surface. On the other hand, adding insulation on the warm side of the existing building envelope reduces these risks, partly because it helps in improving the airtightness and also because the vapor-tight material is on the indoor side of the dew point. The present conclusions and recommendations apply for the sample sections tested for this project under the climatic conditions provided. Though they provide some direction toward the execution of such retrofit work, they cannot be generalized to all existing exterior wall assemblies and all insulation materials.

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