
Temperature and Moisture Performance of Wall Assemblies with Fiberglass and Cellulose Insulation

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ABSTRACT

A three-year study in Champaign, Illinois, was designed to measure the thermal and moisture performance of various typical wall assemblies, especially OSB sheathing, under field conditions. The variables that were studied included

- insulation material (fiberglass and cellulose),
- vapor barriers (none, polyethylene, and facing material),
- encapsulation materials,
- means of attachment of facing material, and
- location within the wall cavity.

Measurements of temperature and moisture content, using Duff probes, were gathered at hourly intervals over three winters, and plugs made of the OSB sheathing material were regularly weighed for gravimetric moisture content measurements. The interior was maintained at constant humidity—50%-55% for one year and 40% for two subsequent years. Following the study, the walls were disassembled and inspected for sheathing condition and mold growth.

Two samples with no vapor diffusion protection, one cellulose and one fiberglass, showed unacceptably high levels of mold growth. All of the samples with vapor barriers or encapsulation remained at a safe level of moisture content. Some of the samples with encapsulated and faced material showed mold growth at the tops of the cavities, particularly where cabling pierced the interior drywall.

The construction and building pressure management for this study were such that the moisture performance is a consequence of the diffusion/capillary regime, not the air leakage regime. The cases that were unacceptably bad in this study were affected by diffusion and capillary moisture, not air leakage, under the interior and exterior loads imposed by the test.

INTRODUCTION

The aim of this research was to characterize the temperature and moisture performance of various wall assemblies under field conditions, particularly with varying insulation materials, facings, and encapsulation fabrics. The variables that were studied included

- insulation material (fiberglass and cellulose),
- vapor barriers (none, polyethylene, and facing material),
- encapsulation materials,
- means of attachment of facing material, and
- location within the wall cavity.

It was not the aim of this study to estimate the effects of air leakage through the envelope assembly. The setup was designed to exclude air leakage effects. Some minor air leakage effects did appear, as are described below.

The concern of the study was to determine the effect of various vapor protection measures on preventing or reducing the sheathing moisture content and incidence of mold growth or loss of structural strength in the noninsulating sheathing.

BACKGROUND

The temperature and moisture performance of wall assemblies has been the subject of much study in the last 50 years. For the history of vapor barriers see Rose (1997).

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Rowley conducted the first measurements of temperature and moisture conditions in wood frame wall assemblies (Rowley et al. 1939). His early work involved measurement of thermal resistance of building materials and the theory of one-dimensional heat flow in building assemblies. His later work in the late 1930s promoted the diffusion theory of moisture transport and led to the introduction of the vapor barrier. He discounted the importance of air leakage in moisture transport.

The first regulation for vapor barriers appeared in the January 1942 revision to the *Property Standards and Minimum Construction Requirements for Dwellings* of the Federal Housing Administration (FHA 1942). This same document is the source of the 1/150 venting rule for crawl spaces and 1/300 venting rule for attics.

Britton (1948a, 1948b) studied heat and moisture transport in walls and attics in a climate simulator, with the FHA 1942 guidelines as the baseline. His results did not fully support the guidelines; then the research was suspended for lack of funds. Nevertheless, Britton (1949) participated in the publication of *Condensation Control in Modern Dwelling Construction* by the Housing and Home Finance Agency (HHFA 1949), which mandated the use of vapor barriers and ventilation in residential construction as a function of climate. Work was also conducted at the National Bureau of Standards under Richard Dill (1946).

Meanwhile in Canada, Hutcheon (1954) and others noted the poor fit between the diffusion theory (upon which the use of vapor barriers was predicated) and findings in the field, and they postulated the relative importance of air leakage as a moisture transport mechanism.

In the 1980s, several researchers investigated the performance of wall assemblies, particularly for the performance under air leakage. The present work is similar in many respects to the work of Sherwood (1983). In that study, a field laboratory in Madison, Wisconsin, was maintained at fixed indoor humidity (40%) over several winters and the temperature and moisture contents of the sheathing materials were recorded. Sherwood varied the sheathing material but used only fiberglass as the cavity insulating material. In the present study, the sheathing material was the same for all the samples, but the insulating materials included not only fiberglass but also cellulose. Sherwood found (as this study does) that the driest conditions were found in those cavities with polyethylene vapor protection. His work, in the second phase, demonstrated that penetrations in the vapor retarder severely compromise the moisture performance of the cavity. He noted, but did not explore, the patterns of mold growth. One aim of the present study was to explore mold growth more thoroughly.

SETUP

In December 1994, the walls of a laboratory building (BRL) at Champaign, Illinois, were configured for this study. The study began with the installation of eight samples in four bays of the BRL. In fall of 1995, eight more samples were added. The instrumented cavities were on the south side of the

laboratory building. It is well known that wintertime moisture problems caused by diffusion are greater on the north sides of buildings, but the placement of wiring conduit and piping on the north side of the laboratory precluded use of that side.

The layout for a typical bay is shown in Figure 1. Each bay wall is 8 ft high and 8 ft wide and contains six framing cavities. Each bay contained two samples, giving three cavities for each sample.

The building was reconfigured as follows: The original rigid foam insulating sheathing was removed and new sheathing of 7/16 in. OSB was nailed to the 2 × 4 stud framing. The framing was several years old, so construction moisture was not an element of this study. In addition, the exhaustion of construction moisture led to greater dimensional stability in the framing and to a snug fit of the gypsum and OSB panels to the framing. The airtightness of the resulting wall assembly was not tested; however, it should be considered tighter than new construction but looser than a designed air barrier system.

Holes of 2 in. diameter were cored in the OSB sheathing in the locations shown in Figure 1. Plugs of 2 in. diameter were cut to fit snugly into the holes (see Figure 2). These plugs were weighed at regular intervals to measure the pickup of moisture by the sheathing, i.e., to determine the gravimetric moisture content. At the end of the study periods, they were oven dried to determine a dry basis weight for the plug, and that dry weight was used in determining the plug moisture content over the course of the winter periods. The plugs from the first year were not usable at the end of the winter, so entirely new plugs were used for the second and third test winters.

The original vinyl siding was replaced directly over the OSB, with allowance for removal of the sheathing plugs.

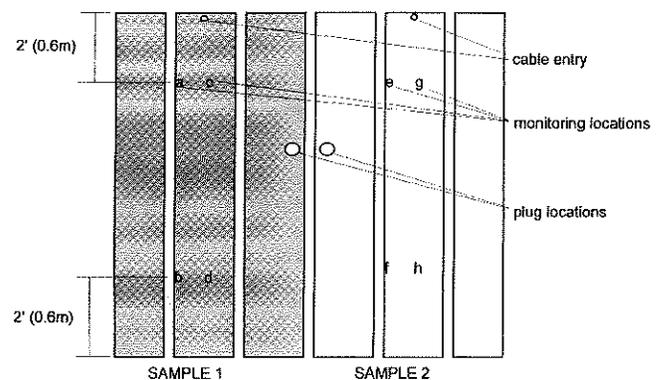


Figure 1 Layout of wall cavities in a typical bay of the laboratory. Each bay contains two samples, each sample occupying three cavities. The two circles indicate the location of plugs used for gravimetric measurement. The letters indicate placement of probes for temperature and moisture content measurement. Note: In the 1996 installation, *e* and *f* were located in the center of the cavity, while *g* and *h* were located at the right-hand edge.

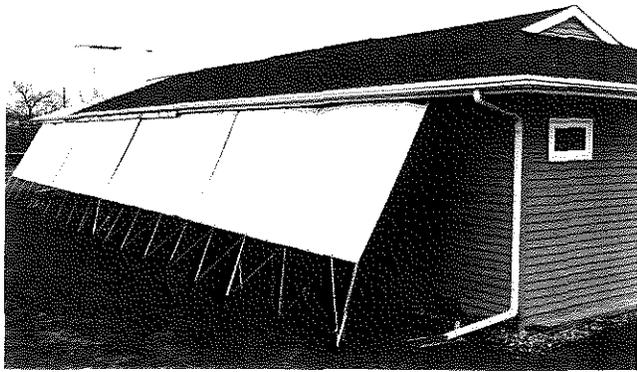


Figure 2 Test building with tarpaulin in place, serving as a solar shield.

A nylon tarpaulin was installed from the edge of the fascia down toward the ground as a sun shade (see Figure 3). The tarp was installed to allow the maximum amount of air to flow across the siding while excluding almost all of the direct sun impingement on the wall. The tarpaulin reduced the slight nighttime radiant cooling that might have affected the wall.

Table 1 contains the pertinent information regarding the setup of the test.

Heating was by individual electric resistance units with recirculating fans. There was no mechanical pressurization or depressurization.



Figure 3 Test building wall with removable plug.

Insulation and Finish

Fiberglass. Fiberglass insulation was installed with attention to filling the cavity and not leaving gaps. In the cavities that were narrower than the standard 14.5 in. due to partition framing, the encapsulated batts were peeled apart, the insulation was trimmed, and the encapsulating sheets were folded back in place. Kraft-faced insulation was face-stapled, except in the unstapled samples 10 and 14 and the inset stapled (sample 7). The blown-in-batt (BIB) system was professionally installed (Bay 6, samples 11 and 12).

TABLE 1
Summary of Wall Insulation Study

Sample	Code	Insulation	Vapor Protection	Conditions	Installation
1	1efgh	Cellulose	4 mil poly	Electrical openings	July 1995
2	1abcd	Cellulose	4 mil poly	No openings	July 1995
3	2efgh	Cellulose	No vapor barrier	No openings	Dec. 1994
4	2abcd	Batt (1)*	Encapsulated poly/poly		Dec. 1994
5	3efgh	Batt (1)	Unfaced, no vapor barrier		Dec. 1994
6	3abcd	Batt (1)	Encapsulated poly/kraft		Dec. 1994
7	4efgh	Batt (1)	Kraft facing	Inset stapled	Dec. 1994
8	4abcd	Batt (1)	Encapsulated non-woven		Dec. 1994
9	5efgh	Batt (1)	Unfaced, 4 mil poly		Dec. 1994
10	5abcd	Batt (1)	Kraft facing	Unstapled	Dec. 1994
11	6efgh	Blown-in-batt (BIB)	No vb		July 1995
12	6abcd	BIB	4 mil poly		July 1995
13	7efgh	Batt (1)	Kraft encapsulated	Stapled	July 1995
14	7abcd	Batt (1)	Kraft encapsulated	Unstapled	July 1995
15	8efgh	Batt (2)	Kraft encapsulated		July 1995
16	8abcd	Batt (3)	Poly encapsulated		July 1995

*Numbers in parentheses refer to batts of different manufacturers.

TABLE 2
Density of Cellulose

Cavity	Location	Density
1A	Top	2.24 pcf
1A	Bottom	1.04 pcf
1E	Top	1.17 pcf
1E	Bottom	1.72 pcf
2E	Top	1.40 pcf
2E	Bottom	0.88 pcf

Cellulose. Cellulose was installed during the first installation in December 1994 and also installed in July 1995. For the 1994 installation in Bay 2, first blown-in-batt netting was stapled over the cavities and the lower drywall board was fastened in place. Then cellulose was blown in place with rented blowing equipment. The installation was messy. In the subsequent installations in Bay 1, the material was hand-poured and packed into place. The resulting densities, measured at the completion of the project, showed considerable variation (see Table 2).

At the end of the test, it was noted that there was considerable settling in the hand-packed cavities, up to 6 in., but there was no settling in the mechanically blown cavities.

Four mil polyethylene was stapled over samples 1, 2, 9, and 12.

Finish. Once the insulation placement was complete, the interior finishes were put in place. Half-inch drywall was installed on the inside with no holes, except for the inclusion of electrical boxes in sample 1. The holes for cable penetration were filled with acrylic caulk; the margin around the cable bundle appears to have been filled well, but the air spaces between the cables appear to have not been completely filled. Two coats of latex paint were applied to all drywall surfaces. Vapor permeances were not tested for any of the materials used in this study.

Instrumentation

The principal electronic instrumentation was for thermocouple temperature measurement and moisture content measurement. Thermocouples were placed in the cavities to measure the temperature on the inside surface of the sheathing at a point 2 ft down from the top plate and 2 ft up from the sill plate in the center cavity of each sample. A thermocouple was placed at the outside of the sheathing on the north side and at a corresponding location on the south side in order to compare the surface temperatures and thereby estimate the likelihood of damage to north-side walls under the same conditions. Findings from this study indicate that the performance at the top and bottom plate is critical; a future study will include instrumentation at those locations.

The moisture measurement technique used for this project was electric resistance, developed in the 1960s by John

Duff. The individual moisture content probes ("matchstick probes") were manufactured for this project. The resistance-reading meter had an output of 0 mV to 2500 mV. Meters were changed during the study, and it was noted that there was a rather high interchangeability error among meters. Thus, the year-to-year electronic correlations are considered suspect, while within any year, the sample-to-sample correlations are consistent and significant.

For each sample, there were four sites where moisture content measurements were taken, as shown in Figure 1. Two probes were placed at each measurement site to help provide an estimate of measurement error. Thus, at each of the positions a through h, two probes were placed, making a total of 64 probe locations.

The thermocouples and moisture probes were connected by cable to moisture meters and data loggers for recording hourly values. The cables were run to the tops of the cavities, and considerable effort was put into ensuring airtightness at the site of the cable penetrations through the insulation and the interior drywall. Nevertheless, the effect of these penetrations was seen to be strong.

Weather measurements were made at the site.

Temperature and Humidity Control

The indoor temperature was set at 21°C. During the winter of 1995, the indoor relative humidity in the laboratory was maintained by capacitance sensors used for control at 50%-55%; in winters 1996 and 1997, the indoor relative humidity was reduced to 40%. The indoor humidity was controlled using humidity probes with $\pm 3\%$ tolerance, but it was found that, compared to humidity measurements using a chilled mirror dew-point sensor, the control probes were over-reporting by about 4%. The control set point was put at 55%, and the measurements varied in the 50%-55% range using the more reliable chilled mirror method.

The bay-to-bay relative humidities were very consistent, varying no more than 2% RH by both capacitance probe and chilled mirror probe.

FINDINGS

General

The results are presented in terms of (1) electronic measurements, (2) gravimetric measurements, (3) observed mold growth, and (4) other moisture-related observations.

The gravimetric measurements were made at regular (and at times infrequent) intervals. The continuous electronic measurements were made every hour during each of the three winters of study, but they require correlation with gravimetric measurements. The electronic measurements have the benefit of continuity (capturing all the events), while the gravimetric measurements have the benefit of direct measurement for accuracy.

The gravimetric measurements are reported in terms of percent moisture content by weight of the wood samples. The output from the moisture meter is an arbitrary scale (0-2500) that is intended by the meter manufacturer to compare linearly to the moisture content by weight. In this paper, the results from electronic and gravimetric measurements are compared. It will be noted that the agreement between electronic and gravimetric measurements is present but is not particularly strong, and the correlation between electronic and gravimetric measurements changed over the course of the study. Because of this, it was decided that the electronic measurements should not be converted to "moisture content." To report both gravimetric and electronic measurements as "moisture content" would have been confusing. As shown in Figure 6, the relation between moisture meter output (MM) and gravimetric moisture content (GMC) for 1996 and 1997 can be expressed as

$$\text{GMC} = 0.0152 \cdot \text{MM} + 0.07.$$

Weather conditions and interior conditions were monitored and recorded but are not used as part of this analysis. The following weather matters may deserve mention:

- The south-facing walls of this study were effectively protected from direct sunlight.
- Winters 1996 and 1997 were very similar, as shown in Table 3.

The similarity of winter conditions for these two years and the similarity in indoor conditions in 1996 and 1997, together with the dissimilarity in moisture meter output, indicate the likelihood of shift in readings by the moisture meters from year to year.

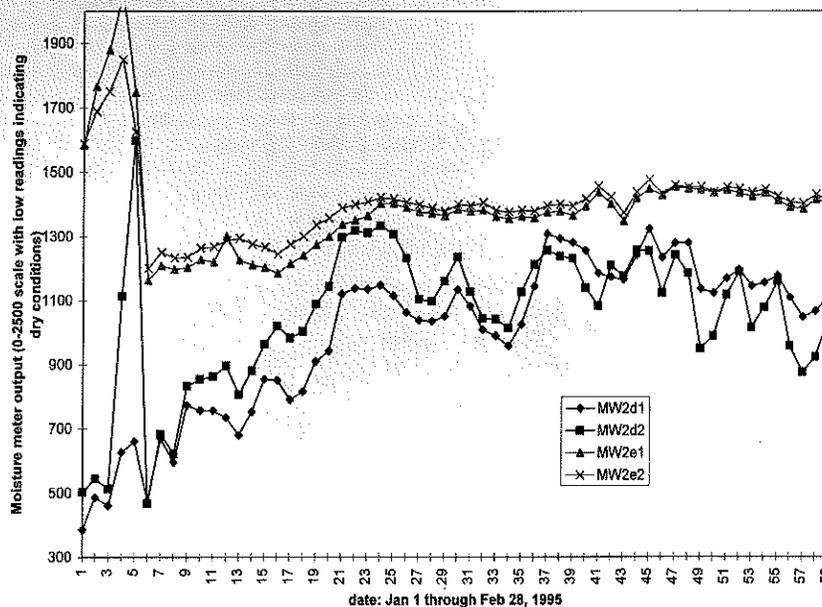


Figure 4 Comparison of two sample locations, two probes in each location, showing probes with slightly varying readings (2d) vs. probes with very similar readings (2e).

TABLE 3
Average and Minimum Winter Temperatures
(January - February)

Year	Average Temp.	Minimum Temp.
1995	-3.43°C	-21°C
1996	-3.86°C	-27°C
1997	-3.82°C	-24°C

Error

The moisture measurements made with the Delmhorst meter measure the electrical conductivity of the wood and correlate that, using electronic shunting, with the presumed moisture content. There are several sources of error. In the short run, the principal error is interchangeability of the matchstick probes; in the long run, the principal errors are salt content of the wood and polarization errors. In order to estimate the short-term errors, the moisture probes were installed in pairs. Figures 4 and 5 can be used to estimate by eye the error due to instrumentation alone.

Figure 4 shows a time line with daily averages from four probes. The two probes at 2e showed very good agreement, while the two probes at 2d showed weaker correlation. Together they illustrate the performance of paired probes. A more rigorous view is seen in Figure 5. Here the pairs of probes are compared. Several points can be noted:

- At low measured values, the probes give very similar results.
- In the high range, differences between two probes can be greater.
- The correlation coefficient (R-squared value) is 0.866.

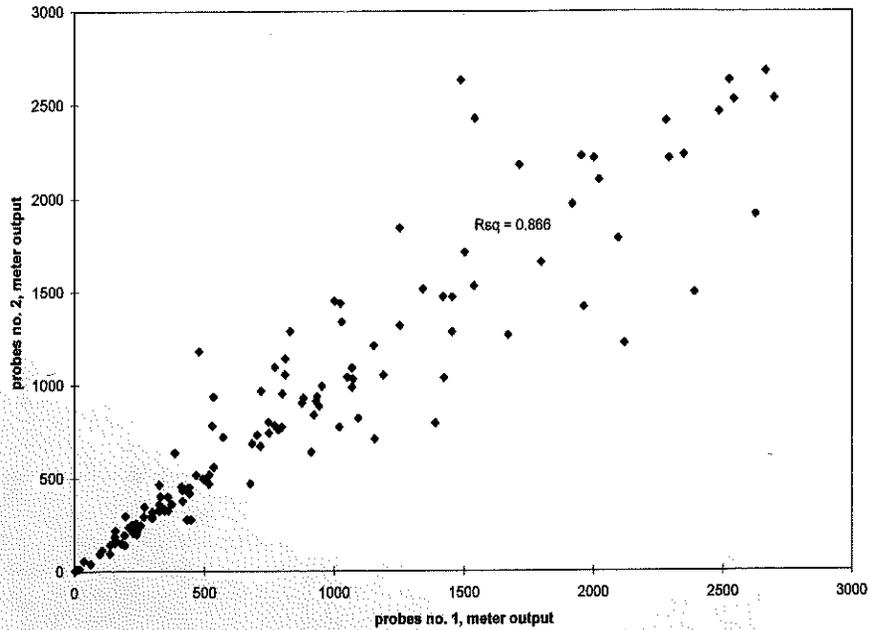


Figure 5 Comparison of output from probe pairs in same locations.

Moisture content in wood bears a relation to the exponent of the electrical resistance. For this reason, a similar difference in resistance will appear smaller under dry conditions (on the order of 103 megaohms) than under wetter conditions (1 megaohm).

A further error lies in the comparison of the electronic and gravimetric measurements. Overall, there is a correlation between these two, but the correlation is not particularly tight. Figure 6 shows the correlation for all of the samples from 1996 and 1997. Here, the correlation, expressed as an R-squared

correlation coefficient, is 0.477. Such a spread may not be disastrous to the results, with the understanding that only a few gravimetric measurements were taken (four measurements during January and February 1997). The discrepancy between these two measurements may be due to several causes, including

- imperfection of the seal around the plugs;
- pair-wise error in probes, as described above;
- difference between surface conditions (detected by the

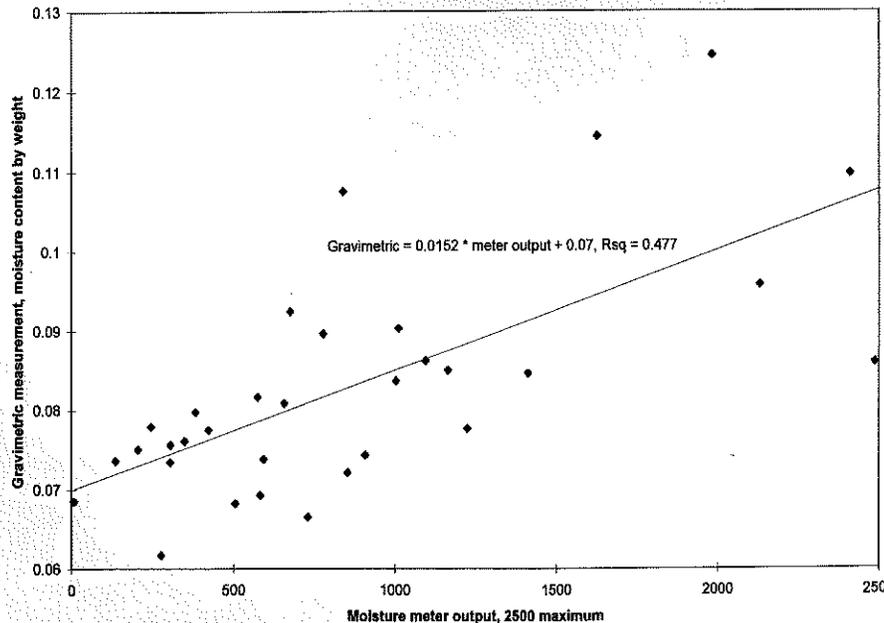


Figure 6 Comparison of average electronic and gravimetric measurements, all samples, 1996 and 1997.

electronic probes) and full-thickness conditions (measured by weighing);

- dissimilarity of conditions at plug and probe locations;
- dissimilarity of sampling times for the two measurement types.

These weaknesses indicate for future work: (1) more gravimetric measurements, (2) better seal on the plugs, and (3) alternative resistance reading circuitry.

The data for this report are the data from January and February of the three years in the study. Other data are on hand, and they confirm the findings here, but the weather was less severe. The January and February data provide appropriate highlights to the winter conditions in this report.

Overall Results

The overall results are shown in Figure 7. Several points can be made.

1. There is a moderate correlation that can be made between the gravimetric and the electronic measurements. This has been seen already in Figure 6. The correlation between electronic and gravimetric measurements holds for the sample-to-sample comparisons but not for the year-to-year comparisons.
2. In 1995, the relative humidity was 50%-55%, while for the subsequent two years, the relative humidity was held at 40%. This appears as a strong influence on the gravimetric measurements. However, it does not appear as a strong influence on the electronic measurements.

3. The clearly unacceptable cases are cellulose insulation and unfaced fiberglass insulation without a vapor barrier of any kind when subject to 50%-55% RH. The other samples exhibit acceptable performance.

During winter 1995 (50%-55% RH), the plugs of the two samples without vapor protection, samples 3 and 5, delaminated from excess moisture content, swelling, and weakening of the plug material.

Table 4 illustrates the performance at 40% RH. The plug weights showed quite low moisture contents, well below fiber saturation or any moisture levels that would indicate mold growth. However, in two of the cases, the electronic measurements showed very high values.

Figure 8 shows the differences from case to case more clearly. In Figure 8, the results have been sorted by their moisture meter performance. The meter values represent the average meter reading for January and February of 1996 and 1997. The 1995 values are not included because of their low meter values, as explained above.

Several points are evident in Figure 8:

1. The four examples with polyethylene sheet are the four samples that present the driest conditions.
2. There is no appreciable difference between the cellulose example with and without electrical openings.
3. Two of the three samples with poly in the encapsulation were the next driest samples. Sample 4, encapsulated poly/poly, performed well but did not appear as low as samples 16 and 6.

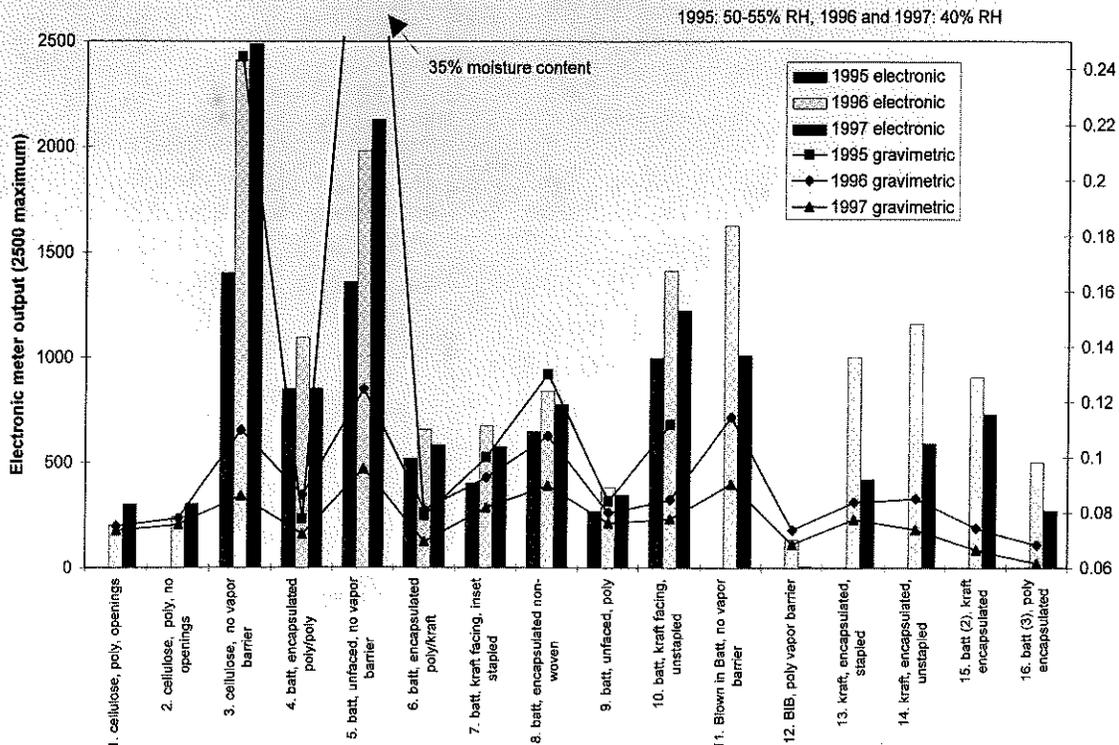


Figure 7 Electronic and gravimetric moisture content, three years.

TABLE 4
Summary of Wall Insulation Study, 1996 Only, 40% RH Interior

Sample	Characteristic	Average	Maximum	Average
1	Cellulose, poly, openings	8.20%	11.09%	203
2	Cellulose, poly, no openings	7.97%	8.79%	243
3	Cellulose, no vapor barrier	11.25%	12.66%	2435
4	Batt, encapsulated poly/poly	8.82%	9.33%	1150
5	Batt, unfaced, no vapor barrier	12.33%	14.78%	2047
6	Batt, encapsulated poly/kraft	8.16%	8.86%	637
7	Batt, kraft facing, inset stapled	9.20%	9.87%	715
8	Batt, encapsulated non-woven	10.32%	11.80%	892
9	Batt, unfaced, poly	7.91%	8.66%	406
10	Batt, kraft facing, unstapled	8.52%	9.28%	1487
11	Blown-in-batt, no vapor barrier	11.24%	12.79%	1639
12	BIB, poly vapor barrier	7.88%	9.19%	133
13	Kraft, encapsulated, stapled	8.24%	9.13%	1002
14	Kraft, encapsulated, unstapled	8.47%	9.34%	1160
15	Batt, kraft encapsulated	7.74%	8.60%	904
16	Batt, poly encapsulated	7.50%	8.46%	504

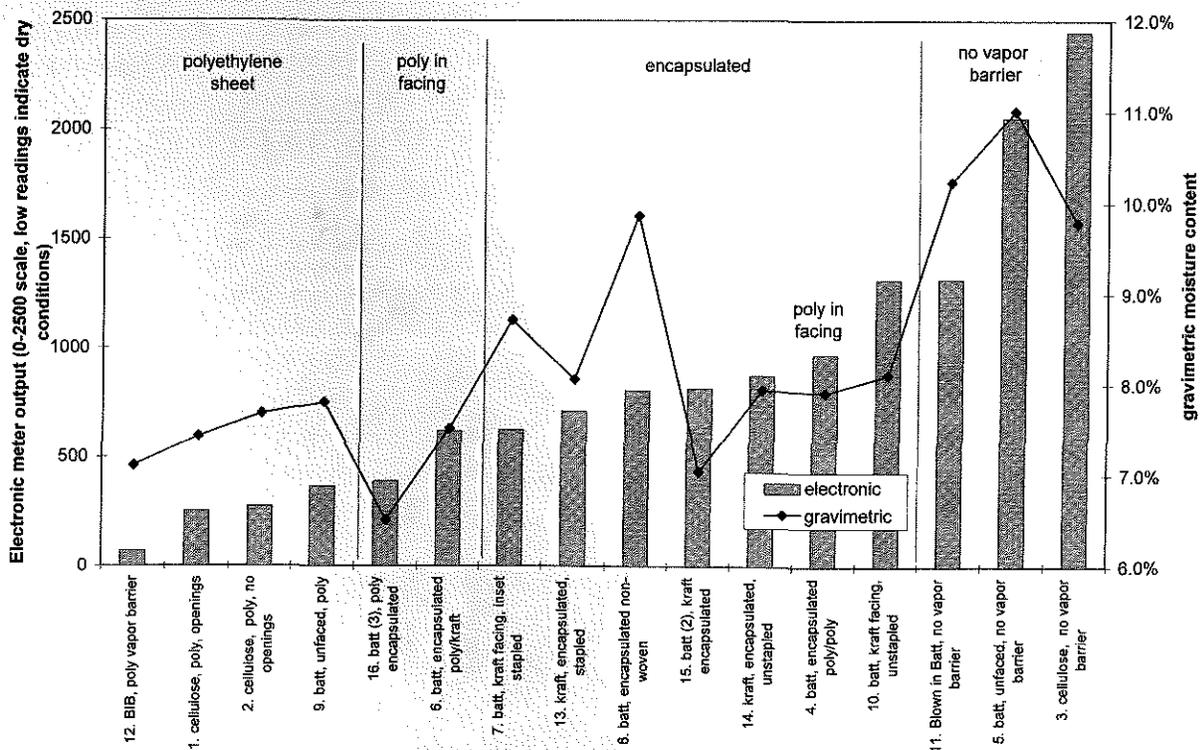


Figure 8 Average moisture readings for 16 samples, ranked, 1996 and 1997 (40% RH interior).

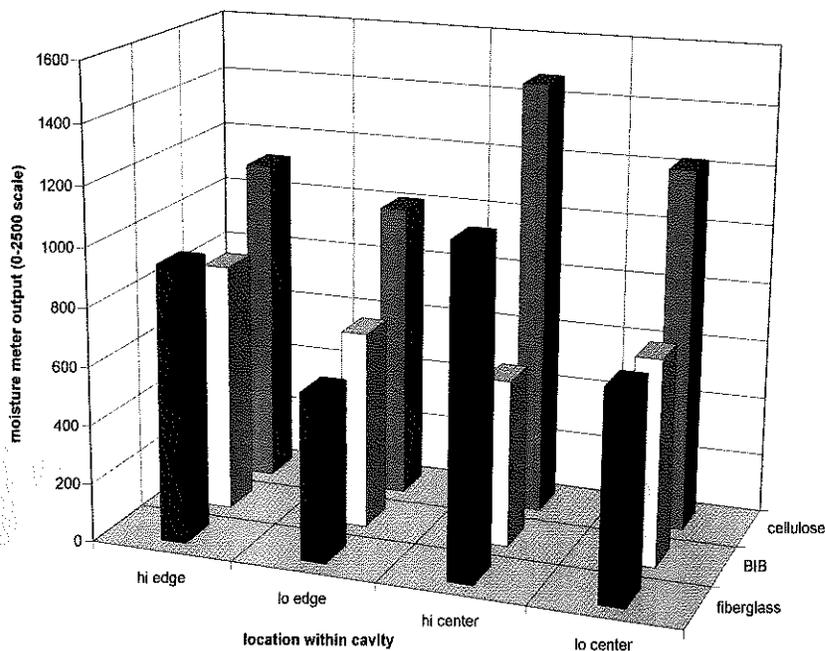


Figure 9 Comparison by location within cavity.

- The encapsulated samples all performed acceptably. The only notable case is the poorest performer, sample #10, unstapled insulation with kraft facing.
- The three cases with no vapor protection at all performed poorly. The plug moisture content remained in the low, safe range throughout 1996 and 1997, but the electronic measurements indicated incipient damage.

Cavity Location of Moisture Readings

The results that show the relation between location within the cavity and moisture content readings are given in Figure 9. What is apparent is that the moisture content is higher at locations high in the cavity compared to locations that are low (2 ft from the bottom) in the cavity. This holds particularly true for the fiberglass insulation, though it is also true for the cellulose insulation and one example of the BIB system insulation. The other case of the BIB system, where the moisture content is highest at the low location in the cavity, remains, for the moment, an anomaly. These findings of high moisture content high in the cavity are consistent with observations of mold growth at the top of the cavity.

The meter output readings in Figure 9 are the averages of all the samples using the indicated insulation material. It would be incorrect to use this chart to compare the overall performance of fiberglass and cellulose, since the averages are a consequence of the various sample setups.

Temperature was measured at the same locations as moisture content, and the finding was that in all of the cavities, the temperature was higher at the measurement location toward the top of the cavity and lower down toward the bottom. The temperature difference averaged around 0.5 K and varied from 1.4 K in sample 15 to 0.05 K in sample 4.

The finding of higher moisture content and higher temperature upward in the cavity deserves explanation. One hypothesis would be the presence of looping convection within the cavity. While this is plausible with low-density, low-porosity insulation, it is less plausible with a dense insulating material such as cellulose. However, both the cellulose and fiberglass cavities exhibited the same temperature and moisture distribution. Another hypothesis is buoyancy of both warmer air and water vapor-rich air within the still air of the cavity. However, the diurnal temperature and moisture variations within the cavity would tend to upset the stillness necessary for a gradient to appear in all of the cavities. The temperature gradient may perhaps be explained simply by a gradient within the indoor space, which was not measured but may be supposed. This may act together with outdoor temperatures lower at the base of the wall due to the configuration of the tarpaulin. If this were the case, however, and given an assumption of uniform distribution of moisture concentration, it would argue against the finding of higher moisture content high in the cavity. In any case, the accumulation of moisture high in the cavity is an unmistakable observation and one deserving of further study. The critical location appears to be the upper corner where the plate and sheathing are fastened together.

A rather consistent pattern was noted in the lateral distribution of moisture contents within a cavity. Higher moisture contents are found in the center of the cavity rather than toward the stud and higher in the cavity rather than lower. It can be speculated that there is increased drying potential toward the stud.

Observations

Following the study, the walls were disassembled and observed for signs of excess moisture content and for mold (see Table 5).

TABLE 5
Observations Following Disassembly

Sample	Characteristic	Observations
1	Cellulose, poly, openings	No problem, 1/2 in. settling in two cavities, 6 in. settling in one cavity.
2	Cellulose, poly, no openings	No problem, 1/2 in. settling in two cavities, 6 in. settling in one cavity.
3	Cellulose, no vapor barrier	Mold growth: mild. Corrosion on metal fasteners severe. Caking of cellulose against OSB sheathing.
4	Batt, encapsulated poly/poly	Mold growth: medium at cable penetration, very mild at tops of other cavities.
5	Batt, unfaced, no vapor barrier	Severe mold growth, uniformly distributed on sheathing. Some mold growth on fiberglass.
6	Batt, encapsulated poly/kraft	Mold growth mild, at cable penetration. Minor rust on tacks.
7	Batt, kraft facing, inset stapled	Mold growth mild, at cable penetration.
8	Batt, encapsulated nonwoven	Mold growth medium, at cable penetration and tops of cavities.
9	Batt, unfaced, poly	No problem.
10	Batt, kraft facing, unstapled	Mold growth: medium at cable penetration, medium at tops of other cavities. Signs of running water.
11	Blown-in-batt, no vapor barrier	Mold growth: medium, uniformly distributed in cavity.
12	BIB, poly vapor barrier	No problem.
13	Kraft, encapsulated, stapled	Mold growth: slight, at cable penetrations.
14	Kraft, encapsulated, unstapled	Mold growth: slight, at cable penetrations. Minor rust on tacks.
15	Batt, kraft encapsulated	Mold growth slight, slight signs of running water on water-sensitive facing.
16	Batt, poly encapsulated	Mold growth mild, mold growth in fiberglass material.

General observations include the following.

1. The three cavities with no vapor protection—3, 5, and 11—showed mold on the sheathing, uniformly distributed top to bottom and among the three sample cavities. The uniformity of the mold distribution is a strong indication of diffusion/capillary moisture transport and not air leakage in these cavities. Figure 10 shows the worst case of fiberglass without any vapor protection. Figure 11 shows the severe corrosion and mild mold growth in the cellulose-insulated cavity with no vapor protection.
2. The four cavities with polyethylene showed no mold growth at all.
3. All of the fiberglass-insulated cavities with facings showed some mold growth at the tops of the cavities. The mold growth was consistently worse in the middle cavity where the cable penetration would allow moisture entry. However, the adjacent cavities also rather consistently showed some mold growth at the top of the inside of the sheathing. Figure 12 shows mold growth at the top of the cavity, associated with presumed cavity air leakage.
4. There was no difference between cellulose-insulated cavities with and without electrical box openings.
5. Evidence of water running down the inside face of the sheathing was found in sample 10, with unstapled kraft. A



Figure 10 Surface of unfaced R-13 batt insulation showing evenly distributed fungal growth.



Figure 11 Rust on metal fasteners in cellulose cavity without vapor diffusion protection.

slighter amount of running water evidence was found in sample 15. This sample, however, had a sensitive coating on the encapsulation material that may have been affected by only a slight amount of water.

We cannot conclude that all of the mold growth occurred during the season of highest humidity (winter 1995). Some mold at the tops of the cavities was seen in the cavities of samples 11 through 16 where the indoor RH was held to only 40% during two winters. Of course, the RH of the air at the surface where the mold grew was higher than 40%.

Samples of the sheathing from each of the bays affected by mold growth were sent to a laboratory for speciation. The following species were found in concentrations varying from high to low: *Penicillium*, *Ulocladium*, *Cladisporium*, *Rhodotorula*, yeast, *Aspergillus versicolor*, *Alternaria*, *Sporobolomyces*, *Candida*, and *Aureobasidium*.

CONCLUSIONS

The correlation between gravimetric measurements and electronic measurements is only moderately strong. Gravimetric measurements represent physical accuracy, but the measurements are made only at infrequent intervals. Electronic measurements, while disclosing performance at specific points and at close intervals, are sensitive to equipment error, especially inconsistent ranges of output from year to year. Moisture probes and meters are reliable, however, for side-by-side comparison. Together, the two types of measurements do a fair job of illustrating temperature and moisture conditions in wall assemblies.



Figure 12 Fungal growth at top of cavity with faced insulation.

The aim of this study was to explore the heat and moisture performance of insulated cavities not subject to air leakage exchange of cavity air with either the inside or the outside. Despite this intent, the effect at the cable penetration was significant, as it was the site of greatest mold growth in the faced and encapsulated cavities.

The temperature and moisture distribution within the cavity—higher temperatures and higher moisture contents at locations upward in the cavity—were found in all of the samples, with one anomaly. The various hypotheses to explain this finding—looping convection within the cavity, buoyancy in the cavity, or conditions on the interior or the exterior of the wall—must await further study.

The test conditions may be considered to be rather severe—50% and 40% constant RH through a winter with 5,500 degree-days. At 50%, the cases without vapor diffusion protection suffered severe damage. At 40%, the principal finding was the presence of mold growth in the tops of the cavities with facings and encapsulation used for vapor diffusion protection. The cases that were unacceptably bad in this study were affected by diffusion and capillary moisture, not air leakage.

Vapor retarders perform an important function when the interior humidity is at the constant levels used in this study and when there is no need for forgiveness of construction moisture or rain entry into the cavity. Two coats of latex paint did not provide sufficient vapor diffusion protection under the humidity loads of this study and for the climate of the study.

REFERENCES

- Britton, R.R. 1948a. Condensation in walls and roofs. Housing and Home Finance Agency Technical Papers 1, 2, 3 (July).
- Britton, R.R. 1948b. Condensation in walls and roofs. Housing and Home Finance Agency Technical Paper 8 (April).
- Britton, R.R. 1949. Condensation in wood frame walls under variable state conditions of exposure. Housing and Home Finance Agency Technical Paper 12 (June).
- Dill, R.S., and H.V. Cottony. 1946. Laboratory observations of condensation in wall specimens. Building Materials

- and Structures Report BMS106. National Bureau of Standards, U.S. Department of Commerce.
- FHA. 1942. *Property standards and minimum construction requirements for dwellings*. Washington, D.C.: Federal Housing Administration (revised January 1942).
- HHFA. 1949. *Condensation control in modern dwelling construction*. Housing and Home Finance Agency.
- Hutcheon, N.B. 1954. Control of water vapour in dwellings. Technical Paper No. 19, Division of Building Research, National Research Council Canada. NRC No. 3343.
- Rose, W.B. 1997. Control of moisture in the modern building envelope: The history of the vapor barrier in the United States 1923-1952. *APT Bulletin*, Vol. XVIII. No. 4 (Oct.).
- Rowley, F.B., A.B. Algren, and C.E. Lund. 1939. Condensation of moisture and its relation to building construction and operation. *ASHVE Transactions*, No. 1115.
- Sherwood, G.E. 1983. Condensation potential in high thermal performance walls—Cold climate. U.S. Department of Agriculture Forest Service, Forest Products Laboratory Research Paper FPL 433, May.