Session XI No. 5

A Study of Moisture Migration and Accumulation in Residential Stud Walls

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ABSTRACT

With the increased levels of infiltration control and insulation in low energy houses such as those designed to the targets in the Energy Performance Design System (EPDS) manual, concern has arisen regarding the increased potential for moisture accumulation in building walls. This issue has been addressed with several long-term environmental exposure tests being conducted on stud wall sections which incorporate the construction details being recommended by EPDS. In these tests, instrumented wall panels were installed in a research facility where panel exteriors were exposed to the environment and panel interiors were in contact with interior conditions of controlled temperature and humidity. For each test the accumulation of moisture in the panels was recorded throughout one heating season in Granville, OH, a moderately cold location which averages 5600 heating degree-days annually. Interior temperature was maintained at 72°F in all cases and interior relative humidities of 30% and 50% were examined. Presented is a description of this moisture study and a discussion of its results.

INTRODUCTION

The increasing costs of heating fuels has prompted construction of residential buildings that incorporate energy-saving features. Most notably, houses are being constructed with higher levels of wall insulation and with greater attention given to envelope airtightness. It is speculated that both measures increase the possibility of moisture accumulation in wall cavities. Tighter construction reduces the air change rate, increasing interior room humidity during cold weather and, thereby, the moisture flow potential into the wall. At the same time, additional wall insulation reduces wall-cavity temperatures at the condensation surface, resulting in decreased vapor pressures and corresponding increases in vapor flow potential from the building interior. This added potential for moisture accumulation in building components has aroused concern in the building community regarding the wisdom of such energy-saving steps.

To address this issue, a long-term study of moisture migration and accumulation in various wall and ceiling systems was initiated in 1978. At that time, an environmental-exposure Moisture Research Facility was constructed in Granville, OH. This facility, fully described in Ref 1, was designed to study moisture accumulation in various wall and ceiling sections exposed to the outdoors and a temperature- and humidity-controlled interior space. Simultaneously, the development and refinement of analytical moisture-migration models began. As described in Ref 2, the standard ASHRAE method for calculating

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steady-state moisture-migration rates was integrated into a computer code using hourly weather data to calculate long-term moisture accumulation.[3] Several wall constructions were evaluated with this method and the results successfully compared with experimental data from the Moisture Research Facility. In addition to wall sections, residential attics and commercial ceiling plenum spaces have been studied.[4]

Examination of numerous stud wall panels in the Moisture Research Facility, was followed by testing of wall sections with construction details such as windows and interior electrical outlets found in actual residential buildings. Two types of wall constructions were examined. One type represents typical construction, and the other represents an energy-efficient design as outlined in the Energy Performance Design System (EPDS) manual.[5]

The wall sample representing standard construction consisted of 2 by 4 in. nominal (3.8 cm by 8.9 cm) studs located 16 in. (40.6 cm) on center, R-11 (RSI-1.9) fiber glass batt insulation with asphalt-impregnated Kraft facing inset stapled in place, i.e., the flanges on the facing are stapled to the inside surfaces of the studs (as seen in Fig. 1) and wood fiber sheathing. The energy-efficient design consists of 2 by 6 in. nominal (3.8 cm by 14.0 cm) studs located 24 in. (61.0 cm) on center, R-19 (RSI-3.4) fiber glass batts, a polyethylene vapor retarder applied directly behind the interior wall board, and foil-faced foam sheathing with R-value of 5 (slightly over RSI-0.9). The actual test sections for both wall types incorporated 0.375 in. (1.0 cm) thick interior drywall and 0.625 in. (1.6 cm) thick exterior plywood siding. Cross-sectional views of the two test section types are shown in Figs. 1 and 2. The experiments were constructed to include design details such as windows and interior electrical outlets found in residential buildings. The main objectives of the study were to determine the magnitude and duration of moisture accumulation in the wooden building members, identify any areas of particularly high moisture concentration, determine the effects of penetrations (specifically, interior electrical outlets), and make comparisons between the two wall system types.

TECHNICAL APPROACH

Experimental Set Up

The two wall types were tested in an environmental-exposure Moisture Research Facility (see Fig. 3) in Granville, OH. This location averages 5600 heating degree-days °F (3110 heating degree-days °C) annually, and represents conditions that are comparable to or colder than those found in the majority of U.S. population centers.[6] Into this facility, full-scale wall test sections were constructed in a manner approximating those in actual residences. The wall exteriors were exposed to outdoor weather conditions and the interiors were in contact with controlled humidity levels. The facility's two test chambers were kept at different humidity levels, 30 and 50 percent RH with a temperature of 72°F (22.2 °C). Moisture testing was conducted on an annual basis; the test sections were installed in early autumn were kept in place until the following summer. From mid-November until early June, moisture levels in the test sections are monitored using nail probes. These probes consist of two noninsulated nails driven approximately 0.4 in. (1 cm) into the wooden structural members in the wall. The two nails were placed in line with the wood grain, approximately 1 in. (2.5 cm) from the the outer sheathing and with a spacing of 1 in. (2.5 cm) between nails. Moisture content of the wood was determined from the electrical resistance between the nails, using a standard lumberyard Delmhorst moisture meter. The electrical resistance of wood is so highly sensitive to moisture content that a change in moisture content from 7 to 20% results in a 10,000-fold decrease in resistance.[7] The net effect is that, in using uninsulated nail probes, the moisture readings obtained with the meter represent those of the wood layer with the greatest moisture. A wooden member might have an extremely low core-moisture content but if the wood surface encounters even slight condensation, high moisture readings would result.

In addition to moisture data, temperatures throughout the test sections were monitored. These temperatures were taken using a computerized scanner system and were recorded at 1-hr intervals. Weather data (dry bulb temperature, wind speed and direction, and total horizontal solar intensity) taken at an on-site weather station were recorded at 3-min intervals.

The standard wall construction was tested during the 1980-81 heating season and the high-efficiency wall during the following year. Although differences in weather during different years can influence the amount of moisture accumulation somewhat, this was, fortunately, a minor factor in this study because of the very similar climatic conditions encountered during these two winters. For November through February of these two heating seasons, the difference in the number of heating degree-days was less than 7%. Previous experience in hour-by-hour analytical moisture modeling based on the standard ASHRAE method has shown this difference to be of minor importance in determining moisture accumulation levels in wall systems (see Ref 2).

In each test, four wall sections were installed in the facility, two in each test chamber and one each on the north and south walls. With this arrangement, the effects of both interior humidity and exposure to solar radiation could be examined. Drawings of the test sections for the two wall types, including nail probe locations, are presented in Figs. 4 and 5. Notice that these wall sections include various construction details such as windows, doors, and electrical outlets as in actual residences. This made it possible to evaluate the effect of these elements on moisture accumulation and locate any local moisture concentrations particular to these details.

Data Reduction

Before any evaluation of the data could be undertaken, it was necessary to make corrections to each of the moisture readings to account for the effects of temperature. This correction was done through application of temperature data collected during the testing period. A temperature correction table[8] was used to perform a least-square fit regression analysis to derive an equation relating actual wood moisture level to the meter reading and local temperature at the time the reading was taken. In practice, moisture readings were taken between 10:00 a.m. and 2:00 p.m., but, for simplicity, the temperature at noon of the specified day was applied to the correction equation. The temperature for a given wall sample consisted of the average of two thermocouple readings, one at the top of the wall cavity and one at the bottom. These thermocouples were located on the inner surfaces of the top and bottom plates approximately 1 in. (2.5 cm) from the outer sheathing, a placement comparable to that of the nail probes. In short, for each moisture meter reading, the temperature on the wall at noon of the particular day, along with the reading, was input into the temperature-compensation equation and the actual moisture level was then calculated.

The first step in evaluating the data consisted of plotting the moisture content at selected probes against time. Because the moisture levels measured in the walls exposed to 30% interior relative humidity were very low--generally, less than 15% with a maximum of 17%--only moisture content plots for those wall sections in the 50% chamber were evaluated. Graphs of each of the following three probe locations were plotted for each of the two wall types and for both northern and southern exposures:

1. Two probes directly under the window--one probe was at the top of a cavity with no vapor retarder penetrations and the other was similarly situated in a cavity with an electrical outlet.

2. Probes in the top plates of full-length cavities with different numbers of vapor retarder penetrations.

3. Probes in the bottom plates of full-length cavities with different numbers of vapor retarder penetrations.

These graphs were examined and compared to determine the peak moisture levels at various locations and the corresponding durations of those levels. This information is important in judging the seriousness of moisture accumulation in degradation of the stud structure of the wall, one of the primary concerns of this study. In addition, the effects of location and vapor-retarder penetrations on stud moisture content were qualitatively studied using these graphs. Dripping onto bottom plates is a serious problem that could easily be identified by proper graph inspection.

The second major aspect of data reduction consisted of comparing the two wall types by applying statistical methods. The first step in this process was, for each probe, to average the readings taken over the period of peak moisture accumulation (Jan. 30 to Mar. 31) so that one moisture level was associated with each probe. This averaging was done for all test panels and the results were examined. Because of the very low (12.9% average) moisture levels observed in the wall test sections kept in the 30% RH chamber, further statistical analysis was performed only on results for those panels in the 50% RH chamber.

For each wall test section, moisture contents throughout were averaged together and the averages compared. The test samples representing the standard wall design were, therefore, somewhat differently configured than those representing the high-efficiency wall, and the probes were somewhat differently distributed. To make the comparison as direct and unbiased as possible, only probes with counterparts in the other wall type were included in the averaging process. Counterparts are probes in comparable positions in the structure of the wall. Examples of categories include: (1) the underside of the rough sill under the window, (2) the bottom plate of the full-length cavity without vapor-retarder penetration, (3) the bottom plate of the full-length cavity with vapor-retarder penetration, and (4) the top of the cavity over the window. The test sections for the standard wall still contained more probes than the test sections for the efficient wall, but the distribution was such that the various types of locations were similarly represented in both tests. In other words, no areas were more heavily weighted in the average of one wall type than in the other.

After averages for each of the panels were obtained, the differences between those of the standard wall and the efficient wall were calculated; the northern and southern exposures were treated separately. The 90% confidence intervals for these differences were calculated using the standard student-t equation given in Ref 9.

For both wall types, the nail probes placed in the rough sill under the windows gave readings significantly higher than those of other probes in the test samples. Under one window, in fact, the moisture readings exceeded the moisture meter scale for much of the heating season. It is hypothesized that either water that condensed on the window ran onto the rough sill, saturating the probes there, or a gap in the vapor retarder at the edge of the window caused significant localized moisture accumulation. These observations demonstrate the impact of window installation details on localized moisture accumulation levels. Because the details of window installation are somewhat variable and are not directly related to the overall wall system design, data taken from the location under the windows was not included in the statistical comparison of the two wall types.

DISCUSSION OF RESULTS

The primary concern regarding moisture in residential construction is the possible degradation of wooden components in the structure. Research in this field has determined that wood degradation occurs when moisture content in excess of 30% in conjunction with temperatures exceeding 50°F (10°C) are encountered.[10] The results of this study are discussed with this criterion in mind.

Under conditions of 30% RH humidity, the moisture levels measured in both wall systems were very low. The average moisture content of all the probes in the two standard wall sections during the peak moisture period was 12.6% with the wettest probe registering 15%. In the high-efficiency wall samples, an average of 12.9% was found, with the wettest probe reading 17%. Considering that the lumber was delivered "kiln dried," with moisture contents in the 9 to 11% range, these measured values can be considered very low.

The average moisture levels for each of the wall test sections kept in the 50% RH test chamber are presented in Tab. 1. It appears from these results that the high efficiency wall experiences somewhat higher moisture levels than the standard wall type, although they still fall within the acceptable limits of 30% wood moisture content. Performance of several simple, one-dimensional, steady-state moisture accumulation calculations by the standard ASHRAE method, indicates that the more efficient wall, with its superior vapor retarder, did not perform better than the standard wall, because the aluminum facing on the outer foam sheathing was of low permeability. That allowed less moisture to diffuse through the sheathing to the outside environment and resulted in somewhat greater moisture accumulation in the cavity. This factor does not serve to make the use of high-performance sheathing undesirable, because it is largely compensated for by increased cavity temperatures that reduce the rate of moisture migration from the building's interior space to the sheathing's inner surface.

Examination and comparison of the wood moisture content versus time plots generated for the four panels exposed to an interior relative humidity of 50% yielded several important observations and conclusions:

1. No evidence of dripping onto the bottom plate was observed in any test panel. Dripping onto the bottom plate is a significant and common symptom of moisture accumulation problems in walls.

2. The highest moisture content levels were consistently observed in the rough sills directly under the windows, probably because of breaks in the vapor retarder around the windows. Under the windows, moisture levels during the peak period generally fell between 25 and 30% with an occasional spike to around 35%. The high-efficiency wall sample having the northern exposure behaved differently, registering moisture contents in the rough sill exceeding the moisture meter range for much of the heating season. It is hypothesized that, during a period of particularly cold weather, condensation on the window glass ran into the wall and onto the rough sill. These findings demonstrate the importance of proper care in the design and installation of windows in averting moisture-condensation problems.

3. With the exception of probes under the windows and one probe in the bottom plate of the north-facing high-efficiency wall sample (which briefly read over 30% moisture content), the moisture levels in both wall systems stayed below 25%. Several probes, in fact, registered maximum moisture levels of less than 15%.

4. Penetrations in the vapor retarder caused by electrical outlets did not significantly increase the moisture levels in the wooden members of associated wall cavities.

5. Many of the plots, particularly in the standard wall system, showed short-term fluctuations, demonstrating considerable sensitivity of stud moisture content to weather conditions. This relationship was evident when comparing moisture content plots with the corresponding ambient temperature plots. Periods of extreme cold were generally accompanied by increased moisture levels. The small response times for both wetting and drying indicate that much of the measured moisture was present at the wood surfaces. Swelling and shrinking of wooden structural members was, therefore, considered minor.

Plots of moisture content versus time for the high-efficiency wall samples are provided in Figs. 6 through 11, and a plot of corresponding outdoor temperatures versus time is given in Fig. 12.

CONCLUSIONS

The findings of this study indicate that residential buildings can be constructed with highly energy-efficient walls without significant moisture accumulation in the wall cavities. Although moisture accumulation levels in the high-efficiency test sections were slightly higher than in the standard wall test section, they fell within acceptable levels, even in the case of 50% interior relative humidity at 72^{0} F (22.2^{0} C). With an interior relative humidity of 30% which is typical of many homes, moisture accumulation was minimal for both wall types. It can be concluded that, for climates and interior relative humidity levels as tested in this study, properly designed and constructed high efficiency walls similar to those recommended by the Energy Performance Design System (EPDS) and discussed in this paper can be applied to residential structures without undue risk of moisture damage.

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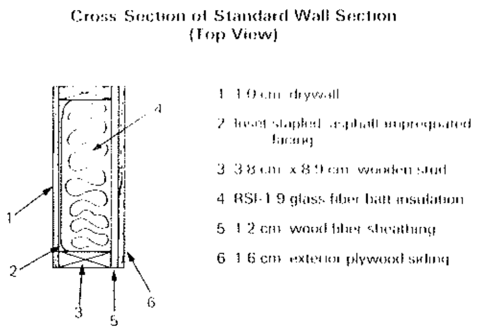

Figure 1. Cross-section of standard wall section (top view)

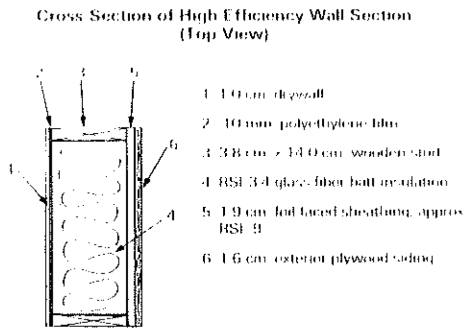

Figure 2. Cross-section of high-efficiency wall section (top view)

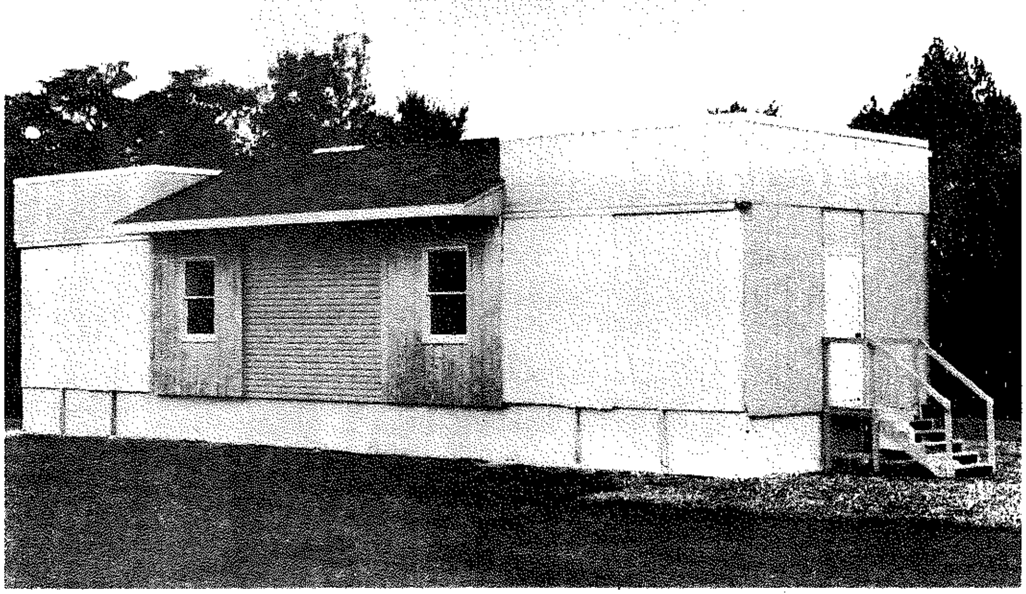

Figure 3. Evnironmental exposure moisture research facility

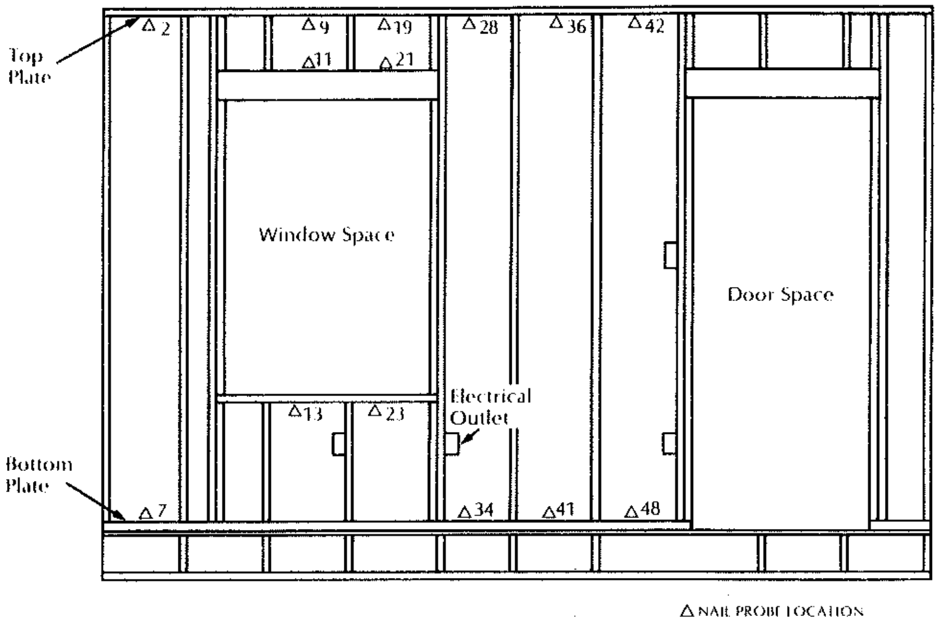

Figure 4. Standard wall test section

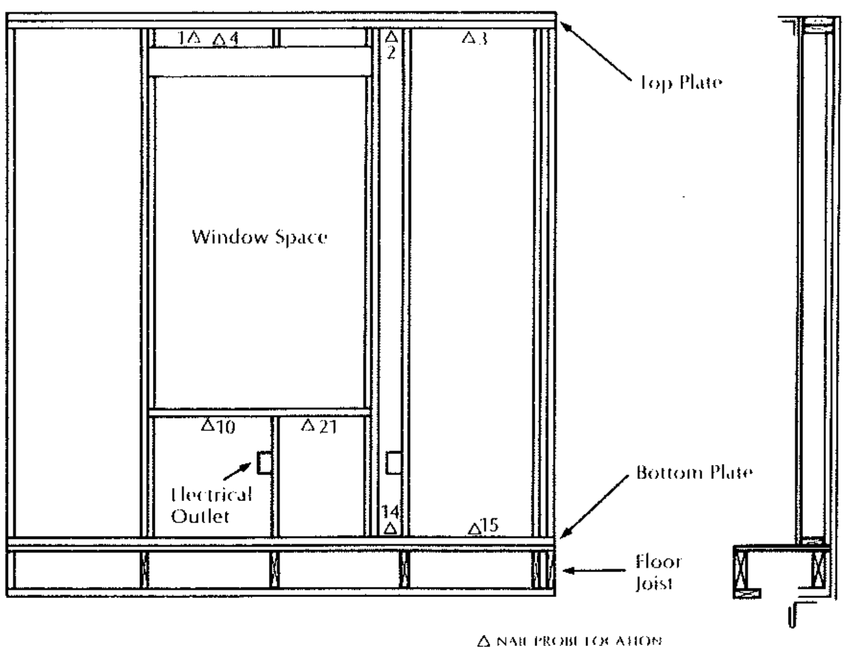

Figure 5. High-efficiency wall test section

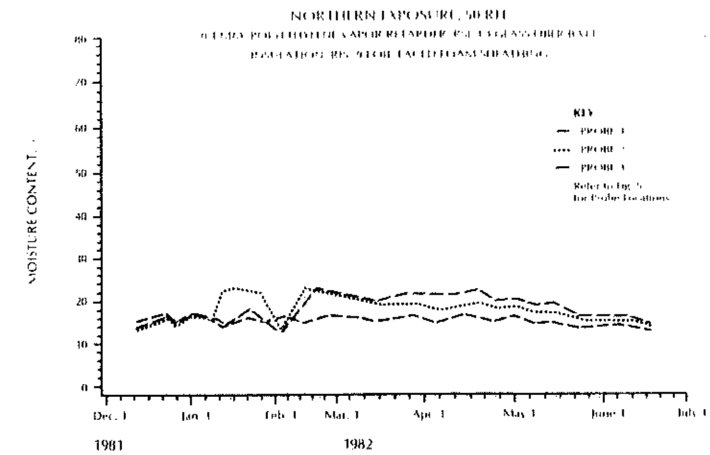

Figure 6. Moisture content in high-efficiency wall sample -- top plate

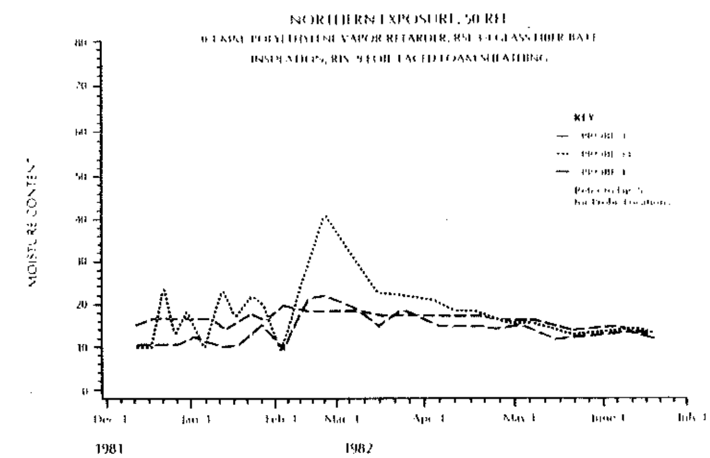

Figure 7. Moisture content in high-efficiency wall sample -- bottom plate

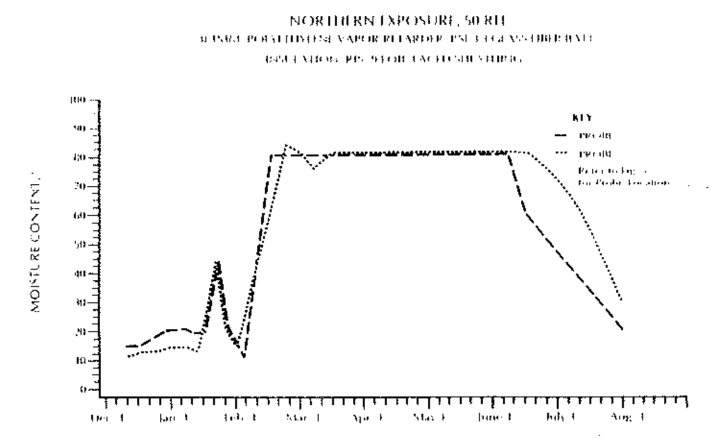

Figure 8. Moisture content in high-efficiency wall sample--rough sill under window

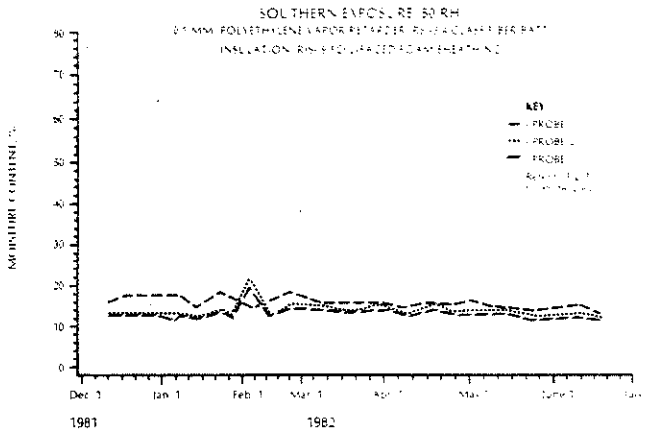

Figure 9. Moisture content in high-efficiency wall sample -- top plate

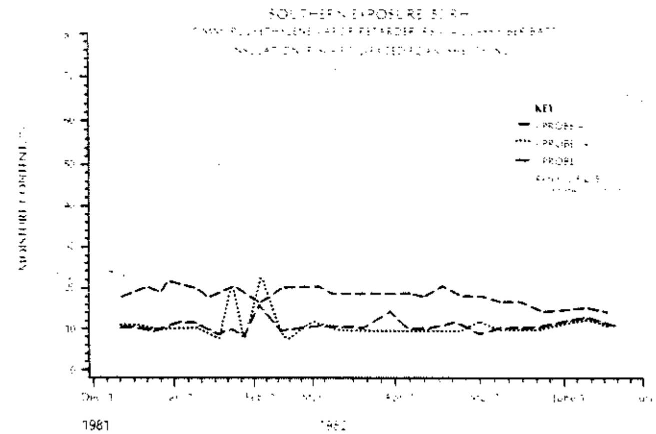

Figure 10. Moisture content in high-efficiency wall sample -- bottom plate

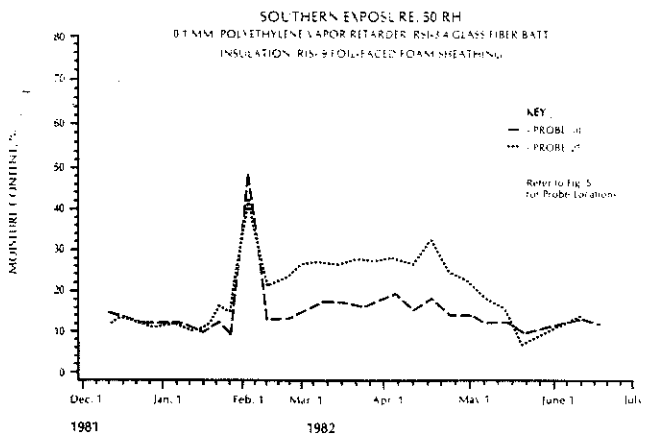

Figure 11. Moisture content in high-efficiency wall sample--rough sill under window

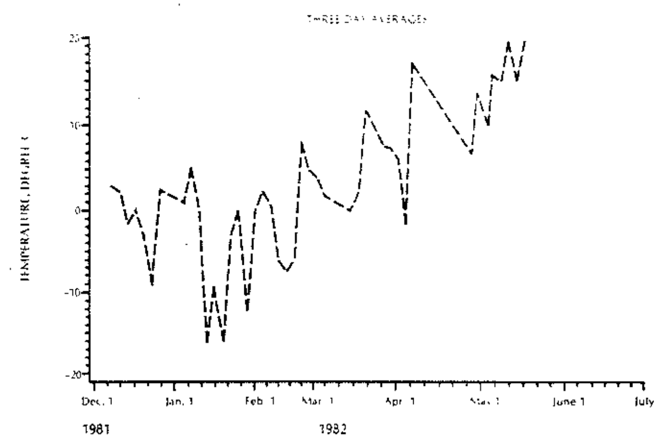

Figure 12. Temperatures in Granville, OH during 1981-82 heating season (three day averages)

Discussion

D.M. Drysko, Forintek Canada Corp., Ottawa, Canada: The moisture probes were installed to what depth? MC of construction lumber was low; wouldn't you expect higher MC in practice?

F.J. Luft: The moisture probes were installed to a depth of approximately 1 cm. It should be noted that they were not insulated, that so given the relationship between moisture content and electrical resistance, the readings taken corresponded to the wettest layer in the wood. This is discussed more fully in the text of the paper.

The lumber used in this experiment was standard kiln-dried material obtained from a local lumberyard. I can't speak for the quality of lumber offered by other vendors but will agree that not all material is delivered with such low moisture levels.

Ray A. Wiley, Bonneville Power, Eugene, Ohio: How close to the sheathing were the moisture probes placed in the studs and plates? Why did you not place any moisture probes on the back side of the siding which would be colder than the framing?

F.J. Luft: The nail probes were placed approximately 1 inch from the outer sheathing. In the standard wall samples, nails were, in fact, driven into the fiber board sheathing and matchstick probes were used to monitor moisture on the foil surface of the sheathing in the high efficiency samples. The results from these probes were not discussed for the following reasons.

1. Being of small size, the matchstick probes become quite easily saturated. As a result, the probes yield moisture content readings exceeding the range of the moisture meter in the presence of relatively low levels of condensation. The net effect is that the matchstick probes become indicators of whether moisture condensation is present but give very little indication of the amount of condensation. For the record, the matchstick probes on the sheathing of the high efficiency wall samples indicated minimal moisture condensation in the 30 percent R.H. test chamber but were saturated for most of the winter in the 50 percent chamber.

2. I would not venture to make comparisons between the nail probes in the standard wall section sheathing and the matchstick probes in the high efficiency wall sections. Because of the hydroscopic character of the fiberboard sheathing, comparisons would not be appropriate even if the matchstick probes were used in both cases.

3. This paper concentrates particularly on the moisture performance of the high efficiency wall system, using the standard wall system as a reference case. Moisture in the structural members of the wall is of much greater consequence to the integrity of the wall then water droplets on the surface of the sheathing.

Doug Burch, NBS, Washington, DC: The moisture measurements were made within the studs. This location is comparitively warm compared with the sheathing and siding. In addition, this place is removed from the plane of condensation predicted from theory. Therefore, the observed moisture contents at this spot may be considerably lower than that at the sheathing and sidings. Please comment.

F.J. Luft: I agree with your comments but would like to stress that this paper is not intended to verify analytical modeling or substantiate theory. Rather, the focus is practical in nature, with the potential for structural damage in the high efficiency wall design being of primary interest. I consider moisture in the structural members of the wall to be of greater consequence structurally than droplets on the surface of the foil-faced foam sheathing. Note that in the event of severe condensation on the sheathing, water would be detected by the nail probes located there.