

Moisture Transfer through Walls

T.W. Forest

ABSTRACT

The movement and deposition of moisture in wall assemblies during cold winter months can lead to deterioration of the wood frame, exterior sheathing, and possibly, the thermal insulation. Of the several mechanisms that can cause wetting of a wall, it is generally acknowledged that the direct movement of warm, moist air from the interior of a house through the wall cavity is one of the most important. For single-story houses, this directed air movement through walls is primarily due to varying wind speed and wind direction and, to a lesser extent, stack effect caused by indoor/outdoor temperature differences.

In this paper, we present some preliminary results of a field study that was initiated during the 1987-88 heating season to study the moisture accumulation in wall cavities. The wall assembly was of standard construction and had a small opening from the interior of the house through which air could infiltrate or exfiltrate, depending on the local climatic conditions. This airflow was continuously recorded along with the amount of moisture deposition and its distribution within the cavity. Most of the moisture was observed to be deposited on the exterior sheathing, which is the first cold surface the exfiltrating air encounters, and to be concentrated opposite the small opening. Maximum sheathing moisture content was measured to be 27% by weight (dry basis) on the north-facing wall panel. A similar wall panel facing south showed little or no moisture accumulation.

Measurements were also made of the total amount of moisture that was exfiltrating through the building envelope, based on the measured infiltration rate and the airflow through a 6 in. (15.2 cm) diameter stack. With the flue open, most of the indoor air passes through the stack, resulting in low moisture transfer rates through the entire building envelope; with the flue closed, the moisture transfer rate through the envelope increases nearly sixfold over that with the flue open. In either case, the fraction of this total moisture flow passing through each wall panel is 1% or less.

INTRODUCTION

Field studies of problems related to moisture in a building envelope were initiated at the Alberta Home Heating Research Facility (AHHRF) during the 1987-88 heating season. In most houses a certain level of moisture is required in the indoor air; too little moisture can lead to problems, eg., increased respiratory infections, while too much moisture can cause damage to the building envelope and even the threat of respiratory disease due to mold exposure. In the latter case, when trying to assess the potential for moisture damage to a building envelope under given climatic conditions, one is confronted with several questions:

1. What is the indoor source of moisture and the rate at which it is generated?
2. Where does this moisture go and what are the important transfer mechanisms?
3. How are these transfer mechanisms related to climatic variables such as temperature, wind speed, etc.?

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4. What control strategies will minimize the adverse effects of moisture on a building envelope?

The answers to some of these questions are emerging. For example, one of the principal mechanisms for moisture transfer through the building envelope is air movement from indoors to the cold exterior regions of the envelope. This air movement is caused by wind acting on the structure and, to a lesser extent, by the stack effect. How this air movement (infiltration or exfiltration) is related to the environmental conditions has not been clearly established and is the subject of many current research activities.

One of the main areas of research needs identified by the Building Thermal Envelope Coordinating Council (Bales and Trechsel 1985) was moisture in wall systems. Concealed condensation/moisture accumulation in wall assemblies during winter generally occurs with high indoor relative humidities and indoor air exfiltrating through the wall cavity. This air exfiltration tends to occur through gaps or faults in the air/vapor barrier and moisture accumulation tends to be concentrated near these openings. The long-term effects are deterioration of the exterior sheathing, wood frame members, and, to a lesser extent, the thermal insulation. Such localized deterioration has been noted in a Canada Mortgage and Housing (CMHC) (1983) survey, particularly in regions where excessive moisture occurs both indoors and outdoors for prolonged periods in the winter and spring, eg. the Atlantic Canada region. The principal objective of research in this area is to develop a method for predicting the amount and distribution of moisture in wall assemblies, based on local climatic conditions. Development of this predictive tool requires mathematical modeling to identify important parameters and laboratory/field verification of the model.

Some laboratory tests of wall assemblies have been carried out. Burch et al. (1979) conducted tests to determine whether the use of low-permeability insulation as an exterior retrofit system increased the moisture in the wall. Results showed that moisture did accumulate at the insulation/sheathing interface but the amount was less than in the original wall (with no exterior insulation). The reduction in the amount of moisture accumulation was a direct result of the increase in the insulation/sheathing interface temperature. No mention was made of any directed air movement through the wall cavity. Verschoor (1985) investigated the moisture performance of typical wall sections with different vapor retarders under conditions where air was, alternatively, infiltrating and exfiltrating. In wall assemblies with poor vapor retarders, moisture accumulation was observed at the insulation/sheathing interface when air was exfiltrating; however, moisture still accumulated (at a reduced rate) when the air was infiltrating. This suggests that water vapor diffusion occurred from the indoors to the cold side of the wall assemblies and can be an important mechanism for transporting moisture. Thus, air infiltration alone may not be sufficient to prevent moisture accumulation in walls with poor or faulty air/vapor barriers. Some of the walls tested had point defects on the warm side of the assembly and these panels showed moisture accumulation directly opposite the defect on the cold side. Other laboratory tests of the "dynamic wall" concept have been conducted by Timusk (1985).

Field testing of the moisture performance of wall systems is more limited than laboratory tests. Sherwood (1983) conducted field tests of wall panels in which the type of exterior sheathing, insulation, and vapor retarder was varied. Duplicate panels facing north and south were tested side-by-side in an outdoor facility. Moisture was generally observed to accumulate at the insulation/sheathing interface, with the north-facing panels experiencing much larger accumulations than the south-facing panels. It was not possible to measure the air movement through each panel and this limited the interpretation of the results. Stewart (1982) carried out field tests of walls that had varying overall moisture permeability as well as individual components of different permeability. No mention was made of directed air movement, as these tests were designed to have moisture transport by diffusion only. Field testing of varying wall assemblies has also been carried out by the CMHC (1987). However, if monitored the drying characteristics of walls that were initially wet, as is typical of new home construction in eastern Canada.

The current field studies at the AHHRF are designed to provide data on air movement through, and moisture accumulation in, a standard wall assembly under extreme winter conditions that are typical of a prairie climate.

TEST PROCEDURE

The field tests on the wall assembly were designed to provide long-term data (several heating seasons) on the following issues. Firstly, if an air leakage path occurs in a wall assembly, how much air infiltrates from the outside or exfiltrates from the inside through the wall and how are these flows related to the environmental conditions, i.e., wind speed, wind direction, and indoor/outdoor temperature difference? In order to measure this effect, the wall assembly (described below) had a controlled opening in the drywall to allow air to flow through the wall test panel. Second, if the leakage characteristics of a building envelope are altered substantially, how is the airflow through the wall affected? For this test, the leakage characteristics were altered six weeks into the test period by blocking off the flue in the test house. This had a significant effect on the house air infiltration rate, which affected the flow through the wall panel. Third, what is the amount and distribution of moisture in the wall panel due to the airflow and other moisture transport mechanisms such as water vapor diffusion? For this test, where the wall panel has a controlled opening on the warm side of the panel, water vapor diffusion cannot be neglected. This point will be discussed in the "Results" section. Fourth, is there any effect of solar gain on the moisture accumulation in the wall? To provide some data on this effect, two identical wall panels were placed in the test house, one facing northward and the other facing southward.

WALL TEST PANEL

For these tests, it was decided to use a wall assembly that was typical of many older houses. Figure 1 shows the construction of each wall panel (46 in. [117 cm] by 92 in. [234 cm]) with interior drywall, polyethylene air/vapor retarder, fiberglass insulation, and exterior plywood sheathing. To simulate actual conditions in a house where air movement can occur, a 3/8 in. (0.95 cm) diameter hole was placed along the centerline of the panel, two thirds of the way up from the bottom of the panel. The 3/8 in. diameter hole is approximately the equivalent leakage area of a typical electrical outlet box, according to ASHRAE (1985). Each panel was instrumented to measure airflow, temperature profile, and moisture accumulation. The 3/8 in. hole was actually a calibrated orifice meter, as shown in Figure 1. Depending on the local pressure difference across the panel, air either infiltrates from the outside or exfiltrates from the inside. For this airflow measurement, during each hour the total air exfiltration and infiltration were recorded separately. Had these two values been added together and averaged over the hour, much of the detail of the airflows through the wall panel would have been lost. It should be mentioned that for either direction of airflow, water vapor will be continuously diffusing through the opening in the wall from the warm side to the cold side, as long as there is a positive vapor pressure difference between the warm side and the cold side. The temperature profile was measured with a set of four equi-spaced thermocouples located at the orifice position. The moisture content in the insulation was measured with three thermal conductivity probes. These probes use the constant line heat source method to infer the value of thermal conductivity, which depends on moisture content and, to a lesser extent, on temperature. Details of the theory, construction, and operation of the probes can be found in Yu (1986). The probes were located 1 in. (2.5 cm) from the cold side of the insulation and at the three positions shown in Figure 2.

Previous studies of wall cavities have indicated that moisture tends to accumulate initially at the exterior sheathing/insulation interface. To determine how much moisture accumulates at this location, an array of removable wooden plugs was cut from the exterior plywood sheathing. The location of the plugs is shown in Figure 3, as seen from the inside of the house. Each plug is 2 in. (5 cm) in diameter and consists of the same thickness plywood as the exterior sheathing and 1 in. (2.5 cm) of insulation bonded to the plug. The plugs are fitted with a neoprene seal and a small wooden handle to facilitate removal. Knowing the initial dry weight of each plug, the moisture accumulation can be determined if the weight of each plug is monitored throughout the test period. The plugs were weighed once a week; during this procedure the plugs were placed in a pre-cooled, insulated box and brought inside for weighing on a precision scale. This prevented the accumulated moisture from thawing and migrating unnaturally. The removal and weighing of each plug was a non-destructive measurement since the plugs were replaced to their original position after weighing.

TEST HOUSE AND BACKGROUND MEASUREMENTS

The test panels were placed in House 6 at the Alberta Home Heating Research Facility AHHRF. This single-story house has 2 by 4 wood frame walls, a gable roof on elevated roof trusses, and a poured concrete basement. The materials, dimensions, and insulation levels of the various components of the building envelope are given in Table 1. The house is electrically heated and is equipped with a single 6 in. class B vent which terminates 5 ft above the basement floor. The vent is included since this is usually the single largest opening in the building envelope through which air normally exfiltrates. The test house is one of six houses at the AHHRF that are all arranged side-by-side along an east-west orientation. The two test panels were placed on a north-south orientation, as shown in Figure 4.

The indoor temperature (held constant at 68°F [20°C]), outdoor temperature, relative humidity, wind speed, and wind direction were monitored on a continuous basis using thermocouples, resistive-type humidity sensors, and a vane anemometer and potentiometer, respectively. Figure 5 shows the variables that were measured using a computer-controlled data logger. The computer read all variables 80 times per minute. At the end of each hour, hourly means and standard deviations were calculated and stored on a floppy disk. For the test period reported, which ran for approximately 50 days after January 26, the average temperature at the site was 28°F (-2.2°C). The coldest temperature of -22°F (-30°C) was recorded at the start of the test period.

One of the important issues in addressing moisture damage in a building envelope is the source of moisture. For this study, all of the moisture was generated inside the house by humidifying the indoor air. Approximately two months prior to the start-up date of January 26, 1988, the indoor relative humidity was set at 40%. This was done to pre-condition the interior of the house. Just prior to January 26, the indoor relative humidity was adjusted to 45%, which is the mid-point of the optimum range for indoor relative humidity. The humidity was kept constant ($\pm 3\%$) with a rotating drum humidifier controlled by a humidistat. The humidifier was supplied with water from a 66-gal (250-liter) reservoir. During the course of the testing period, the amount of water released to the house was measured on a weekly basis by filling the reservoir back to its original level. The "measured" indoor moisture generation rate was based on this measurement and represents a weekly-averaged value for the moisture generation rate. The "measured" moisture generation rate can be compared with the moisture generation rate inferred from the measurement of the building air infiltration. The natural air infiltration rate for House 6 was measured using a constant concentration of sulfur hexafluoride (SF_6) tracer gas. A separate computer system recorded the hourly-averaged infiltration rates for house 6 as well as all other houses on site. The "inferred" indoor moisture generation rate, m_w (lbs water/h) was determined from a steady-state moisture mass balance on the house. The mass balance yields

where

$$m_w = \rho_a Q_{\text{inf}} (W_i - W_o) \quad (1)$$

ρ_a = the density of dry air.

Q_{inf} = the natural air infiltration volume flow rate.

W_i = indoor humidity ratio (related to temperature and relative humidity)

W_o = outdoor humidity ratio (related to temperature and relative humidity)

This mass balance assumes that the materials exposed to the interior conditions, e.g., drywall, exposed wood members, concrete, etc., have reached moisture equilibrium with the indoor air. Initially, when the building elements are absorbing moisture, this may not be true, in which case Equation 1 will underpredict the moisture generation rate. The effects of this initial moisture uptake by the interior were minimized by humidifying the house for two months prior to the start date. It should be noted that the only variable that significantly affects the inferred moisture generation rate is the infiltration rate since ρ_a and W_i are constant while W_o is small compared to W_i during winter conditions. The cumulative mass of water used by the humidifier and that inferred by Equation 1, are shown in Figure 6, for a two-month period after the start date of January 26. The initial moisture generation rate was slightly higher than the inferred rate; this may be due to the adjustment in indoor relative humidity five days prior to the start of the test. During the first 42 days of the test period, the measured and inferred moisture generation rates (approximately 12.1 lb/day (5.5 kg/day)) agreed within experimental error; these were estimated to be 7% to 8% for the inferred values and 1% to 2% for the measured values.

During this initial 42-day period, the 6 in. (15.2 cm) diameter flue was kept open. An open flue provides a major path for indoor air to escape to the outside, thus removing much of the moisture that is generated inside. Of course, replacement air infiltrates through cracks in the building envelope. In order to quantify the flue flow, a calibrated orifice plate (3 in. [7.6 cm] minimum diameter) was attached to the bottom of the flue. The pressure difference across the orifice was recorded with the data logger. The measurements indicate that the infiltration rate was somewhat larger than the flue flow rate during much of the initial 42-day period. A typical record of these data is shown in Figure 7 for a three-day period in February. The percent difference between the two flow rates, $(Q_{inf} - Q_{flue})/Q_{inf}$, where Q_{flue} is the flue flow rate, can be seen to be positive for a large portion of the time, occasionally reaching 20%. This positive difference implies that not all of the moisture is being removed through the flue; a small fraction is escaping through the building envelope via cracks in the walls and ceiling. The total amount of water that passed through the envelope is shown by the lowest curve in Figure 6. These results are obtained by knowing the indoor humidity ratio (constant) and then calculating the amount of moisture that passes through the envelope with the exfiltration airflow, $Q_{inf} - Q_{flue}$. With the flue open, the moisture migration rate through the envelope was constant at approximately 1.5 lb (0.7 kg) water/day.

On March 8, six weeks into the test period, the flue was blocked. The "measured" moisture generation rate dropped from 12.1 lb (5.5 kg)/day to 7.5 lb (3.4 kg)/day as a result of the reduction in the building air infiltration rate. However, the "inferred" moisture generation rate decreased to 6.2 lb (2.8 kg)/day. The total moisture migration rate through the envelope increased from 1.5 lb (0.7 kg)/day to 8.8 lb (4.0 kg)/day. The migration rate is larger than the generation rate since some of the 8.8 lb (4.0 kg)/day enters the module with the outside air; this moisture must be added to the moisture generated indoors. It should be noted that the "measured" moisture generation rate includes moisture that is transported by air movement through all components of the structure and by diffusion from the inside to the outside. On the other hand, the "inferred" moisture generation rate is a value obtained from the building air infiltration alone and only accounts for moisture transport by direct air movement. Thus, the "inferred" moisture generation rate will be less than the "measured" value.

RESULTS

During the winter period, the thermal conductivity probes never indicated any significant moisture accumulation within the insulation. The little moisture that was deposited in the wall cavity appeared in the exterior sheathing immediately behind the orifice. This area showed a moderate increase in moisture content. By mid-February (the end of a sustained cold period), the largest moisture content was 27% wt (dry basis) in the north panel. A map of the sheathing moisture contents is shown in Figure 8, where each point corresponds to the location of a moisture plug. For the north panel, the area immediately behind the orifice had the largest moisture content. In contrast, the south panel showed little moisture accumulation due, in large part, to the effect of solar radiation. At certain times the south sheathing temperature was 45°F (30°C) above room temperature, which is sufficient to drive out any moisture that may have accumulated, thereby keeping the south panel dry. Figure 9 shows the variation in moisture content of the north-facing exterior sheathing at the two locations adjacent to the orifice as a function of time. The moisture content increased steadily in response to the moisture that was transported from the inside of the house by exfiltrating air and vapor diffusion through the opening in the wall. The cumulative amount of moisture passing through the wall, due to air exfiltration only, is shown in the same figure. This was calculated using the indoor humidity ratio and the total measured amount of indoor air that exfiltrated through the wall panel; the data points are weekly-averaged values. Also shown is the ratio of weekly-averaged air infiltration to air exfiltration. The results indicate that even though more air infiltrates through the wall than exfiltrates during the first three weeks of the tests, the sheathing moisture content increased. During the initial three-week period, the rate at which moisture was convected through the wall panel was approximately constant at 0.1 lb/day (0.045 kg/day). Vapor diffusion through the 3/8 in. opening in the wall was estimated based on a typical wintertime indoor/outdoor vapor pressure difference and a permeability coefficient for the fiberglass insulation. The specific diffusion flux was on the order of 0.03 to 0.04 lb/day-ft² (0.16 to 0.2 kg/day-m²). In Figure 8, for the north panel, the moisture in the sheathing was concentrated in approximately a 1 ft² area behind the 3/8 in. opening; this would result in a total diffusion flux of water vapor of 0.03 to 0.04 lb/day (0.014 to 0.02 kg/day). Although

this is a rough calculation, it does show that vapor diffusion through a wall opening cannot be neglected, as this flux may be 30% to 40% of the convectively transported moisture.

During this period, the sheathing temperatures on the north were consistently below freezing. The difference between the indoor and ambient temperatures is shown in Figure 10 for the test period. In the first three weeks, the ambient temperature was consistently below freezing, resulting in below-freezing sheathing temperatures on the north panel. These results suggest that, once the moisture has been deposited into the sheathing, the low temperatures essentially lock the moisture in place. At low outdoor air temperatures, the infiltrating air cannot hold very much moisture which, in turn, means that the infiltrating air cannot provide much drying of sheathing.

During the fourth week of the tests, the amount of exfiltrating air (moisture source) dropped considerably and, at the same time, the amount of infiltrating air increased substantially. This combination resulted in a drying of the exterior sheathing. The drying process slowed considerably in the fifth and sixth weeks of the test, when the rate of moisture transport and the amount of infiltration returned to their previous levels. During this period, the ambient temperature was steadily increasing and, at times, was well above freezing, as shown in Figure 10. The above-freezing temperatures seemed to have some effect on the drying process since the moisture was no longer frozen in the sheathing.

Up to March 8, the flue was kept open. After the flue was blocked, the moisture content of the sheathing began to increase in both the north and south panels. Figure 11 shows the moisture distribution in both panels, one week after the flue was blocked. The moisture content in the north panel increased to a maximum of 12.6% near the orifice; the south panel showed a maximum moisture content of 4.3%, which is larger than the moisture content at any point prior to March 8. Thereafter, the moisture content of the panels slowly decreased with the relatively warm ambient temperatures. The important point is that, with the flue blocked, the neutral pressure level would be lower than with the flue open. This would result in more air exfiltrating through the wall cavity and depositing moisture. This trend is seen in Figure 9, where the total amount of moisture passing through the north panel in the week after the flue was closed shows a sharp increase over the previous week.

It is interesting to note that the moisture flows out through the north wall panel are very small compared to the total moisture flow through the building envelope. With the flue open, the panel moisture flow rate is on average only about 1% of the total moisture flow rate; with the flue closed, the fraction drops to about 0.3%, although as noted above, the magnitudes of the moisture flow rate through the panel and through the building envelope are both larger than with the flue open. This would suggest that a large fraction of the moisture flow is escaping through other cracks and holes in the envelope. Although the distribution of holes is not accurately known, the ceiling probably contains a large number of these holes, particularly around such things as light fixtures. Thus, a large fraction of the total moisture flow is probably escaping into the attic, where moisture deposition can occur. Work has been initiated to measure this indoor/attic exchange rate.

CONCLUSIONS

A number of conclusions can be drawn from the results about moisture movement and deposition in walls:

1. Moisture accumulates at the sheathing/insulation interface and is concentrated directly opposite to the opening. Warm, moist air moves directly through the insulation along a path of least resistance to the exterior sheathing. The moisture movement occurs by a combination of directed airflow and water vapor diffusion. Moisture is deposited on the cold sheathing before the air finds its way to the outside. Modeling of this process may be possible with a simple one-dimensional heat and airflow model.
2. With ambient temperatures well below freezing, moisture that is deposited on the sheathing remains in place and any drying that occurs with infiltrating air is very slow. Drying occurred when the ambient temperature increased above freezing and the amount of infiltration increased substantially; when infiltration returned to more typical levels, the drying process slowed considerably. Thus, sheathing temperatures just above freezing alone are not sufficient for drying. Infiltration must also take place to speed the drying process. Of course, if the

sheathing is heated by direct sunlight (as occurs on the south panel), moisture accumulation can be prevented altogether.

3. In this study, moisture was transported by exfiltrating air and by diffusion. The directed air movement is caused by pressure differences induced by temperature differences and by the wind acting on the structure. Air infiltration studies have shown that of the two effects, wind is usually the dominant factor. Moreover, wind direction can alter the flow through an opening, eg., a north wind will tend to produce infiltration on a north wall, whereas a south wind produces exfiltration through the same opening. Furthermore, large openings in the structure such as flues have a major effect on air movement through the envelope. Any model that is designed to predict moisture deposition in the building envelope must be able to predict the effect that wind speed and wind direction have on the airflow through openings. In addition, the model should include diffusion of water vapor through an opening in the wall cavity.

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TABLE 1

Details of House 6 at AHHRF

Floor Area:	22 ft x 24 ft - 528 ft ²
Wall Height:	8 ft
Basement Height:	8 ft, 6 ft below grade
Walls:	3/8 in. Prestained Rough Tex Plywood 3-1/2 in. Fiberglas Batt Insulation, R10 2 in. x 4 in. studs, 16 in. o/c 4 mil poly vapor barrier 1/2 in. drywall painted
Wall area/Floor area:	1.39
Windows:	N 39 in. by 76 in. double glazed sealed S None E 40 in. by 76 in. double glazed opening W 40 in. by 76 in. double glazed opening
Window area/Floor area:	11.9%
Ceiling:	R-12 batt insulation 3/8 in. plywood sheathing 4 mil poly vapor barrier 1/2 in. drywall painted
Roof:	CMHC approved trusses with 2 ft-6 in. stub 210# asphalt shingles 3/8 in. plywood Ext. GD sheathing
Basement:	1/2 in. preservative treated plywood to 2 ft. below grade 2 in. rigid insulation, R-10, to 2 ft. below grade 8 in. concrete wall 4 in. concrete slab on 6 mil poly vapor barrier
Door:	36 in. by 80 in. insulated metal
Electric furnace capacity:	7.5 kW

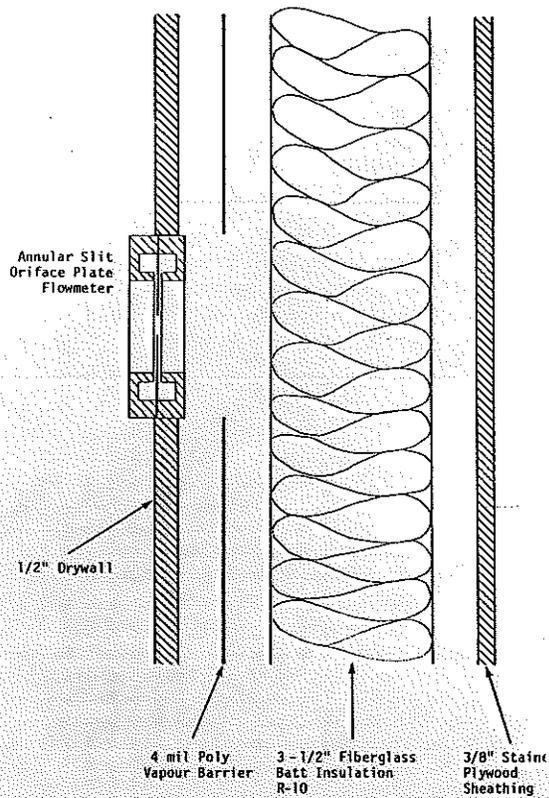


Figure 1. Construction details of the wall test panels

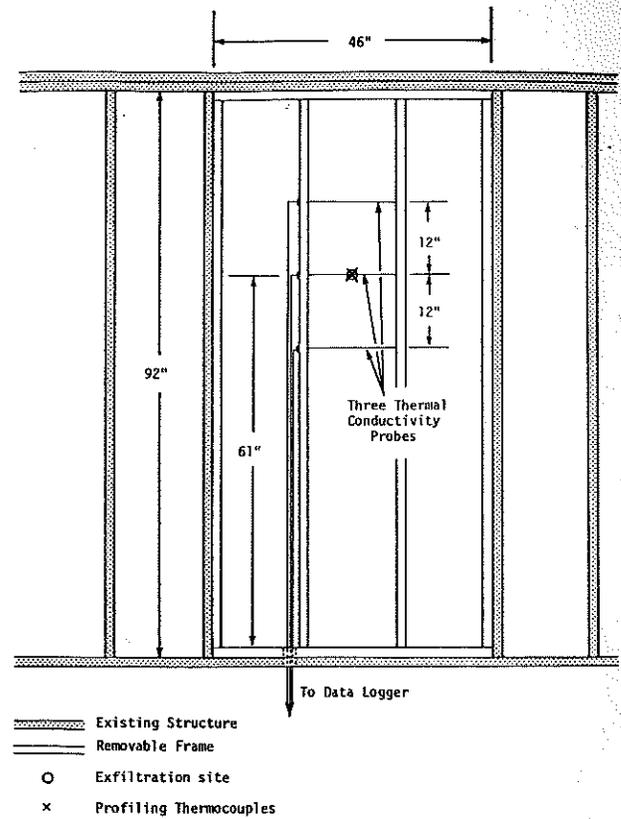


Figure 2. Location of instrumentation used in the wall test panels

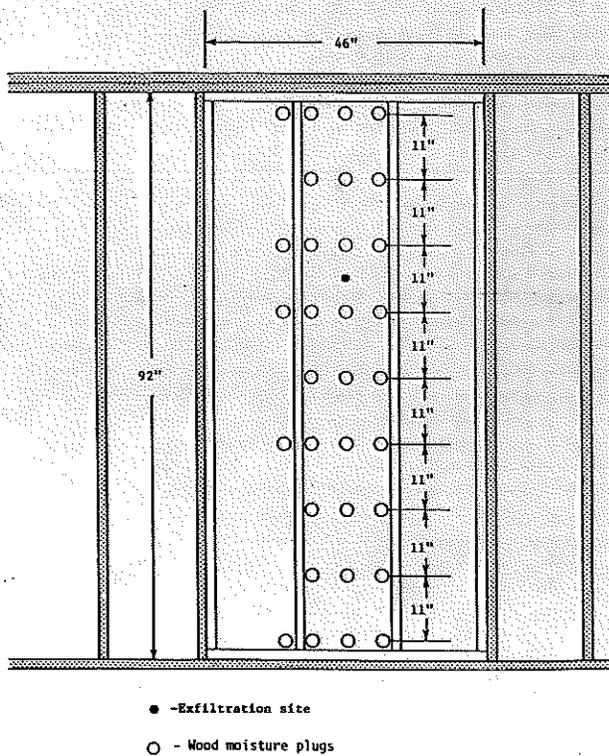


Figure 3. Distribution of wood moisture plugs in the exterior sheathing of the wall test panels

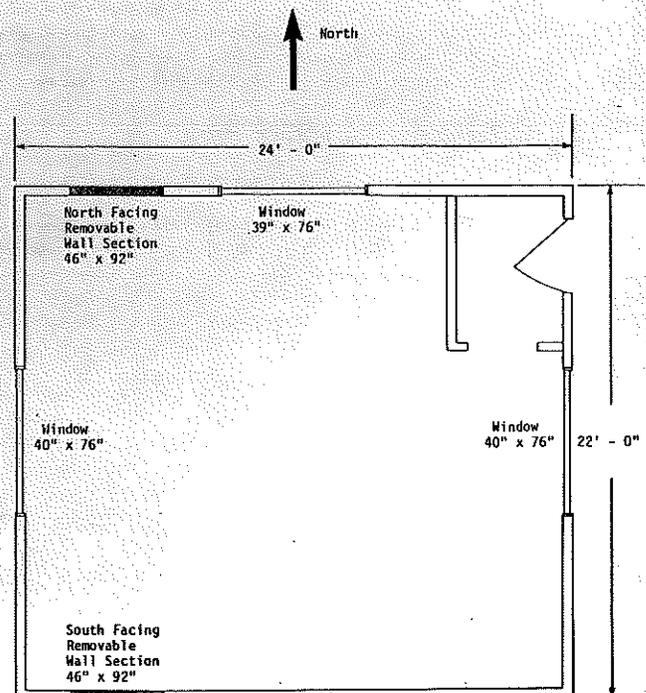


Figure 4. Plan view of House 6 showing the location of the wall test panels

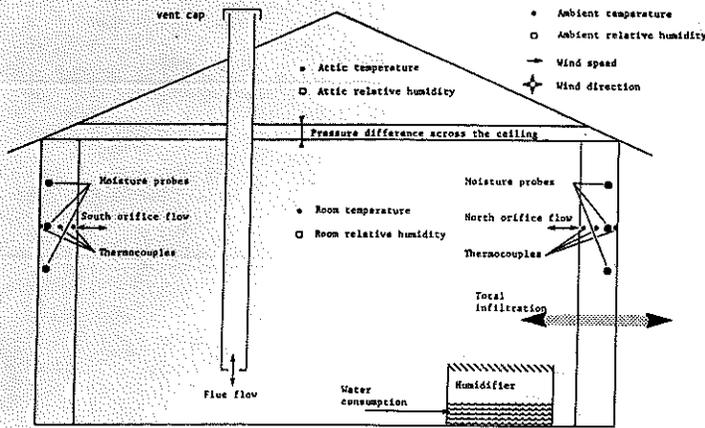


Figure 5. Schematic outlining the variables that were measured during the heating season in House 6 at AHHRF

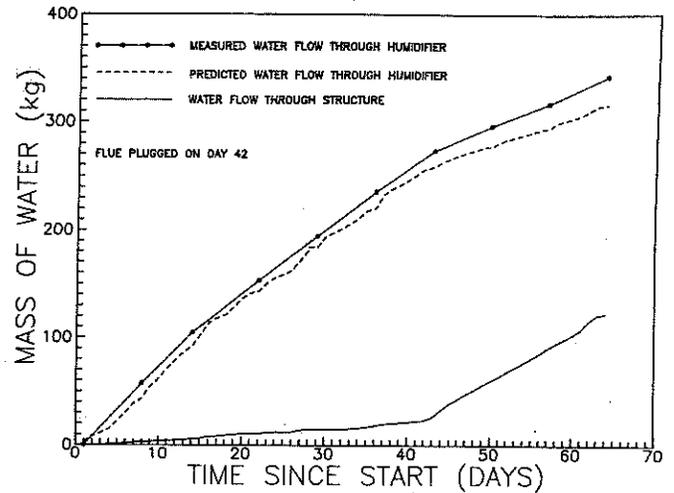


Figure 6. Cumulative mass of water generated in module 6 during the heating season. Start date was January 26 and the flue was blocked 42 days after the start.

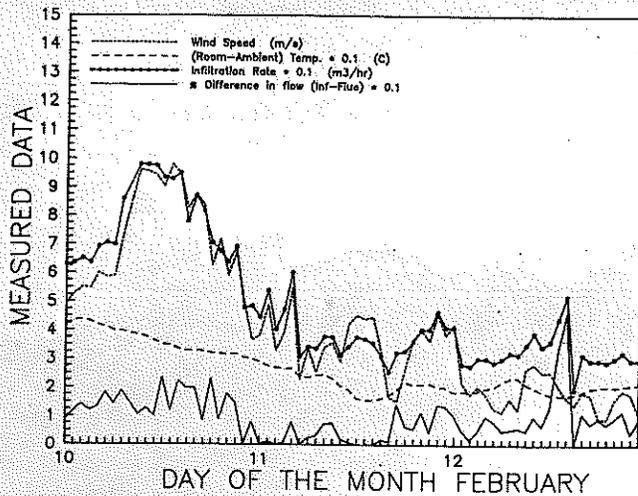


Figure 7. Hourly-averaged values of wind speed, indoor/outdoor temperature differences, infiltration rate and percentage difference between infiltration and flue flowrates for three days in February

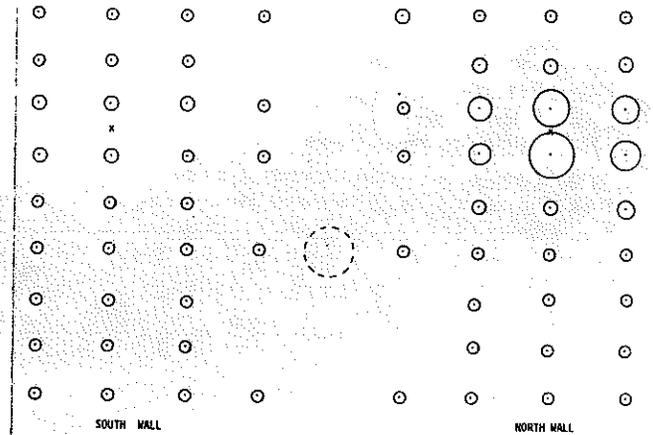


Figure 8. Distribution of moisture in the exterior sheathing at February 16. Each point corresponds to a moisture plug. The dotted circle indicates the 30% wt. (dry basis) moisture full-scale line. The diameter of each circle is proportional to the moisture content. The symbol "x" marks the location of the hole in the drywall.

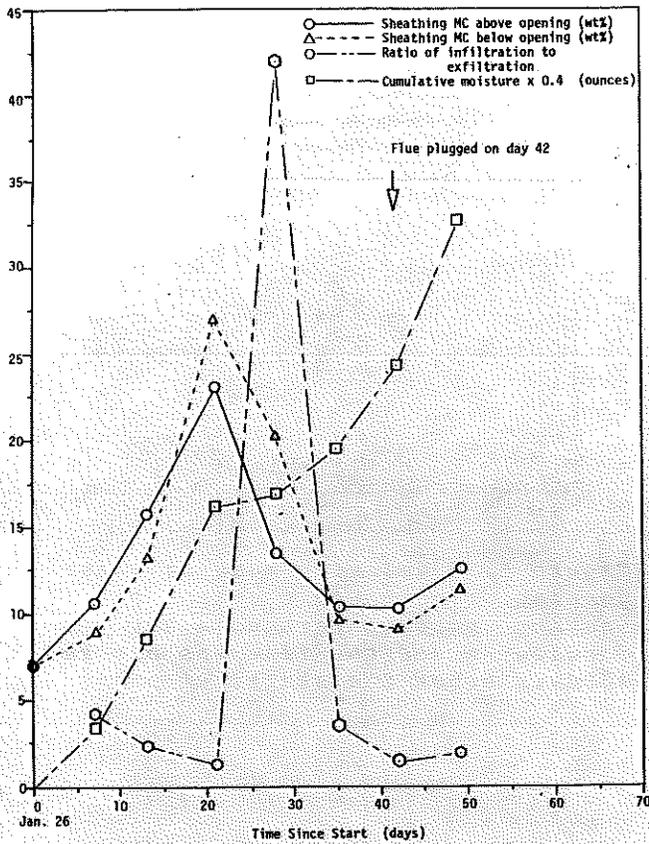


Figure 9. Data for the north wall panel, showing sheathing moisture contents adjacent to the opening, cumulative moisture flow through the panel due to air exfiltration, and the ratio of infiltration to exfiltration over the test period. All data points are weekly-averaged values.

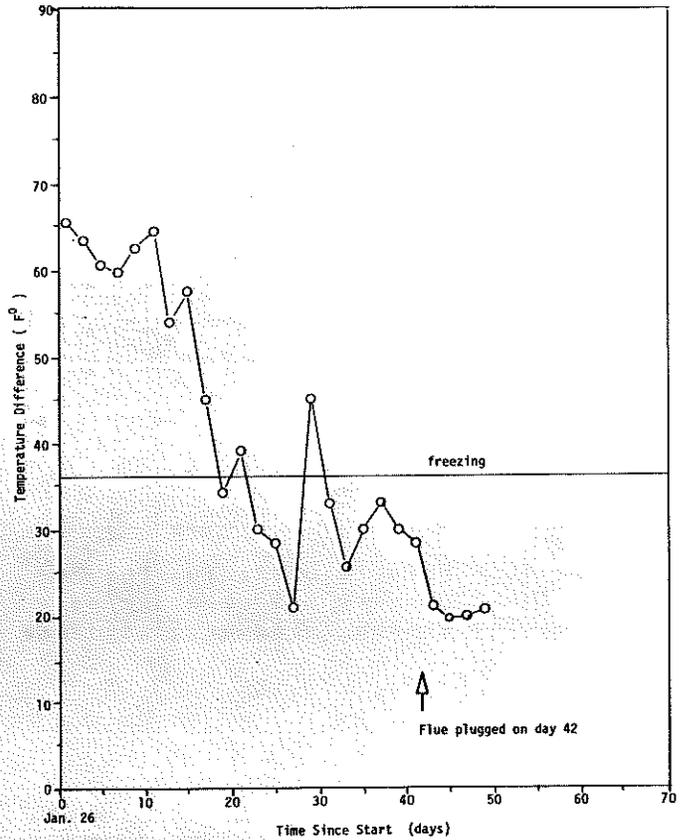


Figure 10. Indoor minus outdoor temperature differences for the test period. All data points are averaged over two-day intervals.

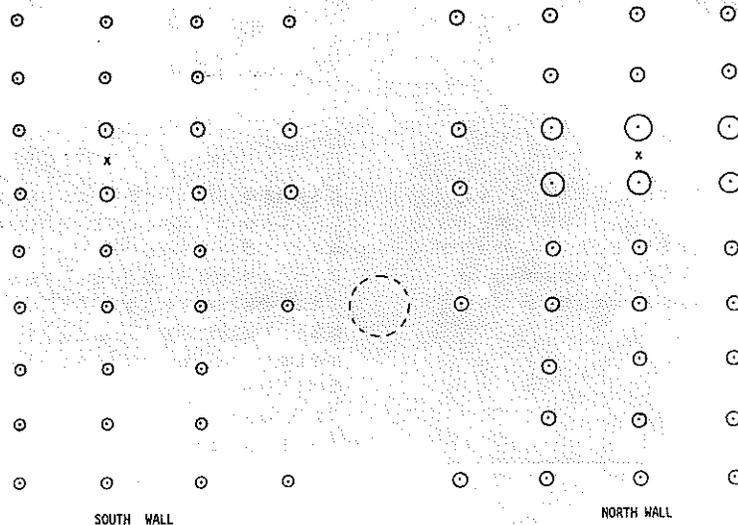


Figure 11. Distribution of moisture in the exterior sheathing at March 15, one week after the flue was blocked