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Condensation Potential in Wood-Frame Walls

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ABSTRACT

As a result of steadily rising energy costs, construction practice for light-frame wood structures has changed over the past few years. The use of 6-inch-thick walls and application of high-"R"-value, low-permeance sheathings to 4-inch walls has caused concern for the moisture patterns that may occur in walls. To observe actual moisture patterns and the potential for condensation, test structures were constructed near Madison, Wis., and near Gulfport, Miss., for exposure of eight types of insulated wall panels at controlled indoor conditions and typical outdoor weather conditions. Panels were instrumented with moisture sensors and tested without (Phase 1) and with (Phase 2) penetrations (electrical outlets) in the indoor surface.

Continuous inside vapor retarders effectively prevented cold weather condensation in all panels. Installation of an electrical outlet changed moisture patterns in both the cold winter climate and the hot, humid summer climate. Although condensation occurred for limited time periods in some panels at both test sites, the moisture content of framing did not rise to critical levels.

This paper should be useful to building designers, builders, and building code officials.

INTRODUCTION

High-efficiency thermal insulation systems for wood-frame residential construction have become essentially standard for many parts of the country in recent years. These systems include rigid foam wall sheathing, foil-backed foam wall sheathing, or nominal 6-inch insulation batts. All of these walls have higher "R" values (measure of resistance to heat loss) and foam sheathings have lower perm values (measure of rate of water vapor movement through a material) than previously used wall constructions. Theoretically, all of these systems should result in within-wall moisture patterns different from--and perhaps in excess of--those of conventional walls with nominal 4-inch studs and wood or wood-base sheathing materials.

Excessive moisture in wall cavities can have several detrimental effects. It may decrease the effectiveness of the cavity insulation [1].[2] If the cavity remains wet for extended periods coincident with warm temperatures in the wall, wood structural components may decay. Under winter conditions, outdoor temperature and indoor humidity are the critical

variables since indoor moisture is moving toward the drier outdoors and may condense on the sheathing or siding. The result may be buckling or warping of siding or paint peeling [2]. Under summer conditions, indoor temperature and outdoor humidity are the critical variables since outdoor moisture is moving toward the drier air-conditioned space and condenses on the gypsum board or vapor retarder when placed on the back of gypsum board. The result may be buckling of interior finish materials or mildew and mold on the surface.

The potential for these detrimental effects an be assessed based on measurements of moisture levels at various locations in walls exposed on one side to a complete annual cycle of outdoor weather conditions and on the opposite side to indoor conditions with controlled temperature and humidity. A better understanding of the moisture patterns in these highly thermal-efficient walls is needed in order to establish moisture control practices.

The objective of the research described in this report was to evaluate the potential detrimental effects of moisture accumulation in wall cavities in both a cold climate [3] and in a hot, humid climate with a long air-conditioning season. The cold climate location was Madison, Wis., with average monthly temperatures from December to February ranging from -7° to -4° C (19° to 24° F) and frequent lows of about -21°C (-5°F). The hot, humid climate location was Gulfport, Miss., where average monthly temperatures from June to August range from 27° to 28°C (80° to 83°F) with frequent highs approaching 38°C (100°F). Average relative humidities at Gulfport during summer months are 85 percent at 4 a.m. (coolest time of day) and 64 percent at 1 p.m. (warmest time of day).

The described work is part of an ongoing program of thermal/moisture research at the Forest Products Laboratory (FPL) to determine the potential for condensation in walls. Because all variables could not be considered in a single study, additional studies are planned in both controlled laboratory tests and field observations of complete houses.

BACKGROUND

The results of previous research at FPL on moisture condensation in walls have been summarized [2]. General recommended practice applies mostly to cold climates, but there is concern for how warm the winter must be to eliminate the need for a vapor retarder on the inside face of the wall. There is also concern that an outside vapor retarder may be needed during hot, humid summers to reduce moisture movement to the interior face of the wall. Closed cell foam sheathings or foil-backed foam sheathings act as outside vapor retarders, and could reduce moisture movement toward the inside in the summer.

The fact that moisture reduces the thermal resistance of insulating materials was established by Joy [1] in the 1950's. A

more recent study by Burch [4] showed that, for certain conditions, condensation occurred as a thin film on cold surfaces and had minimal effect on rate of heat transfer because it did not wet the insulation. However, wet insulation has been found in walls after prolonged periods of condensation. In some cases the condensation runs to the bottom of the wall cavity, saturating the sole plate as well as the lower few inches of insulation.

Moisture also reduces the thermal resistance of wood and wood products. A method for estimating that reduction is presented in the Wood Handbook [5]. More serious effects of moisture on wood are dimensional changes and the potential for decay, though this author is not aware of documented reports of extensive decay in wood-frame walls due to condensation. Such decay is a greater threat in warm climates than in cold climates because decay fungi require temperatures above 40°F for growth [5]. The only problems generally found--and those most visible--are mildew and paint peeling or blistering.

Previous cold-climate studies [6, 7] have shown the increased potential for condensation with high indoor humidities when outdoor winter temperatures are low. As more airtight houses result in higher indoor humidities, an even greater potential for condensation may be expected. Previous air-conditioning studies have been conducted in the relatively mild climate of Athens, Ga. [8], but no documented studies from hot, humid climates are available. Although laboratory tests have included condensation studies, the actual moisture patterns through the cross section of a variety of walls exposed to outdoor conditions are needed to evaluate the effect of construction changes. This can best be accomplished by testing exposure structures in more than one climate to include the effect of climate on moisture patterns.

MATERIALS AND METHODS

Exposure Structures

Two structures were built (one near Madison, Wisconsin, the other near Gulfport, Mississippi) for the purpose of exposing test walls to outdoor weather conditions on one side while exposing the opposite side to typical indoor conditions. The buildings were long and narrow, 8 feet wide by 48 feet long, with the long axis east-west for maximum exposure of north and south walls (Fig.1). The center 8-foot- long section was an instrument room. The remaining length of the building was partitioned every 4 feet, resulting in ten 4- by 8-foot rooms (Fig.2) connected by doors in partitions. The only exterior door was in the instrument room. Support for the roof and ceiling was provided by partitions, so exterior wall panels could be removed and replaced while the building remained intact. Four- by eight-foot wall panels were completely instrumented during fabrication and then installed by lag bolting them to partitions. Identical panels were installed on north and south walls for extremes of

exposure. Both the ceiling and floor were insulated with 12-inch (R-38) glass-fiber batts to limit heat transfer so the walls would be the major element of heat loss from each room.

Rooms were individually heated by a resistance-type electric heater, and individually cooled by a window-type air-conditioner mounted in the floor. Humidification was available by a vaporizing-type humidifier in each room during the heating season to maintain a minimum relative humidity (RH) of 40 percent. Humidity was not controlled during the air-conditioning season. Heaters were controlled by wall thermostats to maintain a temperature between 19° and 21°C (67° and 70°F). Air-conditioners were set to cycle on at 26°C (79°F) and off at 24°C (76°F). Ceiling fans operated when either the heater or the air-conditioner was running.

End rooms were considered buffers rather than test rooms as they had an 8- by 8-foot end wall exposed to the exterior and did not have heat loss, heat gain, or water-vapor loss comparable to other rooms with only a north and south wall exposed. This left eight identical rooms in each building for test and comparison purposes.

Test Panels

For this study, all test panels had 1/2-inch gypsum board on the inside and 7/16- by 12-inch primed hardboard lap siding on the outside. The siding was painted after panels were fabricated. Full-thickness glass-fiber insulation was placed in each wall cavity. The pair of panels for one room was framed with 2 by 6 studs at 24-inch spacing; all other panels were framed with 2 by 4 studs at 16-inch spacing. The primary variables were the sheathing material and the vapor retarder (Fig. 2). In addition, one panel with foil-backed polyisocyanurate foam was vented at the top by a corrugated plastic strip between the top plate and sheathing. Polystyrene sheathing was in 2- by 4-foot sections; all other sheathings werein 4- by 8-foot sections. Sheathing materials included: 1/2-inch fiberboard, 1/2-inch plywood, 1-inch extruded polystyrene foam, and 1-inch foil-backed glass-fiber reinforced polyisocyanurate foam. Only two types of vapor retarders were used: 6-mil polyethylene film continuous over the face of the framing, or asphalted kraft paper backing on blanket insulation stapled between studs. Although the asphalted kraft paper could be installed by the recommended method of lapping all joints over studs, in field practice it is often stapled between studs with no laps. That method was followed to simulate typical field conditions.

Calculated "R" values (measure of resistance to heat flow) for each wall panel are shown in Figure 2. In addition, the outdoor temperature for which freezing would occur on the warm side of the sheathing is shown. This sheathing surface was the plane with the greatest potential for condensation in winter. When condensation forms as ice, it is more likely to accumulate

to critical amounts than when formed as water which can be more easily distributed throughout the wall panel.

Each test panel was instrumented with wooden moisture sensors at 11 locations in the wall (Fig. 3). A thermocouple was also placed at each moisture sensor location. At heights of 1 and 7 feet above the floor, moisture measurements were made at the siding-sheathing interface, at the sheathing-insulation interface, at the center of the cavity insulation, and in the adjacent stud. Sensors were also located in the center of the top plate, the center of the sole plate, and between siding and sheathing at the midheight of the wall. Since the purpose of the study was to monitor the moisture content (MC) of wood components, there was no moisture sensor placed at the vapor retarder interface. Brief periods of condensation could have occurred there and been undetected unless the condensation affected the MC of insulation or ran down to the sole plate. Lead wires from all these data points were brought into the room through the vapor retarder and gypsum board at two points (1 and 7 feet above the floor). The punctures in the vapor retarders were caulked around each wire individually.

All test panels were without open punctures in the gypsum board or vapor retarder for the first year--Phase 1--of the study. In the second year of testing--Phase 2--a standard duplex electrical outlet was installed in each wall panel to observe the effect of air leakage into the wall cavity. In conventional construction, joints around windows or at baseboards and other discontinuities in the vapor retarder may result in additional leakage. For this study the electrical outlet was selected to provide air leakage for comparison purposes.

After installation of test panels, all joints with floor, ceiling, and partitions were caulked. On the outside, vertical joints between panels were caulked, and the joint between floor framing and the bottom edge of the wall panel was caulked. Six-mil polyethylene taped to each face of the partitions extends out between adjoining panels to prevent transfer of moisture between panels.

DATA ACQUISITION

Moisture Content and Temperature

The MC of the wooden sensor gave a qualitative indication of RH of the air at the site of the probe; however no conversions to RH were made. Probe findings in the rooms and outdoors were also recorded.

The sensors were selected wood elements in which electrical resistance changed with MC of the wood. Wooden sensors thus selected typically have an error no greater than ±2 percent MC for readings in the range of 9 to 20 percent MC. Construction and details of operation of this sensor are given by Duff [10].

Determination of MC beyond these limits was less accurate due to difficulties in measuring extreme ranges of resistance, and beads of condensed water were often present on surfaces at sensor readings of 20 percent or higher.

To effectively measure the very high resistance inherent in the sensor and to accurately transmit data to the logger, amplifiers were located as close to each sensor as practical; their output was connected to the data logger and calibrated.

Temperature measurements were made at each wooden sensor with a type T (copper-constantan) thermocouple and used for the temperature corrections. The resistance readings were adjusted for temperature and species to provide MC of wood at 70°F.

Data Recording

All of the moisture and temperature data were digitized and recorded on cassette tape using a multichannel, programmable data logger. Readings were made three times per day--at 1 a.m., 9 a.m., and 5 p.m.--in the Gulfport building. Data logger equipment problems in the Madison building resulted in hand readings being made only three times a week through much of the test period.

RESULTS

In both the cold climate and the hot, humid climate there were major changes in moisture patterns between Phase 1 (no penetrations) and Phase 2 (with penetrations). The installation of electrical outlets that penetrated the vapor retarder permitted air movement through the wall cavity in both directions, resulting in generally higher moisture levels. In both geographic locations moisture conditions during winter were more severe in the north walls than in the south walls, so these were selected for presentation of data. During the air-conditioning season moisture conditions were more severe in some south panels, so those we selected for presentation of summer conditions.

There was only one case of moisture levels in framing that would create a decay potential; that was in the hot-humid summer location and existed for only a 4-day period. All of the walls in the hot-humid summer location were disassembled and examined for signs of condensation or deterioration. There was no deterioration of materials in any wall panels. Signs of moisture such as streaking and water stains generally verified test data. Examination revealed panel 7S had been damaged during installation. The broken sheathing allowed outdoor air to enter the wall cavity near the bottom, so data from that panel was excluded from the results. Results are discussed in more detail under separate headings for the two study locations.

Cold Winter Climate

Moisture levels for critical locations in each test wall panel are shown in Table 1. During both Phase 1 and Phase 2, condensation occurred oinly during the coldest weather--in January, February, or March--when there was little danger of decay. All walls were completely dry by early April when outdoor temperatures began to rise above freezing. Condensation occurred at some location in every wall panel over the 2-year period, but none of the panels had an accumulation that would create a serious problem. Moisture levels are reported at only two locations in the walls because these were points of greatest potential for condensation and they proved to be the only points where major changes occurred. Specific findings were:

1. No condensation occurred during Phase 1 in walls with a continuous polyethylene vapor retarder, regardless of type of sheathing.

2. North walls with fiberboard or polystyrene sheathing and only asphalted paper backing on glass fiber insulation (no punctures) stapled between studs had condensation on the sheathing for a limited time (no more than 6 weeks).

3. Where condensation occurred in walls with fiberboard sheathing, it initially formed on the back of siding and later on the sheathing. Some moisture also passed through horizontal joints in polystyrene sheathing and condensed on siding.

4. A cold-side vapor retarder, such as the glue joint in plywood sheathing, reduced the hazard of condensation at the sheathing-siding interface without unduly increasing the cavity MC.

5. Condensation formed on the sheathing behind electrical outlets in all north-facing walls with batt insulation of R-13 and R-19. No localized condensation formed behind outlets in walls with R-11 blanket insulation. This was apparently due to more air movement through the less-dense insulation.

6. Condensation formed on sheathing near the top of walls with electrical outlets only where sheathing temperatures were quite low.

7. Vent strips at the top of walls with high-"R", low-permeance sheathing resulted in greater air leakage with no apparent benefit in moisture control.

8. After electrical outlets were added, most panels had high enough moisture levels on the back of the siding to create a potential for buckling of long strips of hardboard siding.

9. For both years and all constructions, all data points showed MC to be below 11 percent by early April.

10. MC of framing did not increase significantly at any time during the 2-year study.

Hot, Humid Summer Climate

Moisture levels for locations that exhibited the most change in each test wall panel are shown in Tables 2 and 3. The MC's at all data points were consistently higher than those in the cold winter climate. All framing MC was about 11 percent during Phase 1, but rose to about 14 percent after the vapor retarder was penetrated with electrical outlets. Some framing MC's in the south panel with 6-inch studs, fiberboard sheathing and polyethylene vapor retarder, rose to about 16 percent during the summer when condensation occurred in that panel. Framing MC at one location in that panel rose above the 20 percent level for about 4 days during the summer of Phase 2, but quickly returned to 16 percent. Examination showed no signs of deterioration. Moisture levels are reported for the two locations in walls that had the greatest potential for condensation. These locations are different for summer and winter conditions.

1. No condensation was detected in any of the walls during the first winter (Phase 1, without penetrations).

2. The only wall with sustained condensation during the first summer (Phase 1, without penetrations) was the wall with 6-inch studs and fiberboard sheathing.

3. The MC's at all points in all walls increased from about 11 percent to about 14 percent when the walls were penetrated by an electrical outlet (Phase 2).

4. Although some walls had periods of high MC during the second winter (Phase 2, with penetrations), there were no extended periods of condensation recorded. The only room having extended periods of condensation during the second summer (Phase 2, with penetrations) was the wall with 6-inch studs and fiberboard sheathing.

5. The only wall showing an increase in framing MC ws the wall with 6-inch studs, which had a MC of about 16 percent at the end of the summer in both Phase 1 and Phase 2.

CONCLUSIONS

These conclusions apply only to conventional construction and indoor conditions of 19-21°C (67-70°F), 40 percent RH during winter, and 24-26°C (76-79°F) during summer. Higher indoor humidities, which may occur due to construction moisture, extremely tight construction, or major indoor moisture sources, will increase the condensation potential. Lower air-conditioning temperatures will increase the summer condensation potential. While specific results are limited to the geographic location of the test building, the conclusions from the cold winter climate

study are applicable to much of the upper midwest and northeast of the United States and conclusions from the hot-humid summer climate are applicable to much of the southeastern United States. Condensation potential increases with severity of climate in both cases.

Asphalted paper backing on insulation stapled between studs does not provide adequate vapor retarder protection in cold climates to prevent condensation in the wall cavity or streaking of the siding where a permeable sheathing is used. A continuous 6-mil polyethylene vapor retarder can control winter condensation in insulated walls even where low-permeance sheathing is used. Puncturing the vapor retarder, as with an electrical outlet, completely changes moisture patterns in the wall both winter and summer and results in condensation on the sheathing behind the electrical outlet in cold weather.

In all of the types of construction observed, both with and without penetrations (outlets), condensation in the wall cavity during winter forms on the back of siding or on the back surface of the sheathing and does not wet the bulk of the cavity insulation. Low-permeance foam sheathings present no greater cold-weather condensation hazard in winter than do the other types of sheathing studied and they appear beneficial in reducing moisture movement into wall cavities during summer. Vent strips at the top of walls with high-"R", low-permeance sheathing produce no apparent benefit in moisture control.

While conditions that would promote decay in wood framing do not appear to be a danger in winter, moisture levels can be high enough in most panels to produce significant dimensional changes in thin panel products or long strips of siding. Winter condensation is not a decay hazard at either of the geographic locations in any of the wall constructions tested. Although summer condensation may wet the insulation in high-"R"-value walls with compressed cavity insulation and with low resistance to moisture movement near the outside face, the potential for deterioration of materials is minor. Current moisture movement theory does not explain why condensation occurred in these walls, which points up a need for further study of the mechanisms of moisture movement in walls. There is no high potential for decay in any of the materials of any walls tested.

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and installation of test panels.

[1]The Laboratory is maintained in cooperation with the University of Wisconsin.

[2]The underlined numbers in brackets refer to the list of references at the end of this paper.

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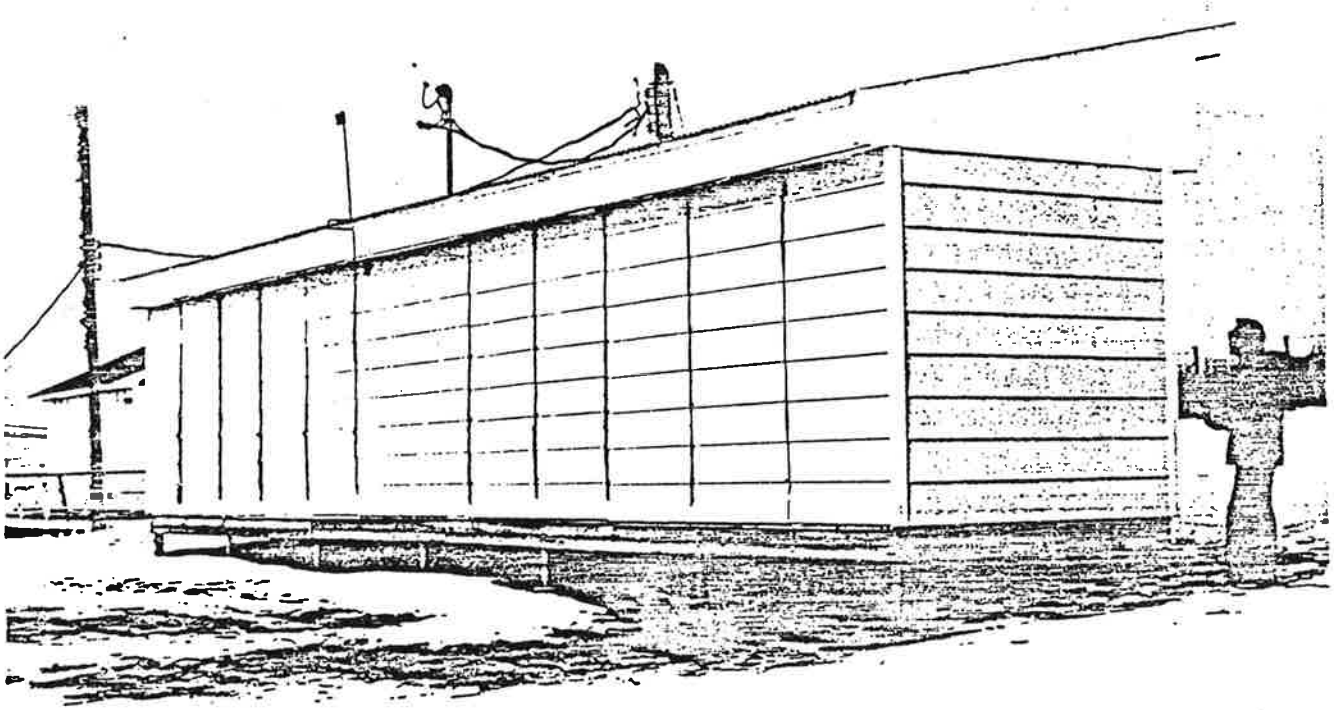

Figure 1. Experimental condesation-study structure near Madison, Wis. The building near Gulfport is identical.

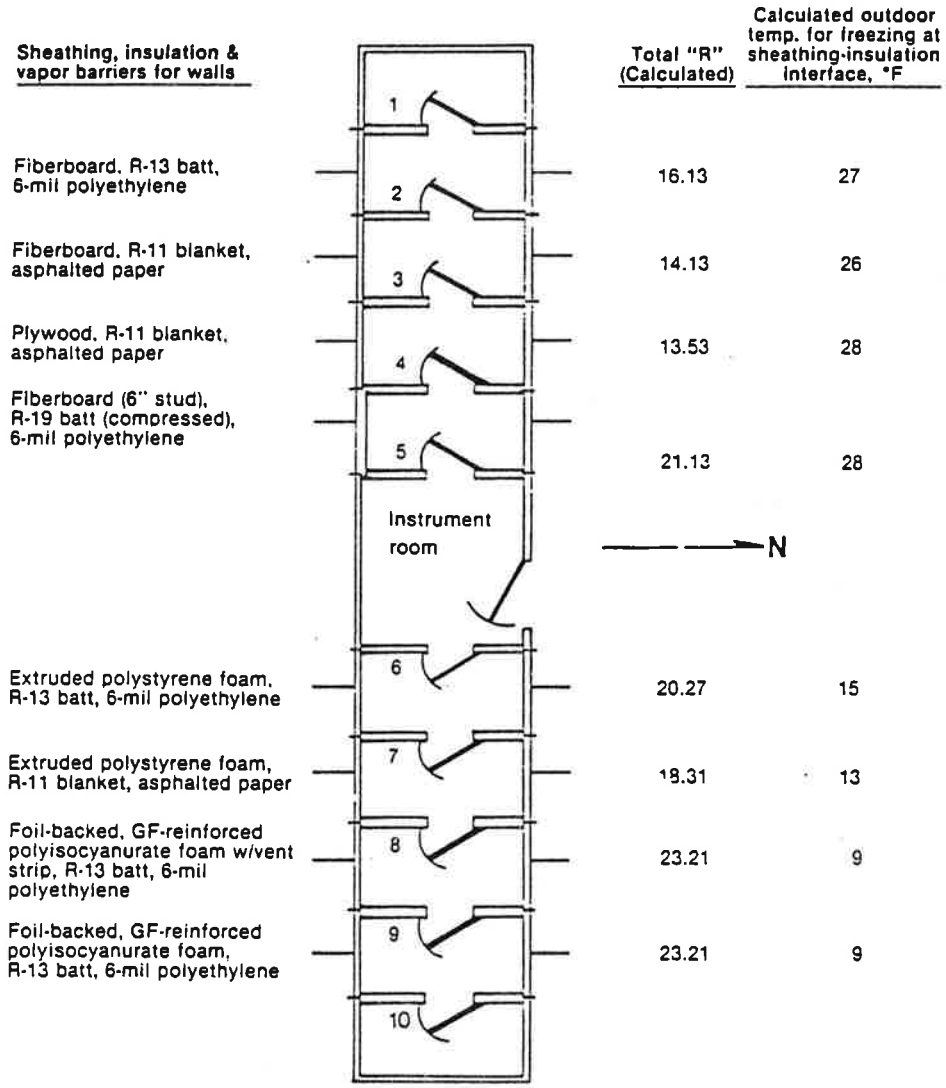

Figure 2. Plan of experimental structure showing variables of construction of each wall panel [3]. Note that both "R" values and interface temperatures are based on calculation methods shown in the ASHRAE Handbook of Fundamentals [9].

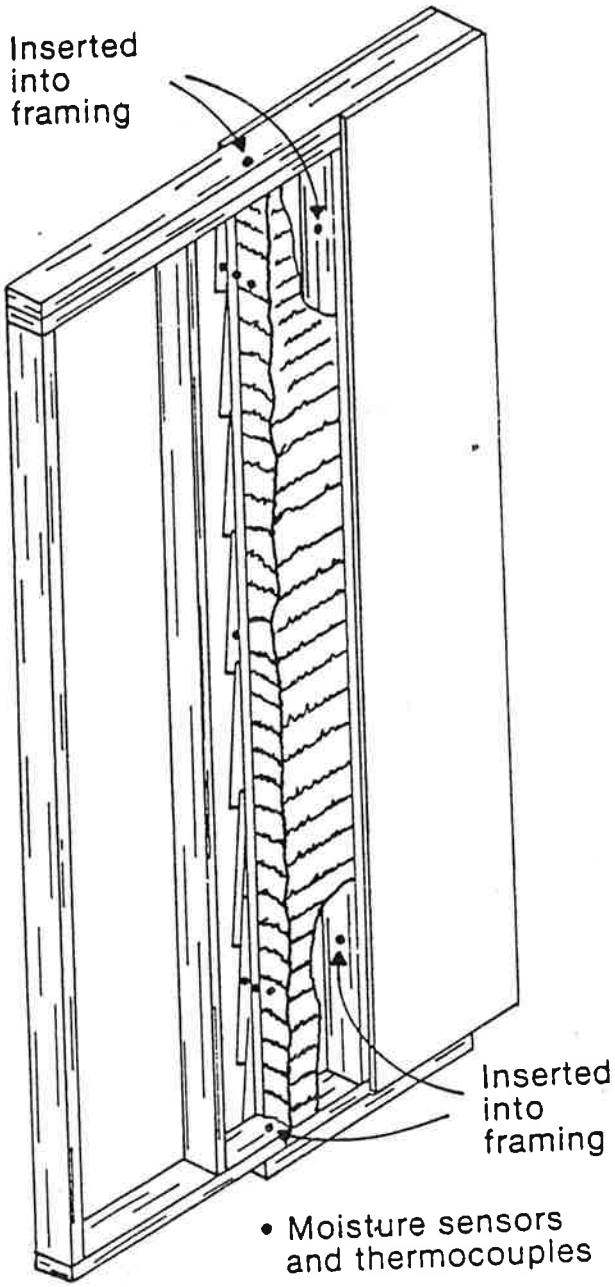

Figure 3. Moisture sensor locations in each test panel. Four sensors are in framing; two are in the center of insulation; two are at the insulation/sheathing interface; and three are at the sheathing/siding interface.

Table 1. Moisture content [MC][a] of wooden probes at key points in north-facing panels at the Madison, Wis., site.

Panel No.	Insulation/sheathing Interface			Sheathing/siding Interface		
	Jan	Feb	Mar	Jan	Feb	Mar
	Phase[b] 1/2	Phase 1/2	Phase 1/2	Phase 1/2	Phase 1/2	Phase 1/2
2N	L/C	L/C	L/C	L/C	L/C	L/C
3N	L/H	M/H	L/H	H/C	C/C	C/C
4N	H/H	L/C	H/H	L/H	M/C	M/H
5N	L/C	L/C	L/C	M/C	M/C	L/C
6N	M/C	H/C	L/C	H/H	M/H	M/M
7N	H/C	C/M	C/M	L/C	M/H	M/M
8N	M/C	L/C	M/C	L/L	L/M	L/L
9N	L/C	H/H	L/M	L/L	L/M	L/L

a L [low] = < 12%; M [moderate] = 12 - 16%; H [high] = 16 - 20%; C [condensation] = > 20%

b Phase 1 is without penetrations in the vapor retarder and is shown to the left of the "/"; Phase 2 is with penetrations in the vapor retarder and is shown to the right of the "/".

Table 2. Moisture content [MC][a] of wooden probes at key points in north-facing panels during winter at the Gulfport, Mississippi site.

Panel No.	Insulation/sheathing Interface			Sheathing/siding Interface		
	Jan	Feb	Mar	Jan	Feb	Mar
	Phase[b] 1/2	Phase 1/2	Phase 1/2	Phase 1/2	Phase 1/2	Phase 1/2
2N	L/C	L/M	L/M	L/M	L/M	L/M
3N	L/M	L/M	L/M	L/M	L/M	L/M
4N	L/M	L/M	L/M	L/M	L/M	L/M
5N	L/M	L/M	L/M	L/M	L/M	L/M
6N	L/M[c]	L/M[c]	L/M[c]	L/M	L/M	L/M
7N	L/M	L/M	L/M	L/M	L/M	L/M
8N	L/M	L/M	L/M	L/M	L/M	L/M
9N	L/H	L/H	L/H	L/M	L/M	L/M

[a] L [low] = < 12%; M [moderate] = 12 - 16%; H [high] = 16 -20%; C [condensation] = > 20%

[b] Phase 1 is without penetrations in the vapor retarder and is shown to the left of the "/"; Phase 2 is with penetrations in the vapor retarder and is shown to the right of the "/".

[c] These conclusions were not replicated on the south-facing wall panels. The reasons for these differences are speculative and indicate the need for further testing.

Table 3. Moisture content [MC][a] of wooden probes at key points in south-facing panels during summer at the Gulport, Mississippi site.

Panel No.[b]	Insulation June Phase[c] 1/2	Insulation July Phase 1/2	Insulation Aug Phase[d] 1/2	Framing June Phase 1/2	Framing July Phase 1/2	Framing Aug Phase 1/2
2S	L/M	L/M	L/	L/M	L/H	L
3S	L/M	L/M	L/	L/M	L/M	L
4S	L/M	L/M	L/	L/M	L/M	L
5S	C[e]/M	C[e]/C[e]	C[e]/	L/M	L/C[e]	M/
6S	L/M[e]	L/M[e]	L/	L/M	L/M	L/
8S	L/M	L/M	L/	L/M	L/M	L/
9S	L/H[e]	M/M[e]	M/	L/M	L/M	L

a L [low] = < 12%; M [moderate] = 12 - 16%; H [high] = 16 - 20%; C [condensation] = > 20%.

b Panel 7S was damaged during installation, which was not apparent until the structure was dismatled after exposure.

c Phase 1 is without penetrations inthe vapor retarder and is shown to the left of the "/"; Phase 2 is with penetrations in the vapor retarder and is shown to the right of the "/".

d Lightning damage prevented obtaining data for August Phase 2.

e Range of humidity was not replicated on opposite-facing walls. The reasons for differences were not resolved, and indicate the need for further study.