COMPARATIVE STUDIES OF VAPOR CONDENSATION POTENTIALS IN WOOD FRAMED WALLS

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1. INTRODUCTION

Vapor condensation within a wall cavity has been somewhat a mystery within the home construction industry, since the introduction of wall insulation. Most of the early designs and analyses were based on vapor permeation under steady state condition and the theoretical dew point position. Laboratory experiments and tests in the 1940's proved the permeation theory. But also there was sufficient evidence to indicate the strong dependence of the moisture balance on the air convection.

Based on the permeation theory, a vapor retarder (barrier) was designed on the interior side of the insulated wall, which would reduce the vapor permeation rate so that condensation can be avoided. For an insulated wall with no vapor retarder, the permeation theory predicted a five to one ratio of the permeances on the exterior and interior sides of the wall. This evolved to be the rule of thumb for the industry.

It has been recognized more recently that the condensation and evaporation process, and the vapor balance within the wall is much more complicated than the steady state, vapor permeation. The dominance of the air convection in the moisture balance was further observed in laboratory tests and deduced in field experiments.

The present studies explore the sensitivity of the condensation potential in response to the position of the insulation. A moisture balance is performed for a hypothetical home of 1,650 square feet of living area to illustrate the relative significance of different modes of vapor transport. The logic of five to one ratio was repeated to include the insulation sheathing system. The results indicate that this ratio changes with respect to the temperature profile across the wall.

Field inspection techniques are discussed. The inspection results of over 70 homes are discussed. A controlled field test experiment, and the test results are given to show the comparative performance of two wall systems, with and without asphalt coated kraft paper vapor retarder (barrier).

2. PERMEATION AND DEW POINT DESIGN

Vapor permeation is a diffusion process, which is activated by the vapor pressure gradient. The permeation process also allows one to estimate the vapor flow with an equation similar to that used in heat conduction analysis. Vapor permeation and dew point calculations have been the primary design methods used to analyze the vapor condensation potential and moisture balance within a wall.

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A. Dew Point Position and Insulation

Assuming that there is no vapor retarder (barrier) on the interior side, the dew point position would move within the wall depending on where and how much insulation was applied. A typical wood frame wall without insulation is used here as a base case. Consider an insulation material having an R value of 5.0 installed at three different locations: on the interior side, in the cavity, and on the exterior. The indoor condition was assumed to be $70^{\circ}F$ and 25% RH. The outdoor condition was assumed to be $0^{\circ}F$ and 90% RH. The dew point of the indoor air is $32.6^{\circ}F$ (or 0.185 inch of Hg).

The four temperature profiles corresponding to the wall systems mentioned are shown in Figures 1, 2, 3 and 4. The position of the $32.6^{\circ}F$ line represents the theoretical dew point of the wall. Compared to the uninsulated wall, cavity insulation does bring the theoretical dew point from the wood sheathing to within the wall cavity. If the position of the theoretical dew point may serve as an indication of the vapor condensation potential within the wall cavity, then one can rank the preference of the insulation positions accordingly.

B. Rule of Thumb and the Variable Ratio

An insulated wood frame wall, like the one shown in Figure 5, was analyzed by Professor Lund.[1] There was no vapor retarder (barrier) on the interior side. The temperature at the interface of the wood sheathing and the cavity insulation was calculated for each set of indoor and outdoor temperatures and humidities. They are listed in Table 1. If vapor condensation occurred at the interface, then the interface temperature became the dew point. From here the saturation pressure was determined.

A vapor balance was made to see whether the vapor permeation rate from the warm side to the interface was faster, equal to or slower than that from the interface toward the cold side. The permeation rate was proportional to the vapor pressure difference, ΔP (driving force), and inversely proportional to the permeation resistance (1/perm). Hence, the ratio of the vapor pressure difference of the incoming permeation to that of the outgoing permeation ($\Delta P_i/\Delta P_o$) can be used to gauge the ratio of the perm on the interior side to that on the exterior side.

Referring to Table 1, under the conditions of $70^{\circ}F$ and 40% RH indoor and $0^{\circ}F$ and 80% RH outdoor, the ratio is close to five to one. This ratio has been used by the old Minimum Property Standards of the Department of Housing and Urban Development, and was quoted frequently over the years. It has evolved to be a rule of thumb for the industry.

However, this ratio changes with different constructions. For instance, when the wood sheathing is replaced with an insulation board of R-5.4, then the ratio of the vapor pressure differences becomes 1.4 to 1. The reason for this reduction is because the temperature at the interface has been increased with the insulation board. Higher interface temperature would reduce the vapor pressure difference on the interior side, (ΔP_i), and in the meantime, increase the vapor pressure difference on the exterior side, (ΔP_o). By the same token, this ratio would be increased to over ten to one, when a sheathing board of R-0.2 is used in place of the wood sheathing.

3. MOISTURE BALANCE

An indirect way of showing that vapor permeation is not the only means to move the moisture within a house, is to perform a moisture balance on a house. This hypothetical house is single story and has 1,650 square feet of floor and ceiling area, 1,500 square feet of opaque wall area, and 13,200

[1]BRAB Conference report N.4-Proceedings Condensation Control In Buildings, February 26, 1952.

cubic feet of air space. The house is constructed with current standard of insulation, and average workmanship. The air exchange rate under average winter conditions is assumed at one (1) air change per hour. The indoor conditions are maintained at 70°F and 30% RH (2.43 grn of H_2O/cubic feet of air), and the outdoor conditions are 0°F and 100% RH (0.563 grn of H_2O/cubic feet of air).

The wall construction is of 1/2 inch gypsum drywall with two coats of paint, 2x4 studs 16 inches on center, 3-1/2 inch glass fiber insulation, 1/2 inch wood fiberboard sheathing, and aluminum siding. The vapor retarder (barrier) used is asphalt coated kraft paper, carefully installed on stud face. The same vapor retarder (barrier) is used on the ceiling. The floor has polyethylene film as the vapor retarder.

The vapor resistance of the ceiling and wall cross section is estimated at 2.0 (1/perm), and the floor is 8.0 (1/perm). The driving force, vapor pressure difference (ΔP) between indoor and outdoor, is 0.176924 inch of Hg. Hence, the amount of moisture moved out by permeation through the wall, ceiling and floor is 133, 146 and 36 grains per hour respectively. The total by permeation is 315 grains per hour.

The amount of moisture moved out by air exchange is estimated at 24,644 grains per hour. Therefore, the amount of moisture moved by permeation is only about 1.3% of the total moisture movement. The total moisture transferred is 24,959 grains per hour, or 3.56 pounds per hour, which is about 86 pounds per day. It is generally true that the air exchange in a house is by and large the dominant means of moving moisture.

Such dominance was also proved in laboratory tests.[2] In fact, the breathing holes or vent strips used in the industry to prevent or rescue a wall from vapor condensation are devices to promote the air exchange rate. However, such devices should be recommended as a second line defense against vapor condensation in walls. The first line of defense is the vapor retarder (barrier) installed on the interior side of the wall. The most effective vapor retarder (barrier) is the one that is installed as an air barrier as well.

4. FIELD TESTS AND INSPECTIONS

A. Field Tests

A series of condensation and evaporation experiments was conducted at Midland, Michigan, during the winter of 1976 and 1977. Two windowless houses of 12'x18' were constructed side by side, Figures 6 and 7. The walls had hardboard siding, R-11 fibrous insulation, and 1/2 inch gypsum drywall. One house was sheathed with one inch, low perm (0.6) extruded polystyrene plastic insulation board (R-5.4), and the other house sheathed with 1/2 inch intermediate density wood fiberboard (R-1.3). Within each house, half of the walls had asphalt coated kraft paper, inset stapled on the interior side, as vapor retarder (barrier) and the other half had no vapor retarder at all, Figures 8 and 9.

Eight condensation detectors were installed at the interface of glass fiber insulation and the interior side of sheathing per each house. The detectors were grouped into four pairs, two pairs on the north wall, and one pair each on the east and west walls. Each pair was installed in one stud cavity. One detector was one foot above the floor, and the other was one foot below the ceiling. Such detectors were very sensitive to liquid water. They provided the yes-no type of signals on the recorder chart.

[2] Kusuda, T. and Ellis, W., "Vapor Condensation in Cold Storage Walls," NBSIR, April 1975.

A total of twenty-four (24) thermocouples was installed in these two houses to monitor the temperatures. Temperatures at the condensation detectors, between the hardboard siding and the sheathing, between the glass fiber insulation and the drywall, and the indoor and outdoor temperatures were all recorded. The test houses were heated with electric resistance heaters. The indoor temperature was regulated by a commercial thermostat. The kick-on and kick-off temperatures of the two units were equalized. The furnace on-time was balanced to within a few seconds.

The indoor humidity was regulated by a console type, commercial humidifier. There were three levels of settings, high, low and medium. The medium level setting yielded a humidity about 30-35% RH at 75°F. The high level setting would give 50-55% RH at 75°F. The humidifier had a reservoir capacity of three gallons. Both units were filled simultaneously. The houses were checked daily, except on the weekends, during the experiment.

The outdoor conditions were the natural environment of winter in Midland, Michigan. The air temperature may vary between 0°F to 20°F. The indoor temperature was regulated at 70 to 75°F. The indoor relative humidity was maintained at 30-35% RH for three weeks, then the humidifier was shut off for two weeks, then the humidity was maintained at 50-55% RH for three weeks, and finally the humidifier was shut off for three to four weeks.

During the first humid cycle (35% RH), condensation was observed in both houses at the wall sections where the asphalt coated kraft paper (vapor retarder) was absent. But no condensation was detected at the wall sections with the kraft paper. Therefore, the importance of the interior side vapor retarder (barrier) is far greater than the perm of the sheathing used.

During the first drying cycle, evaporation took place at the wall sections where condensation had occurred. Within the time limit, all the wall sections recuperated and became dry. However, it was observed that the wall section having plastic foam insulation sheathing was the first one to recuperate.

During the second humid cycle (55% RH), condensation was observed in all wall sections in both houses. When condensation did occur, the wall section having plastic foam insulation sheathing was the last one to condense.

During the second drying cycle, evaporation took place in all wall sections. But the wall sections having plastic foam insulation sheathing were the first ones to recuperate. In fact, the wood fiberboard sheathing was saturated so much it never completely recuperated within the four weeks time period.

Also demonstrated in this test is the advantage of warmer stud cavity. The wall sections with plastic foam insulation sheathing always registered 9 to 15°F warmer than the corresponding wall sections with wood fiberboard sheathing. Logically the warmer stud cavities had less chance for condensation and more chance for evaporation. This is exactly what was observed in this series of experiments. Another observation was made during the condensation cycles--the water consumed by the humidifier. The humidifier in the wood fiberboard house consumed almost twice as much as that in the plastic foam house.

B. Field Inspections

Since there are so many factors that may affect the vapor condensation potential within the wall cavity, the most reliable way to obtain accurate information is through field inspection. Our field inspection program consisted of opening the wall cavities either from the exterior or from the interior of selected houses.

When examined from exterior, either the siding was taken off or a 2-1/2 inch hole was drilled. The sheathing was cut off to expose the wood framing and the cavity insulation (Figure 10). For interior examinations a rectangular area of the drywall was cut off, the vapor retarder (barrier) was carefully removed, and the wood members, insulation and sheathing were exposed (Figure 11).

Visual observations were made to check water stain marks, traces of liquid water, rusty nail heads, or any sign of wood decay and fungus growth. The insulation was touched by hand to feel any liquid water or dampness. A wood moisture meter was used to measure the moisture contents of the wood members. After the inspection was completed and pictures taken, the insulation was put back into position, the vapor retarder (barrier) carefully put back and taped, and the sheathing, siding, or drywall returned to their original positions.

Such field inspections have been conducted over several winters since 1974. So far over 70 homes (Tables 2 and 3) have been examined in Canada and this country and some of the homes have been inspected more than once. This population of samples includes a wide range of variables.

1. Occupancy and life-style
2. Different heating systems - combustion furnace, electric resistance heater, heat pump, etc.
3. Climatic locations - 4,000 to over 8,000 D. D. heating; North Carolina to Quebec City
4. Age of houses - under construction to ten years old
5. Different wall constructions -
   sidings: aluminum, vinyl, wood, hardboard and plywood

   sheathing: plastic foam, wood fiberboard and plywood

   cavity insulation: glass fiber and cellulose fiber

   vapor retarders: none, asphalt coated kraft paper and polyethylene film
6. House size, style and orientation
7. Ordinary workmanship and construction

There was no vapor condensation, water stain marks, wood decay or fungi growth observed in all the walls inspected. The moisture contents of the wood members were mostly between 7 to 12%. All of them were below 15%. This held true regardless of the sheathing used.

The Research Foundation of the National Association of Home Builders (NAHB) participated in the field inspections performed in 1977.[3] As nearly as one can tell, there was no indication of vapor condensation in the walls inspected. There was no appreciable difference in moisture content measurement between walls sheathed with extruded polystyrene plastic foam board and wood fiberboard or plywood.

5. CONCLUSIONS

From the dew point design and permeation analysis, moisture balance over a typical house, the field condensation experiments, and the extensive field inspections, the following conclusions can be safely drawn.

A. Position of the theoretical dew point does change with where the insulation is applied. In frame wall construction without insulating sheathing,

[3]Johnson, Arthur, "A Field Investigation To Measure Moisture Content of Building Materials Used In Conjunction With Extruded Polystyrene Exterior Sheathing," NAHB Research Foundation, Inc., Rockville, Maryland, March 1978.

the theoretical dew point almost always remains within the wall cavity no matter how much cavity insulation is used. Its position can be moved out of the cavity when insulation sheathing is used.

B. The traditional five to one ratio of interior to exterior perms was based on only one standard construction. Calculations varified by temperature measurement show that the permeability ratio rule of thumb should vary considerably depending on the ratio of R between cavity and sheating. For example, the five to one rule of thumb ratio changes 1.4 to one when R=5.4 sheating replaces wood fiber sheathing in standard insulated frame construction.

C. The dominant mode of vapor transport in the moisture balance of a house is air convection, not vapor permeation.

D. A vapor retarder (perm.<1.0) installed on the interior side of the wall, which also functions as an air barrier, is the single most important factor in minimizing the potential for vapor condensation.

E. The asphalt coated kraft paper, properly installed, is an adequate vapor retarder (barrier) for both extruded polystyrene plastic foam sheathings and conventional sheathings.

F. Warmer cavity temperature reduces the chance for condensation and increases the chance for evaporation. Sheathings with higher insulation value definitely help to decrease the condensation potential within wood frame walls.

TABLE 1

EFFECT OF OUTSIDE AIR TEMPERATURE ON THE CONDENSATION RATE WITHIN AN INSULATED WALL*

Temperature °F		Vapor Pressure — Inch H_g				
Outdoor	Sheathing	Outdoor	Sheathing	Diff. Warm Side	Diff. Cold Side	Ratio $\Delta P_I/\Delta P_O$
20	26	.051	.137	.159	.086	1.85
10	19	.032	.098	.198	.062	3.20
0	**11**	**.019**	**.067**	**.229**	**.047**	**4.86**
-10	2	.011	.042	.254	.031	8.20
-20	-6	.006	.027	.269	.021	12.80

*Prof. Lund; BRAB Conference Report, Feb. 26, 1952

TABLE 2

FIELD INSPECTIONS IN USA

YEAR	LOCATION	NO. HOUSES
1974	MIDLAND, MI	3
1975	CLEVELAND, OH	3
	ST. PAUL, MN	2
	COLUMBUS, OH	2
1976	MARION, IL	2
	MIDLAND, MI	5
	MADISON, WI	5
	PORTSMOUTH, NH	1
	BOSTON, MA	4
1977	MIDLAND, MI	4
	CLEVELAND, OH	7
	BOSTON, MA	7
	ROCHESTER, NY	2
1978	MIDLAND, MI	2
1979	CHARLOTTE, SC	6
	MIDLAND, MI	2
	COLUMBUS, OH	2

TABLE 3

FIELD INSPECTIONS IN CANADA

YEAR	LOCATION	NO. HOUSES
1975	Quebec City, Que.	2
1976	WINNIPEG, MAN.	4
	QUEBEC CITY, QUE.	4
1977	QUEBEC CITY, QUE.	4
	WINNIPEG, MAN.	2

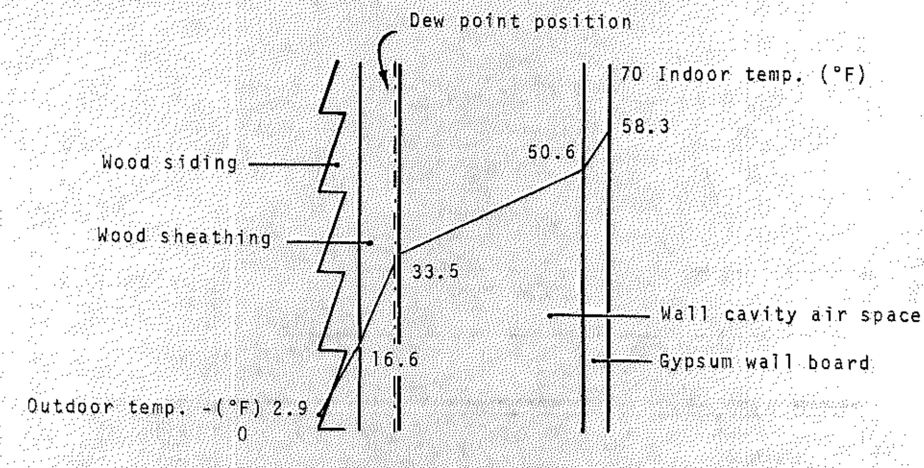

Fig. 1 Uninsulated wall

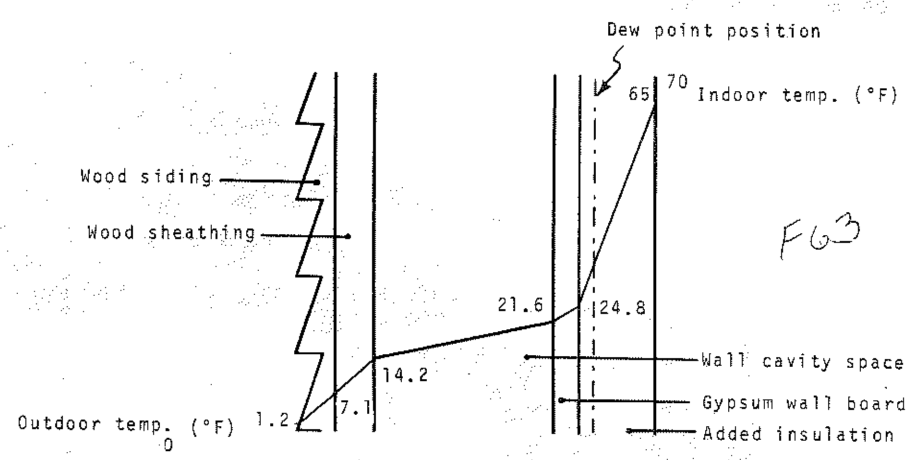

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Fig. 2 Insulation on the interior

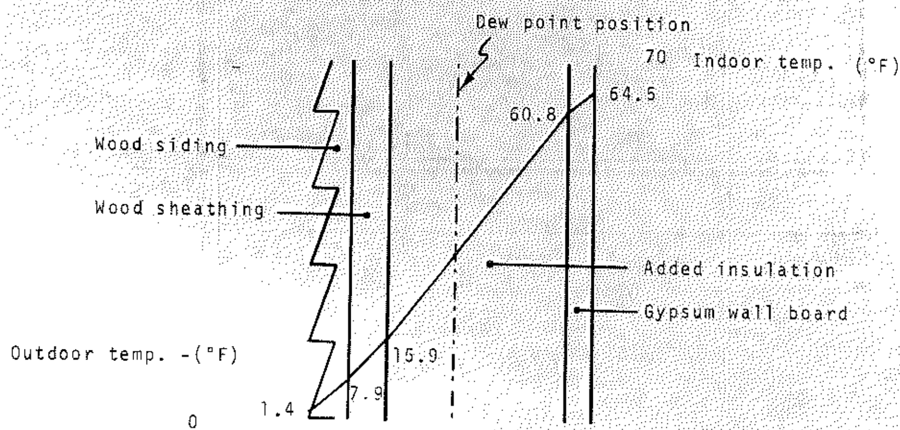


Fig. 3 Insulation in the cavity

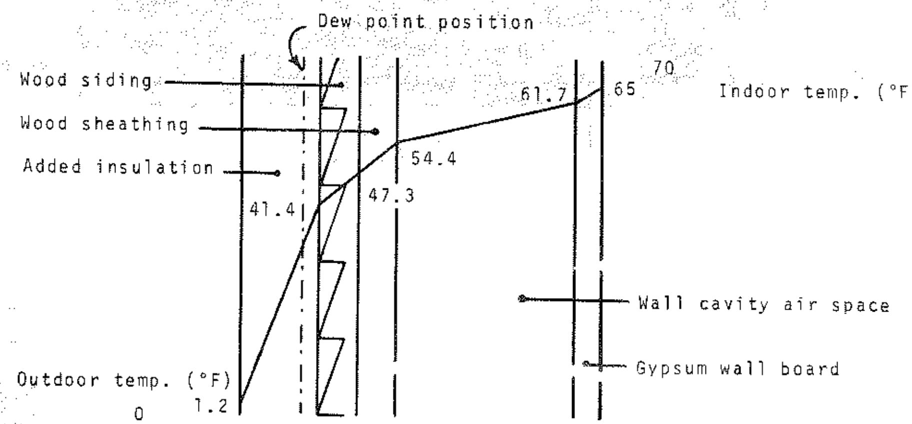


Fig. 4 In..lation on the exter..

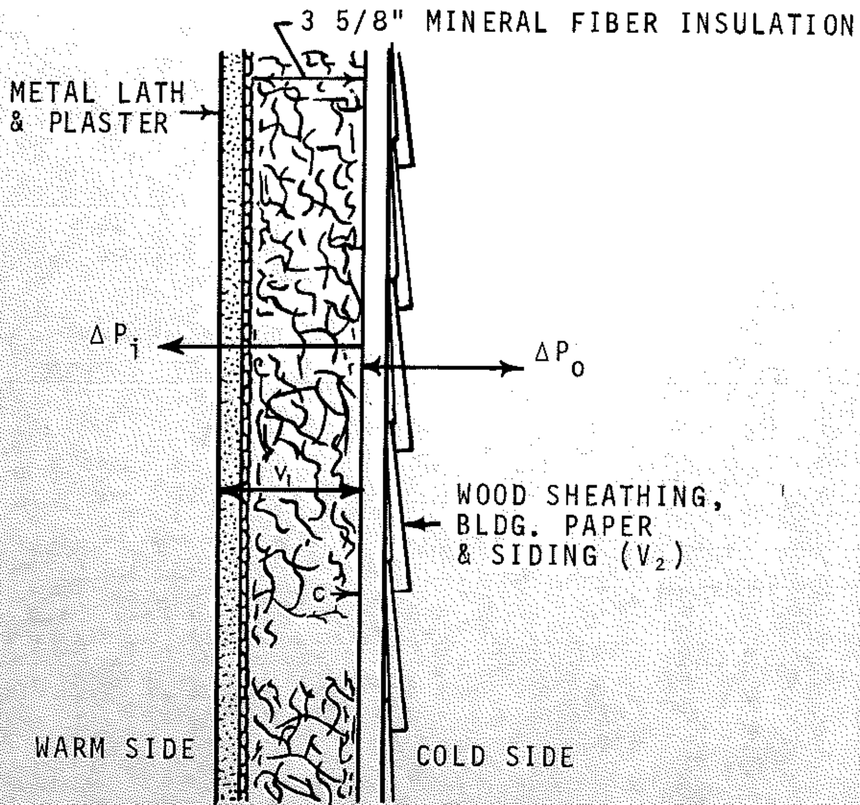


Fig. 5 Insulated wall without vapor retarder (barrier)

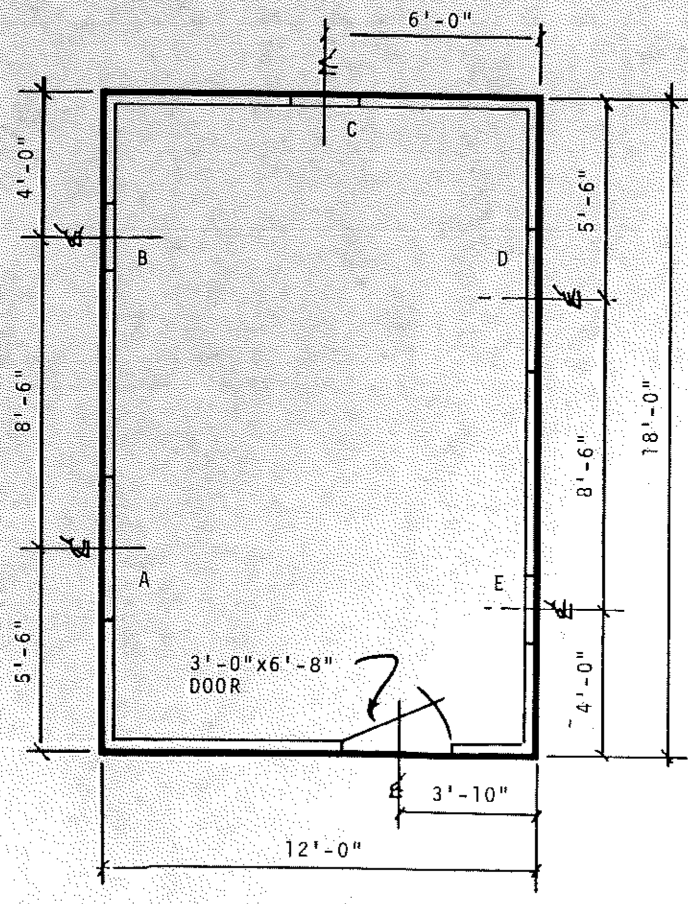


Fig. 6 Midland Test Houses; two 12-ft x 18-ft units

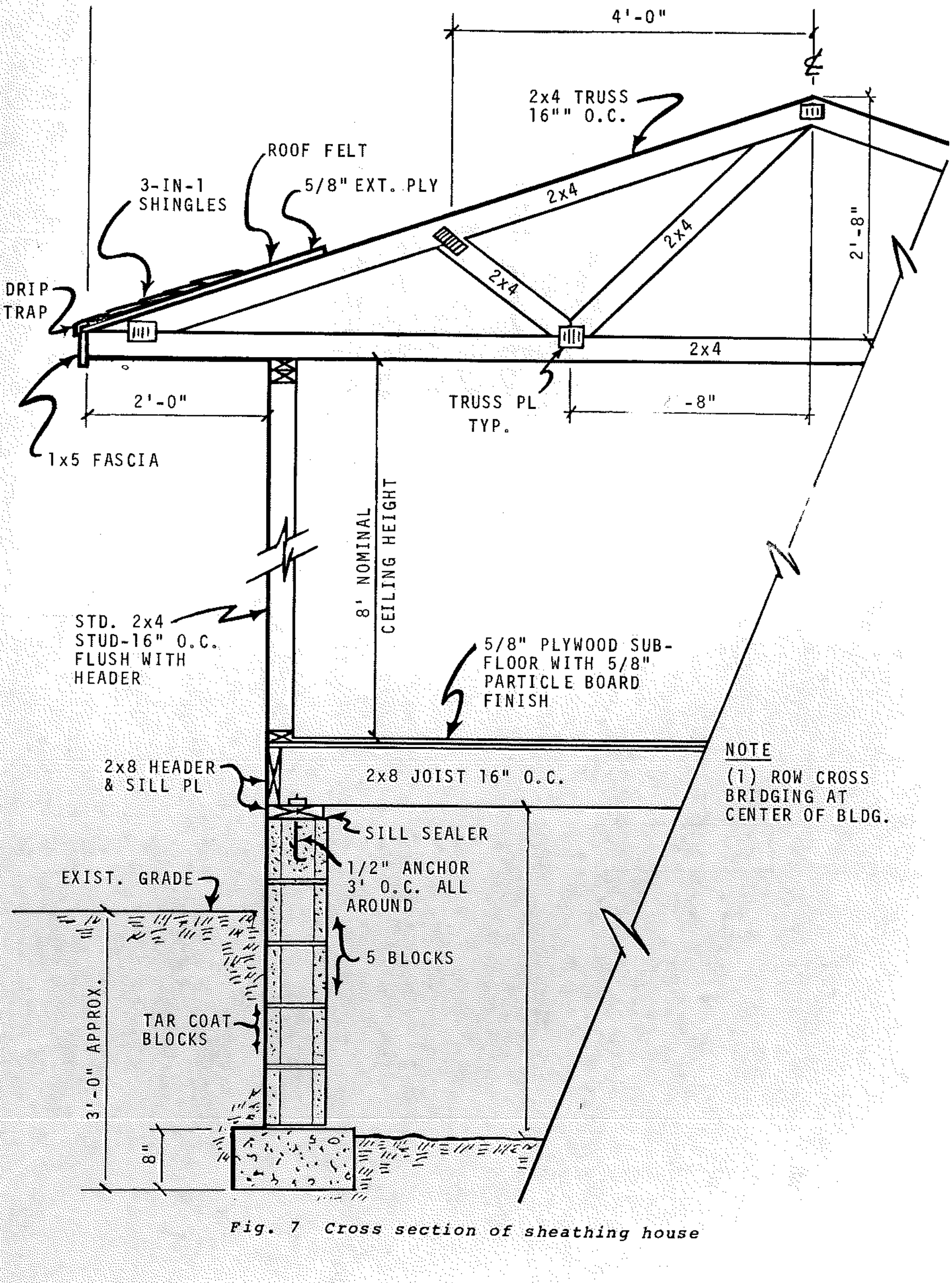


Fig. 7 Cross section of sheathing house

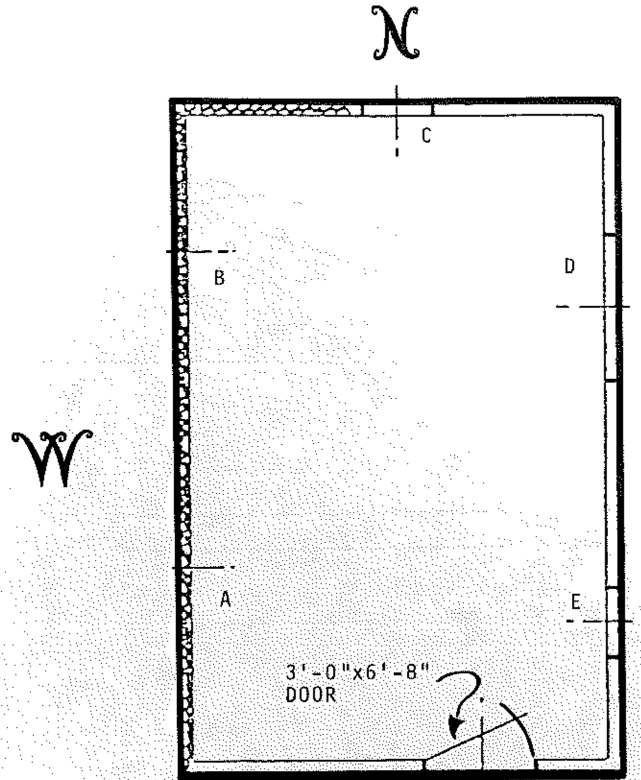


Fig. 8 West wall and half of north wall of both units have no vapor barrier on warm side

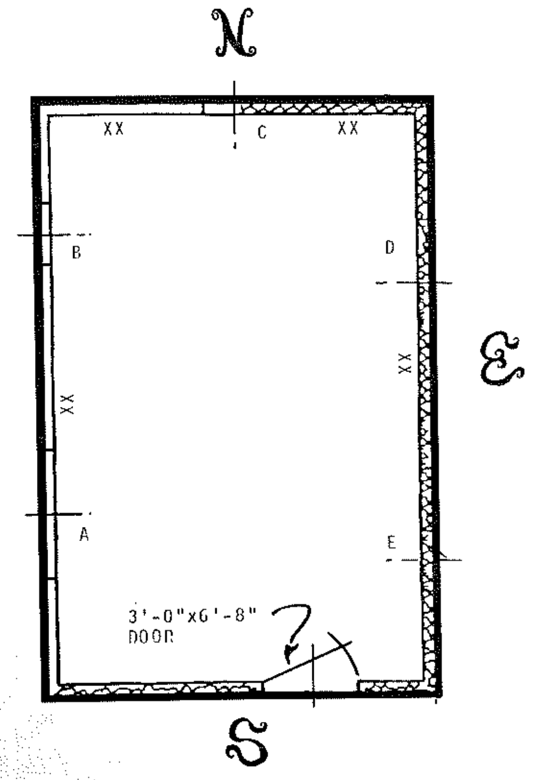
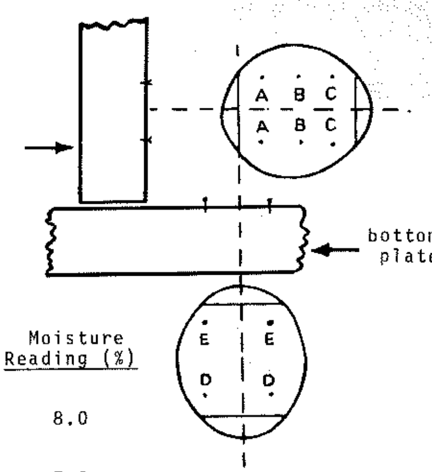
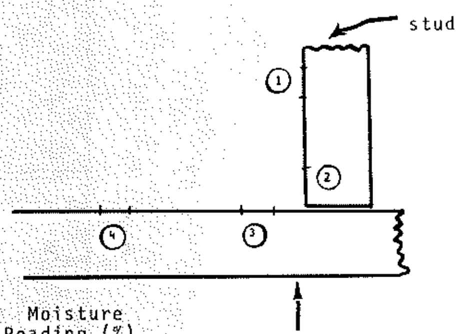


Fig. 9 East, south walls and ½ of north wall of both units have asphalt coated kraft paper on warm side and inset staple; 8 condensation detectors per unit



Probe Location	Moisture Reading (%)
A	8.0
B	7.8
C	6.7
D	8.1
E	7.3

Fig. 10 Wall cutting from outside



Probe Location	Moisture Reading (%)
1-F	7.4
1-B	7.5
2-F	9.3
2-B	7.8
3-F	10.5
3-B	9.7
4-F	10.8
4-B	10.1

F-front
B-back

Fig. 11 Wall cutting from inside