

THE SPOKANE WALL INSULATION PROJECT: A FIELD STUDY OF MOISTURE DAMAGE IN WALLS INSULATED WITHOUT A VAPOR BARRIER

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ABSTRACT

Considerable uncertainty has existed over whether or not the addition of wall insulation without a vapor barrier might increase the risk of moisture damage to the structure. Although it was concluded from a 1979 field study that there is no such risk in mild climates like that of Portland, Oregon (4792 degree-days), it was not clear if a problem might exist in colder climates. Thus, a second major field study was undertaken in Spokane, Washington (6835 degree-days). During the study the exterior walls of 103 homes were opened, of which 79 had retrofitted cellulose, rock wool, or fiberglass, and 24 were uninsulated as a control group. Field and laboratory test results are presented which, contrary to diffusion theory predictions, show the absence of moisture accumulation and consequent moisture damage caused by the addition of retrofitted wall insulation. The study strongly concludes that the addition of wall insulation without a vapor barrier does not cause moisture problems in existing homes in climates similar to that of Spokane.

PROJECT DESCRIPTION AND PURPOSE

Background

In order to conserve energy, walls of existing homes can be retrofitted with a variety of types of insulation blown into wall cavities. While numerous existing homes have been insulated, major questions have been raised over the possible effects of moisture migration through walls on moisture damage in the wall structure. Moisture is continually added to the warm air inside a house and escapes in part by leaking or diffusing into or through a wall cavity that has no vapor barrier or retarder on the inside wall surface to reduce moisture migration. The addition of insulation lowers the temperature of the outer portion of the wall and increases the chances that water vapor may possibly condense inside the wall cavity. Accordingly, in theory, condensation is more likely to occur in an insulated wall than in an uninsulated one. If these processes do occur, then water could conceivably accumulate, with the possibility of structural damage occurring due to wood decay. Furthermore, natural drying may be reduced because circulation is impaired.

There is, of course, the possibility that insufficient quantities of water are produced by the postulated mechanism to create the necessary high moisture content conditions required for growth of the fungi that create wood decay. A variety of other factors may also affect this question, such as the structural tightness of interior walls and exterior siding. Moreover, even if moisture does condense, little is known about the extent of natural drying processes within the wall cavity or of water storage within wall wood members or insulation. The condensed water vapor could be revaporized by the transient warming of the wall that occurs

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during the winter daytime, especially in mild climates, or by infiltration of cold dry outdoor air. Possibly convection of warm indoor air through the wall cavity could provide sensible heat that would result in drying. More likely, migrating water vapor or condensed liquid is absorbed and stored within the wood members of the wall structure or the insulation until conditions are such that it dries out naturally. In fact, there is sufficient capacity to store the water that would normally migrate through a wall by convection and diffusion for long periods of time (on the order of months). As evidence of long-term storage of moisture, it is well known that the moisture content of house wood members is highest in the winter months and decreases as warming occurs (Duff 1972). Interestingly, the lack of observable condensation in an attic study has been attributed to storage within the wood structural members (Burch 1984).

It is important to note that the development of wood decay requires high moisture content in the wood, sufficient oxygen (wood can be so wetted, such as by leaks, that this condition is not met), and high wood temperatures for periods long enough for the decay to progress. While decay can occur at wood moisture contents as low as about 20%, serious decay occurs only when the moisture content of the wood is above the fiber saturation point (average 30%) (Wood Handbook 1974). Thus the wood must be quite wet. For the most part, wood decay is relatively slow at temperatures below 50 F and much above 90 F (Wood Handbook 1974). The optimum condition for decay occurs at temperatures above 75 F (Baumeister 1967). Hence, wood decay is not likely to occur during the winter. By the time of the year that extended periods of high temperature are sustained within the wall cavity, the water may be vaporized. Such might not be the case, however, if water has leaked into the wall cavity and accumulated during the warm summer months. In fact, except when leaks are present, it would appear unlikely that wood decay should occur, especially in northern climates.

Nonetheless, there are many reported cases of wood decay or rot occurring in walls insulated without a vapor barrier. Documentation of most observations has been uneven, however, and has provided no information as to whether the addition of wall insulation was responsible for beginning or accelerating the decay or whether the decay was produced by other causes such as roof, gutter, or bathroom leaks.

In order to provide answers regarding the advisability of insulating walls without a vapor barrier, the Oregon Department of Energy, with the cooperation of the U.S. DOE and a number of Northwest utilities, funded the first major field study aimed at scientifically and objectively determining whether the addition of wall insulation without a vapor barrier in existing homes in the western region of the Pacific Northwest significantly increased the probability of moisture damage within wall cavities. The study took place in Portland, Oregon (4792 degree-days), during the winter of 1979 and is hereafter referred to as the "Portland study" (Tsongas 1980).

The results of the Portland study strongly suggest that the addition of wall insulation without a vapor barrier does not cause moisture damage in existing homes in the mild western portion of the Pacific Northwest. However, there still was doubt as to whether similar findings would occur in a colder climate that has more condensation opportunities.

Although it is not obvious that the results of the Portland study can be extended to colder climates, it is interesting to note that no evidence of moisture accumulation and condensation or damage was found in homes in cold climates during three other field studies involving far fewer homes (Weidt 1980; Rossiter, Weidt, and Saxler 1980; and Wisconsin 1980). To settle the question for the rest of the Pacific Northwest and similar colder climates, a followup major moisture study was thus planned for Spokane, Washington (6835 degree-days), during the 1982-1983 winter. Spokane was considered to be representative of the climatic zone for the eastern portion of the Bonneville Power Administration (BPA) service area and similar to much of the Middle West and northeastern United States. The details and results of that study are reported herein and in much more detail in a final report for BPA (Tsongas 1984).

Walls were scheduled for opening in late December 1982 and January and February 1983 at a rate of two to three homes (three holes per home) per day. It was presumed that the highest moisture content would be found during those months (Duff 1972). Moreover, it was assumed that there was considerable opportunity for condensation to occur within the insulated wall cavities of homes in the relatively cold Spokane climate.

SELECTION AND DESCRIPTION OF TEST HOMES

Each test home was selected through a series of four sequential processes: a media effort to inform and solicit potential study participants; examination and screening of questionnaires to determine eligibility of volunteered homes; completion of in-home interviews and a pre-opening inspection to determine and verify technical data; and finally, opening walls for inspection and collection of data and samples.

Criteria for Selection

Initial Criteria. The original study design proposed a test sample of a minimum of 100 homes distributed among insulation types as follows: 20 homes not insulated as a control group, 40 homes insulated with cellulose, 40 homes insulated with mineral wool (either rock wool or fiberglass), and no homes insulated with urea-formaldehyde foam. Test homes were to use electricity as the primary heating source. Within each insulation group, half were to have a combustion-type secondary heating source such as a wood stove or fireplace. All insulated homes were to have been retrofit with insulation at least two years prior to opening. All homes were to have no vapor barriers in the walls, and all homes with a crawl space were to have a ground cover. Moreover, all homes were to have less than 1300 square feet of floor space. Some of the openings were to be made in walls with inside penetrations such as electrical outlets.

Relaxed Criteria and Other Test Home Characteristics. Shortly after the solicitation and screening process began, it became apparent that the desired total sample of 100 homes would not be met if the original criteria were maintained. A major problem arose due to the existence of numerous homes with continuous aluminum foil (a vapor barrier) behind the wallboard on the warm side. Because of that, about one out of every three homes that was otherwise qualified was rejected. Thus, selected criteria were successively relaxed. Criteria modifications include: (1) increased size of homes (up to 2400 ft²), (2) homes without a ground cover in the crawl space (full or partial crawl) allowed, (3) heated basements allowed, but basement size not included in living space restriction, (4) wood stoves and fireplaces allowed even if primary heating, (5) no wood furnaces as primary heating system, and (6) homes with brick or stucco exterior would not be opened because of cost and time. The final sample met the following criteria:

1. Distribution among insulation types:

24	Uninsulated
61	Cellulose
11	Fiberglass
7	Rock Wool
<u>103</u>	

There simply were not as many homes available with mineral wool insulation as with cellulose.

2. The breakdown of the various primary heating system types is as follows:

61	Electric baseboard or cable
12	Electric forced air, ducts within heated space
12	Electric forced air, ducts outside heated space
16	Heat pump
2	Hydronic

Many homes utilized more than one type of heating; for example, many had a wood stove or fireplace that was often used.

3. All insulated homes were retrofitted at least two years prior to the study. The average age of the wall insulation is shown below.

Age (yrs)	Cellulose (%)	Fiberglass (%)	Rock Wool (%)	All Types (%)
2-5	74	27	14	62
6-10	16	55	14	22
10+	10	18	72	16

4. Most of the homes had no vapor barrier such as plastic sheet, aluminum foil, or vinyl wallpaper on the inside wall surface. However, near the end of the study, 10 homes were opened that had continuous foil inside the cavity on the warm side; these homes were added in order to get enough test homes and also as a small mini-study to examine the influence of the vapor barrier. Of the 103 test homes, 72 had wood exterior siding, whereas 23 had retrofitted metal or vinyl siding. Almost all had a 15# felt or building paper moisture barrier just inside the wood siding. An aluminum foil moisture barrier that was usually, but not always, perforated was often used behind the metal/vinyl siding. The majority had lapboard sheathing, but five homes had plywood sheathing and five had asphalt-coated fiberboard sheathing.
5. Most (85) of the homes had a full or partial basement and 37 homes had completely heated basements. Among the 18 homes with a full crawl space and the 19 others with a partial crawl space were 24 homes without ground covers in the crawl spaces.
6. The maximum allowed size of the home (total heated floor space) was 2400 square feet; however, 98% had 2200 square feet of living area or less, while 67% of the test homes had less than 1300 square feet, and 41% were smaller than 1000 square feet.
7. One of the three openings in each house was to be in a wall cavity with an electrical outlet on the inside wall, where possible.
8. No limitations were placed on the number of occupants. The average sample home was occupied by three persons, with 86% housing four or fewer persons. In addition, it is worthy of note that the test homes were older homes. None of the homes was less than 20 years old; 35% of them were between 20 and 40 years old, while 65% were over 40 years old.

In addition to the above characteristics, which were controlled in the selection process, an additional group of factors with direct bearing on energy consumption and moisture accumulation were identified in the course of the study. Taken together, they provide a profile of the typical Spokane test home as one that had ceiling insulation and storm windows, but no underfloor insulation and some air conditioning; about one half the homes had weather stripping around doors and windows and a fireplace or wood stove in use.

Qualification Interview and Pre-Opening House Inspection

If a house appeared to meet all necessary criteria, the homeowner was asked to set a time when project representatives (the interviewer and an engineer) could inspect the home and gather necessary data prior to scheduling the wall openings. During that first visit, the interviewer asked several questions and filled out a checklist profiling characteristics of the house, as well as the occupant's life style (e.g., use of fireplaces, kitchen fans, etc.). Simultaneously, the inspecting engineer verified the categorization of the house, inspected it carefully (e.g., in looking for signs of moisture, moisture damage, or leaks in the attic, basement, or crawl space, as well as around the interior and exterior walls), made some measurements (e.g., house dimensions), and identified relevant characteristics of the home using another checklist. All checklists were designed for ease of transfer of data into computer files. The house inspection included use of a metal detector to determine if aluminum foil existed in the wall cavity, since it is a vapor barrier and its use was common in Spokane in the early 1950s. The detector could distinguish between foil and other metal in the cavity (such as nails or outlet boxes) or metal siding so that houses were not unnecessarily excluded. The complete survey, which typically took about an hour, served as the final qualification of the home for opening and field testing.

Determination of Opening Locations. One of the major tasks accomplished by the engineer during the inspection was the determination of the three locations for wall openings. The selection of wall sites with the highest moisture content, where decay would be most likely to occur, was based upon the following criteria:

1. For each house, three openings, normally 12 inches high by 16 inches wide (spanning two adjacent studs), were to be made from the outside of the building near the floor line. No openings were to be made near the top of the wall cavity because in the Portland study (Tsongas 1980) they were found to be generally drier than openings near the floor line.
2. Only north-, east-, and sometimes west- (see item 6 below) facing walls were to be opened.
3. Specific locations on these walls were to be, to the extent possible, opposite high moisture production rooms such as bathrooms or kitchens, on exterior shaded locations, and in areas showing evidence of possible moisture such as blistering paint, warped siding, discoloration, mold/mildew, and termite or dry rot damage.
4. Sites were not to be located on south or upper story walls, or in walls with an interior vapor barrier (e.g., aluminum foil behind the wallboard, or tile, or vinyl wallpaper, etc.). However, late in the study a few houses with foil in the wall cavity were allowed.

In addition:

5. An effort was to be made to locate one or two of the three holes in the vicinity of an electrical outlet where moisture might flow into the wall cavity.
6. An effort was to be made to locate sites in homes in relatively cool wall areas not directly behind an electric baseboard unit or a forced air heating duct that could keep any moisture in the wall dried out. This would not always be easily satisfied, so west openings were allowed if no north or east wall opening could be made because of the existence of baseboard heaters or heating ducts. A minimum distance of two feet from such heat sources was required.
7. When no signs of moisture or damage were apparent, other factors such as accessibility, visibility, ease, or homeowner desires could sometimes become important in selecting suitable opening sites.

After examination of the inside and outside of the building, and with consideration of all the selection criteria in mind, the inspection engineer selected the three best sites and noted their location for the opening crew. Walls were not opened in locations where leaks were found.

Scheduling of Wall Openings. Two and sometimes three houses were opened per day. The openings began on December 20, 1982, and were completed on February 25, 1983; 12, 39, and 52 homes were opened in the months of December, January, and February, respectively.

FIELD TEST METHODOLOGY

Development of a Test Methodology

A standard procedure for the field testing, as well as the home interview/inspection, was developed and refined using several homes as a proving ground. A common crew, consisting of the head field engineer and a journeyman carpenter, was present at all openings. The training and consistent use of the same personnel resulted in an efficient and uniform opening and data/sample collection procedure.

Wall Opening

The walls of each test home were opened from the outside in three locations selected during the initial house inspection. At each location an opening about 12 inches high by about 16 inches wide (one stud space) was made near the floor line. The siding was removed in whole pieces in order to avoid making unnecessary cuts in it. The opening exposed the cavity with or

without wall insulation and extended down to the sill (mud) plate. The carpenter removed the exterior siding and then cut through the exterior moisture barrier (typically 15# felt or building paper) and the sheathing (typically 1 x 8 lapboard, fiberboard, or plywood).

Data Collection and Recording

Indoor and outdoor dry- and wet-bulb temperatures were measured with a psychrometer; the corresponding indoor and outdoor relative humidities were found from a psychrometric chart. Immediately upon opening each hole, a sample of insulation was removed from the wall cavity and sealed full in a 100 ml glass jar. The sample was removed quickly to avoid any change in its moisture content and treated carefully to avoid contamination with skin or other moisture sources. The samples were later gravimetrically analyzed in a laboratory for moisture content.

The next step was the measurement of the surface and interior temperature of the wood in the hole opening. A thermocouple probe with digital readout was used to determine the wood temperatures, which were required to correct the wood moisture content readings. After careful testing, the temperature of the rim joist was found to be the best average of the various hole wood members. Because the temperature of the other members was never more than a few degrees different from that of the rim joist, and because the correction is not sensitive to such small differences, only the rim joist temperature was recorded in order to save time.

In each wall opening the wood moisture content was then measured whenever possible at seven locations, both on the surface and in the interior of the wood member (about 0.75 in (19 mm) deep), using a resistivity type of moisture meter with two insulated pins. The seven measurement locations in each hole are: right stud, left stud, sole plate, sheathing (warm side), subflooring, header (rim joist), and sill (mud) plate. They are illustrated in Figure 1. The moisture content of the sole plate and studs was measured about 1/4 in (6 mm) in from the exterior surface edge, whereas all other measurements were made at the exposed exterior surface. Readings were recorded to the nearest one-half percent within the meter's range of 6% to 30%. For the sheathing, a number of measurements were made at various locations on the part of the surface exposed to the insulation or the uninsulated cavity, and the highest reading was recorded. It should be noted that since for the Portland study (Tsongas 1980) the corrected meter readings were essentially the same as the moisture contents obtained by laboratory gravimetric analysis of wood samples taken from the same locations, it was decided to forego taking any wood samples for such a check in this study.

The moisture meter is factory-calibrated for use with a four-pin electrode in Douglas fir at 70 F (21°C), so that if those conditions are not met, it is necessary to correct the readings for type of probe pins, wood species, and temperature. Hence, the wood temperature was also determined at each location where moisture content was measured. The moisture readings were then corrected for temperature. A small correction was also made to account for use of the meter with two insulated electrode pins rather than four. No correction was made for type of wood since most of the wood tested was Douglas fir. The combined correction typically increased the value measured in the field a few percent; the maximum correction was 5.5%.

In addition, wood samples to be bioassayed were taken from the sole plate, one stud, and sheathing with a simple chisel. The samples, about 1/4 inch (6.4 mm) in width and one inch (25.4 mm) long, were placed in plastic containers and stored in a cool place until they were cultured in a laboratory to determine the presence or absence of decay fungi. A careful visual inspection and photographic documentation of the conditions within the wall cavity were performed with the aid of a checklist to indicate such factors as discoloration, mold or mildew, signs of rot, apparent condensation, etc. Any moisture or damage found was documented in writing and photographically. The existence of any corrosion on outlet boxes, wiring, or metal brads holding the wiring was also noted.

Finally, during the time the walls were opened and closed, an infrared thermography scan was made from the outside of the walls to locate uninsulated areas and any other insulation installation problems. Results are reported elsewhere (Tsongas and Ball 1985).

Laboratory Analysis

Insulation Sample Moisture Content Determination. One sample of insulation from each wall opening was analyzed gravimetrically for moisture content by placing in an oven and drying to a

constant weight. The percentage moisture content (MC) by weight of each sample was determined on a dry basis from the relation:

$$MC = (W_w - W_d) \times 100/W_d \quad (1)$$

where W_w and W_d are the wet and dry weights of the material, respectively. The moisture content was determined to within 0.02% per one gram sample. The minimum net sample weight was about one gram. The samples were stored in an airtight, metal-capped 100 ml glass jar prior to analysis in the laboratory. All sample jars were kept at room temperature (no less than 65 F) for a minimum of eight hours prior to opening the jars for sample weighing and analysis; this was to prevent moisture in the sample from condensing on the jar's inner wall surface prior to opening. The 48 mineral wool samples were weighed, dried at 100 F (38°C) for eight hours, and reweighed; whereas the 180 cellulose samples were dried at 125 F (52°C) for 24 hours. The reasons for using these drying conditions are discussed in the "Results" section. Weighing was completed within one minute of exposure to air prior to drying and after drying and desiccating to prevent loss or gain of moisture from or to the sample.

Test for Presence of Decay Fungi in Wood Samples. One hundred wood core samples from the wood members with the highest surface moisture content were bioassayed to determine the presence or absence of decay fungi. All the wood samples were stored in a cool place and cultured at the same time at the end of the test period.

RESULTS

Wood Moisture Content Findings

Three wall openings were made from the outside near the floor line in each of 103 test houses in Spokane, Washington (6,835 degree-days). In each wall opening, the wood moisture content was measured using a resistivity type of moisture meter both on the surface and in the interior of wood members at seven locations: right and left studs, sole plate, sheathing (warm side), subflooring, header (rim joist), and sill plate. The overall mean moisture content of all 3,675 valid, corrected readings (approximately 1,800 locations) was 11.3%, which is just slightly lower than the 11.8% mean found for 93 homes in the Portland field study (Tsongas 1980) and typical of moisture contents found in framing members in the Pacific Northwest (Peck 1960; Hann et al. 1970). No significant difference existed between insulated and uninsulated holes, thus indicating that adding wall insulation does not increase the potential for moisture problems.

In an effort to better understand the wood moisture content results, they were also broken down by a number of other wall and house characteristics, including: wall orientation, date of opening, total heated floor space, indoor relative humidity, number of occupants, type of room (moisture production), type of exterior siding, type of sheathing, existence of an electrical outlet in the opened wall cavity, existence of electrical outlet/switch plate gaskets, and existence of continuous foil inside the wall cavity. The complete analysis of those breakdowns is presented in a more detailed report of this study (Tsongas 1984). The salient results are briefly noted here.

For example, as expected, the moisture content of holes with a north orientation was slightly higher than that for the east or west orientations. The 137 holes with a north orientation averaged 11.8%, the 128 with an east exposure averaged 11.1%, while those 40 facing west averaged 10.3%. These small relative differences are in agreement with the results of the Portland study (Tsongas 1980) and Duff's results (1972) and were expected because of the drying associated with solar heating and the southerly winter winds in Spokane.

As has been noted by Duff (1972) and others, the average wood moisture content peaks in the late winter. To see if that was the case in this study, the mean moisture content for all wood members and for all sheathing was compared for the periods when the first, second, and last third of the homes were opened. Indeed, the mean values for the openings made during the first third of the study were lower than those made during the later two-thirds of the study by about one and one-half percent for all wood members and about two percent for all sheathing interiors.

Regarding the effect of the total heated floor space and the indoor relative humidity of

the test houses on the mean wood moisture content, generally speaking, the smaller houses do, in fact, have higher wood moisture contents, as has been presumed. However, the differences are generally not significant. Their trend does appear to follow the indoor relative humidity variations. The fact that the mean wood moisture content is lower in this study (11.3%) than in the Portland study (11.8% [Tsongas 1980]) may be in part attributable to the fact that the indoor relative humidity was lower in this study (46.7% versus 56%).

It is worth noting that the mean indoor relative humidity increased slightly as the number of occupants increased. This is not unexpected, since one of the main sources of moisture in a house is from human respiration. What is most interesting is that homes with a large number of occupants had the highest indoor relative humidities, the highest average wood moisture content, and the highest mean sheathing moisture content. While the mean moisture content of all wood members increased only slightly with number of occupants, the sheathing showed a substantial increase, especially the interior values (almost 4%). This strongly suggests that excess moisture is stored in the wood members, particularly in the interior of the sheathing.

It is also generally believed that moisture problems would most likely occur in the walls of rooms with high moisture production, such as kitchens and bathrooms. In this study kitchen wall openings exhibited average wood moisture content, whereas bathrooms were above average. What is most interesting is that rooms that are characterized by lack of air circulation and poor heating (hence cooler temperatures) consistently had the highest opening moisture contents. In fact, all closets were above average in moisture readings. Bedroom closets, along with bathrooms, appear to be most susceptible to relatively high moisture contents in their walls. However, the mean wood moisture content of those holes was only about two percent higher than the mean of 11.3% for all rooms.

Another concern has been that homes with metal (aluminum or steel) or vinyl siding might be more prone to relatively high wall moisture contents and/or moisture problems because of the siding acting as a relatively impervious exterior barrier to the migration of water vapor. Hence, the average wood moisture content results were broken down by type of exterior siding in three categories: metal-vinyl, wood, or other (asbestos shingles, lapped hardboard, and panel shakes). Somewhat surprisingly, the 68 holes with metal-vinyl siding added over other siding were drier (10.4%) than the 213 wood siding holes (11.6%) and the 24 other holes (11.8%). Moreover, the average indoor relative humidity for those houses with metal-vinyl siding was lower than for those with wood siding. It may be that the small amount of insulation often added behind metal-vinyl siding plays a more important role in keeping walls drier than has previously been realized. Burch, Contreras, and Treado (1979) found that walls with full insulating sheathing added were drier than with regular sheathing. More likely, in this case the walls with metal-vinyl siding added were drier because they are less prone to water entering from the outside. As will be noted shortly, that was a major problem, especially for those homes with wood shingles as siding.

In addition, the wood moisture content field results were examined on a member-by-member basis; those results are presented in Table 1. Of major importance to this study is the fact that there were very few readings of high moisture content. While 61 (1.7%) of the 3,675 readings were greater than the fiber saturation point (30%), almost all of these abnormally high readings were caused by leaks, untreated wood members directly in contact with the ground (older, unconventional construction), or a surprisingly widespread "splash back" phenomenon whereby melting snow and/or rain dripped from roofs (most of which did not have gutters), splashed up from the ground, and wet the siding (notably shingles) from the underside. In fact, it is very likely that the overall average wood member moisture content would have been lower had it not been for the existence of splash back. In only one case of an uninsulated wall of a bedroom closet did the high moisture content appear to most likely be caused by condensation, although splash back could possibly have been the cause.

A statistical analysis of the field results was performed to see if the existence of high wood moisture content could be explained by any of a number (25) of factors that might influence the data, such as indoor relative humidity. The correlation was notably poor, which underscores the conclusion that high wood moisture content that could lead to problems occurs mainly as a result of other factors such as leaks and splash back that overwhelm the influence of all other variables.

Insulation Moisture Content Findings

Insulation samples were taken from each hole and analyzed gravimetrically in a laboratory for moisture content. The average moisture contents for 27 samples of fiberglass, 21 samples of rock wool, and 180 samples of cellulose were 0.25%, 0.15%, and 6.4%, with ranges of 0.06-0.71%, 0.01-1.43%, and 1.9-14.8%, respectively. The fact that the mineral wool samples were extremely dry is in close agreement with the results of other studies (Tsongas 1980; Weidt 1980; Rossiter, Weidt, and Saxler 1980) and suggests that the thermal performance of mineral wool wall insulation should not degrade due to the presence of normal moisture in it (Jespersen 1953). Cellulose wall insulation, being hygroscopic, had a much higher moisture content; subjectively, the moisture content ranged from dry to damp. Even when damp, there was no indication of an associated wood moisture problem. However, the influence of the normal moisture content on the thermal conductivity of the insulation is as yet unknown.

One of the interesting findings of this study is that the conventional oven-drying procedure for determining the moisture content of cellulose can result in considerable error, so that most previously reported values of moisture contents of either laboratory or field samples are probably incorrect. The usual procedure of drying at 220 F (105°C) volatilizes not only the normal moisture, but a surprising amount of the fire retardant's chemically bound water of hydration, resulting in apparent moisture contents that are much too high. For this study, tests indicated that drying samples at a rather low 125 F (52°C) for 24 hours would provide more accurate results (typically about one-half the conventional results). It is also worth noting that many wall cavities may exceed 125 F (52°C) during the summer, and so the fire retardant's water of hydration may be partially or even completely driven off.

Moisture Damage Findings

During the home inspection prior to the wall openings, a number of signs of possible moisture damage or moisture problems were observed, including condensation and mold/mildew on windows, clothes dryer vented inside, partial crawl spaces without a ground cover, no gutters or downspouts, mold/mildew, staining, warped siding, blistering/peeling paint, corrosion, and condensation in attics. Most were minor in nature. In addition, a variety of roof/flashing, bathroom and plumbing, and foundation leaks were noted that resulted in three cases of wood decay, considerable staining/discoloration, mold/mildew, and wet attic insulation. Most of the leaks were directly attributable to homeowner neglect. However, the homeowners were often unaware of the existence of the leaks, although about 50% of them indicated the existence of previous moisture or water leak problems, most of which were minor and involved leaks.

A number of other checks were also made during the inspection of each opening and the adjacent wall while the hole was open, including the insulation moisture condition (ranging from dry to wet). There were a few cases of minor wood decay, but they mainly occurred where there was a previous or existing leak or where wood members were in direct contact with the ground. There were also a few signs of mold, mildew, or discoloration within the wall cavity, blistered paint, warped siding (noted fairly often), and metal corrosion; there was no wiring corrosion. Many of these signs were very likely caused by splash back. Generally speaking, most of these pre-opening and opening moisture problems were not particularly significant, other than as an indication of the poor state of repair of some of the test houses.

In spite of the relatively frequent occurrence of external signs of possible moisture problems or actual moisture damage, there was essentially no evidence of high moisture content or moisture damage within the wall cavities, except where leaks or splash back had occurred or where wood members were directly in contact with the ground. All the evidence from this study suggests that the addition of wall insulation in existing homes does not lead to major moisture damage (wood decay) and most likely not to minor damage, either inside or outside the wall cavity. In fact, comparison of the occurrence of pre-opening and openings signs of minor moisture problems between insulated and uninsulated homes indicates that most problems occur less or no more frequently in homes with insulation added. This result was also noted in the Portland study (Tsongas 1980). This thus appears to be an additional benefit of adding wall insulation that is not normally accounted for.

Of considerable importance in this study is the fact that there were no observations of frost/ice or liquid condensation in any of the wall insulations, nor were there any cases where the insulation itself came even close to the fiber saturation point. The only time liquid condensation was observed in any of the 309 wall openings was once on the outside of plywood

sheathing of an uninsulated wall cavity, and that case was possibly caused by splash back. However, the usual application of moisture migration theory based on simple diffusion only (ASHRAE 1981; Tenwolde 1983) would predict the existence of considerable condensation and liquid accumulation in the Spokane test home wall cavities. This discrepancy between diffusion theory predictions and actual field observations noted in this study and others suggests some other mechanism(s) is occurring that either dries out or removes the condensed moisture, or condensation as we normally think of it simply does not occur. In fact, the results of this study suggest that much of the moisture that migrated through walls is not visually observed as accumulated liquid or frost because it is absorbed into and stored in wood members (especially sheathing) until conditions are such that it dries out naturally. As a general rule, even if condensation does occur, that does not imply that it will accumulate or that wood decay or other moisture damage should necessarily exist. Interestingly, although it is seldom done, diffusion theory can be used to predict the occurrence of evaporation that may in fact be responsible for offsetting the effect of condensation.

The use of the diffusion theory has grown widespread out of a desire to be able to easily predict when condensation and associated moisture damage might occur. Yet moisture migration and condensation are just not that simple. There are many mechanisms other than diffusion alone that occur simultaneously and may need to be considered. In fact, some may be even more important than diffusion, and so the simple diffusion theory as typically applied is most often quite inappropriate. Unfortunately, its use has created a concern about condensation and attendant moisture damage that is not justified because it is seldom observed in actual field situations. Thus, use of the diffusion theory is misleading and probably should generally be temporarily avoided. What is needed is a more comprehensive theory that incorporates the effects of other moisture migration mechanisms in addition to diffusion. Unfortunately, there is no suitable alternative moisture migration model available at this time.

MOISTURE PROBLEM CONCLUSIONS

The purpose of this field study of 103 homes was to determine scientifically and objectively if the addition of wall insulation without a vapor barrier in existing houses in the eastern portion of the Pacific Northwest significantly increased the probability of moisture condensation in the wall cavity and caused physical damage to the structure. Based on a comparison of field data and moisture damage observations from both insulated and uninsulated homes, it is strongly concluded that the addition of wall insulation does not increase condensation and cause moisture damage. In fact, the addition of insulation appears to reduce the incidence of some types of moisture damage.

While some moisture damage was found inside and outside both insulated and uninsulated walls, it was usually minor in nature and seldom caused any major physical damage such as wood decay. Moreover, much of the damage was caused by a variety of types of leaks or water splashing back from the ground onto the wall and usually was not noticed by the homeowner. It is also worthy of note that the overall findings and conclusions of this Spokane study are extremely similar to those from a comparable field study in Portland, Oregon (4792 degree-days).

The Spokane field test results and conclusions should apply throughout the eastern portion of the Pacific Northwest because of the similarities in climate and housing construction. They should also apply to other areas with winter and dry summer weather similar to that of Spokane (6835 degree-days), which may include parts of the central portion of the Middle West and northeastern United States (condensation zone II). Extrapolating these results to regions where the winter weather is as cold but the summers are wetter may be inappropriate. It is not clear whether the results of this study can be extended to colder climates, and very likely they should not be extended to warm, humid climates such as in the southeastern United States.

These field test results suggest that it is not necessary to add a vapor barrier, such as a vapor barrier paint, to control moisture migration and potential condensation when insulating the walls of existing homes in the Pacific Northwest. Adding cavity insulation simply does not create a moisture problem. However, it should be emphasized that continuous vapor barriers or other means of reducing air leakage in newly constructed homes are extremely worthwhile as a means of reducing infiltration losses and saving energy - especially since in well-insulated homes infiltration losses can be the major source of energy loss. While there has been a concern within the construction industry that using continuous vapor barriers might lead to

moisture problems, the results of this and other studies suggest otherwise.

RECOMMENDATIONS FOR FUTURE STUDY

Based on the results of this study and others, a number of topics appear worthy of continued or new study. This type of field moisture study, where a large number of conventional homes are scientifically examined, should be repeated in two climates. There is still some doubt as to whether or not similar findings would occur in an even more severe climate with greater condensation opportunities. Minneapolis, Minnesota, might be an ideal city because the climate is considerably colder than that of Spokane, it is large enough to get a sufficient number of test homes, and results from there should apply to most of the north central United States (condensation zone I and the coldest area of the U.S.). In addition, it seems clear that a similar type of field study is even more necessary in a warm, humid climate like that of the southeastern United States (condensation zone III) where walls may be subjected to potential moisture damage conditions during both the winter and the summer. In that case, a two-phase study taking place during both seasons may be necessary.

There is also now some concern that building new homes using tight energy-efficient construction with heavily-insulated walls, poly wrap, and/or rigid insulating sheathing may create moisture problems that did not exist with the older conventional construction. Some studies of this issue have already been undertaken (Sherwood 1983; Burch et al. 1979; and Hill 1985). Others are in progress. The results so far suggest that there probably will not be a problem. However, the studies to date have been limited to small numbers of selected types of homes or construction techniques, often in laboratory or test cell conditions, and in only a few climates. Thus, a major field study is planned for the 1986-87 winter in which a large number of occupied new energy-efficient homes will be opened in three different climatic zones within the Pacific Northwest.

In addition to needing more large-scale moisture damage field studies, it is important to emphasize the critical need to develop an improved moisture migration modeling capability. The influence of a number of important effects needs to be accounted for, including evaporation, air convection, transient effects, capillary action, moisture storage, and non-constant permeance values. Such a detailed model would be an invaluable tool in determining the potential for moisture accumulation or damage in a wide variety of real-world situations without time consuming and expensive field or laboratory testing.

There is also a need for more study of the effect of moisture as it migrates through walls on the thermal performance of the wall insulation. In particular, cellulose can be somewhat damp, and yet it is not clear what, if any, effect its normal moisture content has on its thermal conductivity. There have been extremely few studies aimed directly at resolving this question, and the results from those that have been completed are conflicting. Moreover, as noted in this study, the fact that the moisture content of cellulose has probably been incorrectly determined in most previous studies suggests that a fresh approach be made. It would be extremely worthwhile to measure local heat flux and insulation moisture content simultaneously and more or less continuously for an extended period of time in a wall section of an actual building exposed to real transient weather conditions; then the results could be correlated to see if the moisture that normally exists in the cellulose really does increase heat transfer. A steady-state laboratory study most likely is not appropriate.

During this study it was found that the conventional oven drying procedure used to determine the moisture content of cellulose probably causes considerable error in the results. The approach taken to solving this problem for this investigation was to dry the samples at a much lower temperature for a longer period of time. It would seem wise to study this problem in greater depth and verify the proposed oven-drying procedure and its results with results obtained over a much wider range of conditions and fire retardant types. In addition, since the results of this study suggest a possibility that normal summertime heating of walls could volatilize all or part of the fire retardant's water of hydration in cellulose, a study is needed whereby walls with cellulose are opened and samples taken to check for the existence of the fire retardant's water of hydration. While certainly not popular, it may even be wise for those government agencies or utilities sponsoring wall retrofitting programs to consider delaying the use of cellulose insulation until this fire safety issue is settled.

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ACKNOWLEDGMENTS

Special thanks must go to the Bonneville Power Administration for recognizing the need for this study and for providing the necessary funding. Appreciation is especially extended to Phil Thor, BPA's contract monitor, for his assistance and able coordination of this project. The success of this project is due in large measure to the conscientious efforts of Chris Holz, the home solicitation coordinator, and Tim Ball, the head field engineer, who both moved to Spokane for the duration of this project. A special note of appreciation is also extended to Jeff Stern of McVay Brothers Construction, who skillfully opened and closed the test home holes. The efforts of Gary Helms of Seton, Johnson & Odell at efficiently loading the reams of field data into the computer and performing most of the statistical analysis is also worthy of note. Finally, special thanks must go to the owners and families in the test homes; their interest, support, and patience made this study possible.

TABLE 1
Moisture Content in Wall Opening Wood Members

Wood Member	Valid Readings	Moisture Content (%)				No. of Readings		
		Avg	Max	Min	SD	>20%	>25%	>30%
Right Stud-S*	305	10.6	22.5	6.5	2.8	2	0	0
Right Stud-I*	305	10.8	22.5	6.5	2.8	2	0	0
Left Stud-S	304	10.6	24.5	6.5	2.8	4	0	0
Left Stud-I	303	10.9	24.5	6.5	2.8	3	0	0
Sole Plate-S	304	10.9	26.5	6.5	2.9	3	1	0
Sole Plate-I	304	11.0	26.0	6.5	2.9	3	1	0
Sheathing-S	283	12.7	>30	6.5	4.0	13	4	2
Sheathing-I	283	13.2	>30	6.5	4.0	16	4	2
Subflooring-S	268	10.7	20.0	<6	2.5	0	0	0
Subflooring-I	268	10.6	19.5	<6	2.6	0	0	0
Header-S	283	11.2	22.5	<6	2.6	1	0	0
Header-I	283	11.3	22.0	<6	2.8	2	0	0
Sill Plate-S	91	14.0	>30	<6	4.5	6	5	2
Sill Plate-I	91	13.8	29.5	<6	4.3	6	5	0
All	3675	11.3	>30	<6	2.5	61 (1.7%)	20 (0.5%)	6 (0.2%)

* S: surface, I: interior

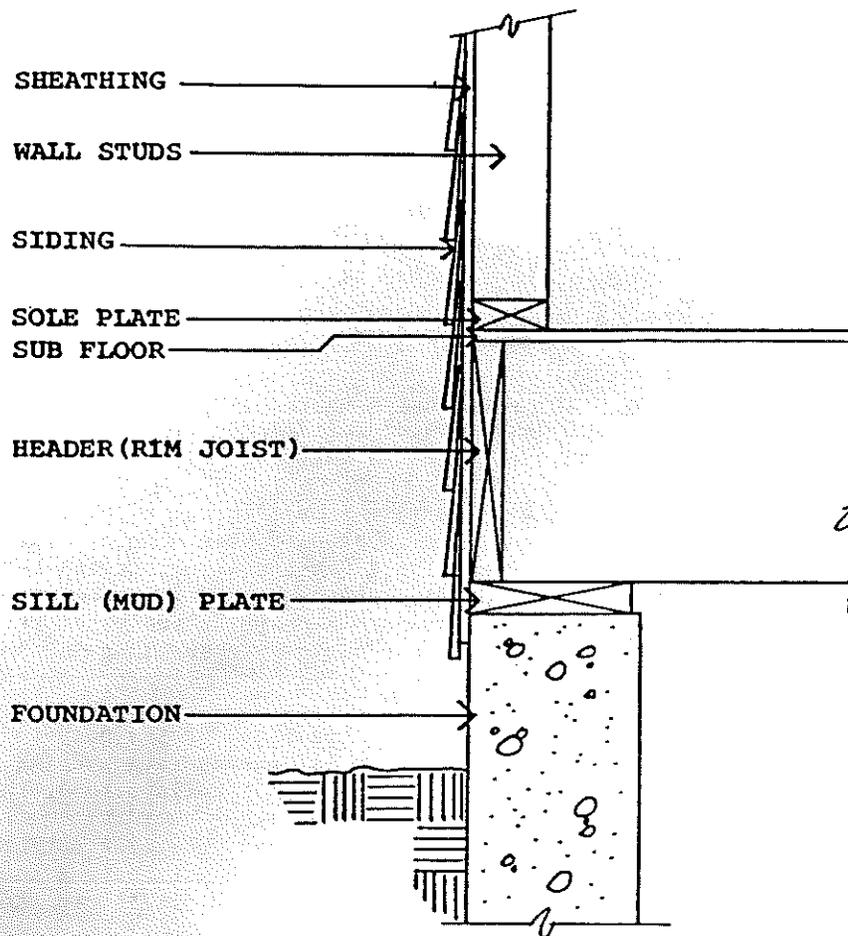


Figure 1. Wall opening wood member
 locations of moisture content
 measurement