TRI STATE HOMES: A CASE STUDY OF EXTENSIVE DECAY IN THE WALLS OF OLDER MANUFACTURED HOMES WITH AN EXTERIOR VAPOR RETARDER

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ABSTRACT

The first known cases of extensive decay in the wall framing members of hundreds, if not thousands, of manufactured homes involve the Tri State Homes in Wisconsin, Minnesota, and Michigan (the company has gone bankrupt). About 6,000 such homes were built in the 1970s. The decay has been attributed to high levels of indoor moisture, but recent field test and computer modeling results indicate that the primary cause is the presence of an exterior vapor retarder (EVR) that trapped moisture within the wall cavity. The low-permeability retarder (building paper) was on the outside of the plywood sheathing behind hardboard lap siding. The presence of the vapor retarder caused the plywood to get much wetter than normal during the winter and spring, and it reduced the rate of drying of the plywood. Thus the wood was still quite wet in the late spring and early summer, when temperatures were high enough to promote the growth of decay fungi. The result was severe and extensive rotting of the plywood sheathing that occurred over the last 20 years. But the decay progressed slowly, such that it was first noticed only about eight years ago. Moreover, the wet wall conditions led to the growth of substantial mold that seriously impacted the health of many of the occupants.

An inspection of 15 Tri State homes in Wisconsin that had siding removed (completely removed in 11 of the cases) revealed that 14 had plywood decay and 12 of the cases were severe enough that the plywood could be torn apart by hand. Ten of the 11 homes with siding completely removed had decay present. In addition, decay was noted in five of six houses with siding removed only in two localized areas; those homes were not inspected by the authors. Thus, overall, 19 of 21 homes inspected had plywood decay. It is conjectured that most, if not all, of the Tri State homes either already have experienced or eventually will experience severe plywood decay. Plywood delamination also was observed in 8 of 10 of the cases.

Many of the walls were unusually wet during winter and early spring, and plywood moisture contents above 60% (the meter limit) were measured during late June and early July, when the plywood in a conventionally constructed wall is considerably drier. The plywood moisture contents measured in the Tri State homes during that early summer, as well as during the previous winter and early spring, were higher than the highest values measured in any of three Pacific Northwest wall moisture field studies. While it has long been noted that the outside layers of a wall should be less permeable than the inside layers, these results dramatically emphasize the catastrophic results that can occur when the rule is not followed.

A comparison of sheathing and siding moisture levels for walls with and without an EVR also was undertaken using the MOIST computer model developed at a national laboratory. The modeling results further reinforce the field inspection finding that the EVR is the cause of the structural damage.

Details of the field tests and the computer modeling are presented, along with conclusions and recommendations. Practical lessons learned from this case study are presented to avoid similar problems in the future with presently available building products that act as an exterior vapor retarder.

INTRODUCTION

Since 1986 field inspections of manufactured homes produced by Tri State Homes have shown that a large percentage of those homes have serious and relatively extensive wood decay of the plywood sheathing. There are literally thousands of such cases (Merrill and TenWolde 1989). There is no other instance of such extensive wood decay in North American homes.

For decay to occur the wood has to be both wet (typically above about 30% moisture content or the so-called fiber saturation point) and relatively warm (generally above 50°F and optimally between about 75°F and 90°F) (USDA 1987). Wood such as plywood in walls in climates such as found in Wisconsin can get wet enough in the winter, but the wood is too cold for decay to occur; in the spring and summer, when the outdoor temperatures are warm enough for decay to occur, the wood typically has

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dried out sufficiently so decay is no longer possible. Thus, the occurrence of wood decay in walls in cold northern heating climates is relatively rare.

In fact, it is almost never observed in conventionally constructed walls, whether they are site built or manufactured. Three U.S. Department of Energy (DOE) wall moisture field studies undertaken in the Pacific Northwest, including one involving 20 homes in Montana where the weather is similar if not colder in the winter than in Wisconsin, have conclusively shown that in conventionally constructed walls without an exterior vapor retarder located in northern heating climates there is no evidence of wood decay (Tsongas 1980, 1986, 1990). The only exception is in very isolated cases, where leaks or wood members directly in contact with earth cause the wood to be wet when outdoor temperatures are warm enough to allow wood decay fungi to grow.

It has been alleged and widely believed that the decay observed in the Tri State homes was caused by elevated indoor relative humidities and lack of sufficient indoor moisture control (Merrill and TenWolde 1989). It has been presumed that the elevated indoor moisture levels were caused by a combination of relatively tight construction, lack of bathroom or other ventilation, damp basements, and relatively small home size.

If those were the only factors, then one would expect to see such decay occurring commonly in many homes in northern climates. Yet that simply does not happen. Thus, something must be different about the Tri State homes. It would appear that the unusual difference in those homes is that they were made with building paper with a fairly low permeability on the outside of the wall cavity (just outside of the plywood sheathing).

It is common to install a permeable building paper as a moisture barrier between siding and plywood sheathing. However, it is very unusual to install a relatively impermeable vapor retarder on the outside of a wall cavity. For years it has commonly been prescribed that the outside of the wall cavity be permeable, and much more so (at least five times) than the inside of the wall cavity, so that water vapor could escape out of the wall cavity to the outside and not accumulate and cause deterioration of the wood members (Anderson and Sherwood 1974).

The Tri State homes field evidence indicates that the wood decay observed was limited primarily to the plywood and not the siding or the studs. It appears that the decay started in the plywood outer layers, where moisture migrating through the wall from the inside to the outside would accumulate between the plywood outer surface and the inner surface of the impermeable building paper. Since the vapor retarder slowed the wall's drying rate, moisture could accumulate such that the wood stayed wet well into warm weather and decay occurred. Without the impermeable vapor retarder in place, the plywood presumably would have dried out and no decay would have occurred.

It should be noted that, based on limited early field inspection evidence, Trechsel (1994) hypothesized that the decay was caused by the presence of the impermeable building paper. However, many building scientists disagreed. The issue was contentious and embroiled in two lawsuits. Thus, as part of a class action suit involving 393 Tri State homeowners, it was decided to remove the siding from a suitable sample of those homes in an effort to pinpoint the cause of the plywood decay.

A Relevant Case of Decay in Older Mobile Home Walls

One other situation involving substantial decay in the walls of older single-wide mobile homes has relevance to this issue (Tsongas 1995). The metal (or wood) siding of 12 mobile homes located in the Pacific Northwest was temporarily removed during the late fall and early winter of 1993 in two small sections to install moisture-sensing instrumentation for a research project. In a number of the homes there was an impermeable vapor retarder (such as polyethylene) installed on the outside of the wall cavity right behind the siding (typically metal). Presumably it was installed there to keep condensation that formed on the inside of the siding from wetting the fiberglass insulation since none of these 12 homes had plywood or other wood sheathing or building paper. However, in most cases, extensive condensed moisture was noted during the wall openings on the inside surface of the vapor retarders (see Figure 1). Often the bottom plate was relatively wet. Maximum measured wall cavity wood member moisture contents were 33%, 44%, and 52% for three of those homes..

Most important, there was associated decay in wood members such as the bottom plate or the subfloor of four homes with an EVR. Some of it was isolated and relatively minor, but some was major. The decay could be even more extensive if all the siding were removed and the rest

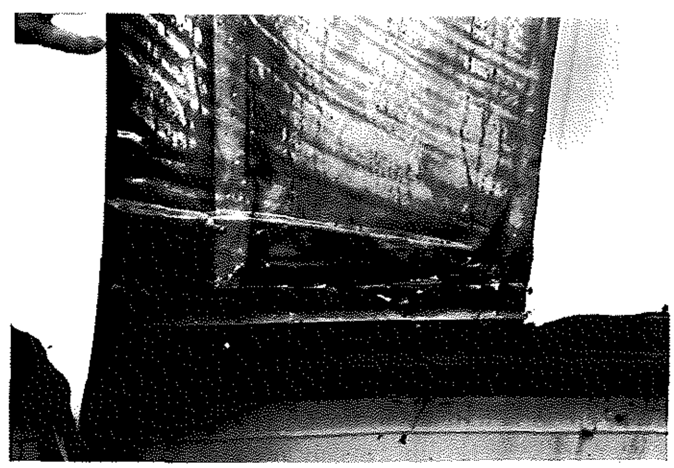

Figure 1 *Wood decay and extensive condensed moisture on inside surface of polyethylene vapor retarder*

of the wall areas were inspected. There was no decay in any of the other homes that did not have an EVR. Moreover, for those homes the maximum wall cavity wood member moisture content was less than 16%, which is considerably drier than the maximums for the walls with an EVR.

These preliminary results, along with the Tri State Homes results, strongly suggested that the decay was caused, at least in part, by the presence of a relatively impermeable exterior vapor retarder. Thus, it was hoped that a detailed field inspection of Tri State home walls with all or part of the siding removed would provide an irrefutable answer.

TEST HOME DESCRIPTION

Houses Studied

The homes under consideration in this study were manufactured homes built in Wisconsin by Tri State Homes during the period 1974-1978. The major components (e.g., individual walls) were all manufactured in a factory and site assembled. About 2,000 such homes were built during that period. The owners of 393 of those homes participated in a class action suit due to alleged structural damage caused by the existence of an exterior vapor retarder. Of those, 25 homes from all parts of the state were randomly selected as representative for detailed inspection.

From those 25, only 11 homes had no repairs to siding or plywood. Incidently, that indicates the extent of known damage to these homes. Those 11 unrepaired homes were selected to have *all* their siding and exterior vapor retarders removed to thoroughly inspect the plywood sheathing for elevated moisture contents and moisture-related deterioration and to determine the extent of any wall damage. Another four homes had small amounts of siding removed to inspect the plywood in areas where siding or plywood had not been replaced. The other 10 homes, including two inspected by the authors (no siding was removed), were not considered part of this study for a variety of reasons. Of those 10 homes, 6 were inspected by the defense without either of the authors present; all of those homes previously had siding or plywood partially or completely replaced. Siding was removed to inspect the plywood in only a few locations in each of those homes.

Wall Construction and House Details

All of the 15 test homes were single-family detached homes with wood-frame construction. Almost all were single-story with an unintentionally heated unfinished basement. Some had a partially or fully finished and heated basement. The areas of the heated living space ranged from 816 to 1,800 ft^2 (76 to 167 m^2); the average size was 1,222 ft^2 (114 m^2). The homes had double glass windows that were well flashed and sealed. The natural infiltration rate of one of the homes was estimated from a blower door test to be 0.29 air changes per hour (ACH) using a national laboratory's methodology (ASHRAE 1993). That is close to the average of 0.28 ACH for 73 other Tri State homes tested prior to this study (Merrill and TenWolde 1989). Tests, both by blower door and passive tracer gas and described briefly by Trechsel (1994), found values of 0.2 to 0.6 ACH.

From inside to outside the 2-by-4 walls were constructed of 0.5-in. (12.7-mm) gypsum board, R-11 $ft^2 \cdot h \cdot °F/Btu$ (1.94 $m^2 \cdot K/W$) fiberglass batts, 0.5-in. (12.7-mm) plywood sheathing (interior type with exterior glue), a low-permeability asphalt-impregnated building paper (44 field samples tested to be 0.65 perm on average), and 0.5-in. (12.7-mm) hardboard horizontal lap siding (except house 10, which had panel siding). The exterior vapor retarder was applied in continuous sheets and properly lapped at the joints.

The fiberglass batts typically had asphalt-impregnated kraft paper on their inside face and an asphalt-impregnated kraft paper backing on their outside face. The batts were usually face-stapled on the outside of the studs. The permeabilities of the inner insulation facings and the outer backings were tested to be, on average, 4.09 perms (53 field samples) and 7.10 perms (34 field samples), respectively.

All but one of the 17 homes inspected had a working exhaust fan in the main bathroom, all but three had a working kitchen exhaust fan, and all had their dryer exhausted to the outdoors. Most of the homes did have a dehumidifier in the basement, but it was typically used only in the summer. The homes generally were heated either with electric baseboards or with a hydronic baseboard system (the natural draft boiler was located in the basement); a few relied heavily on a wood stove for heat. The number of occupants ranged widely from two to nine.

THE FIELD INSPECTION PROTOCOL

The first three homes were visited during August 1993 to perform a preliminary informational inspection. Only minor amounts of siding were removed. Site visits were made to the remaining 14 homes during late winter, early spring, and early summer of 1994. The inspection dates are noted in Table 1. Some of the homes were visited on more than one occasion. Generally speaking, only minor amounts of siding were removed during the late winter and early spring visits. All the siding was removed from the 10 homes visited during the week of June 27-July 1, 1994, plus one visited on April 1, 1994.

For each wall of the 17 homes, the siding and EVR were removed and the moisture content of the plywood was surveyed using a hand-held capacitance-type surface moisture meter with a penetration depth of about 0.5 in. (12.7 mm). The plywood moisture content was systematically measured in all areas of all the exposed walls (typi-

TABLE 1 Tri State Homes Field Inspection Data Summary

Home ID#	Dates Inspected	MCmax(%) 8/23	MCmax(%) 2-3/94	MCmax(%) 4/94	MCmax(%) 6-7/94	Ply-wood Delam.	Plywood Decay Major Gable	Plywood Decay Major Other	Plywood Decay Minor Gable	Plywood Decay Minor Other	Stud/Plate Decay	Siding Drip Marks	Amt. Siding Removed	Winter Indoor RH	Fib. Batt Char.[a]
1	6/27/94				45	Y	Y	Y	N	Y	N	Y	All		KP-KP-OFS
2	6/27/94				40	N	N	N	Y	N	N		All		FL-KP-OFS
3	3/1/94 6/28/94		36		30	N	N	Y	Y	N	N		All	32	
4	3/01, 4/01, 6/28/94		45	47	>20	Y	Y	Y	N	N	N		All	28	FL-KP-OFS
5	3/1/94 6/29/94		49		>20	Y	Y	Y	N	Y	N		All	29	KP-NO-IIS
6	3/94, 6/29/94				30	Y	N	N	Y	N	N		All		
7	3/94, 6/30/94				55	Y	Y	Y	N	Y	N		All		
8	3/94, 6/30/94				47	Y					N		All		
9	2/28/94, 7/01/94		53		>60	Y	N	Y	Y	N	Y	Y	All	41	KP-KP-OFS
10	4/02/94, 7/01/94			>60	>60	Y	Y	N	Y	N	N	NA	All		FL-KP-OFS
11	2/28/94, 4/01/94		>60	80				Y				Y	All	33	
12	2/28/94		29				Y	Y					Minor	32	PY-??-??
13	2/28/94		13			NA	NA	NA	NA	NA	NA	N	Minor	26	
14	3/01/94		18					Y					Minor	30	
15	8/04/93	16					Y	Y				N	Minor		??-KP-OFS
16	8/04/93	19				NA	NA	NA	NA	NA	NA	Y	Minor		FL-KP-OFS
17	8/04/93	15					Y	Y			Y	Y	Minor		

[a]KP : asphalt-inpregnated kraft paper facing; FL: foil facing; NO: no facing; OFS: face stapled on outside face of stud; IIS: inset stapled on inside surface of stud near inner face.

Home ID#	Remarks
1	Six-year-old piece of plywood covered with spin-bonded polyolefin on S gable wall
2	One inch cedar siding with tar paper over building paper; building paper badly deteriorated in one spot
3	Siding was vented high and low in each stud cavity
4	Water condensed on warm side of building paper where Lstiburek opened wall
5	New vinyl siding with spin-bonded polyolefin (SBP) over old building paper; water ran out when JL cut SBP open in M
6	
7	
8	
9	Building paper frozen to plywood
10	Verticle board and batten siding (4-ft-wide panels)
11	Water droplets on inside of building paper up against plywood
12	Building paper removed and some plywood replaced; new polycoer with foil facing and vinyl siding
13	Original hardboard siding and building paper removed and replaced with aluminum siding with fiberboard backer
14	Repaired in 1987; new vinyl siding with 0.5-in. foil-faced rigid insulation over plywood
15	
16	Only one gable end opened in one small area; plywood decay likey because of siding drip marks
17	

cally 50 to 100 readings per wall). If that meter indicated a moisture content of greater than 20%, then sometimes the moisture content was determined using an electric-resistance-type moisture meter with insulated pins, automatic temperature compensation, and a range of 6% to 60% at 70°F (21°C). All moisture readings were recorded on sketches of the wall in the locations where the readings were made.

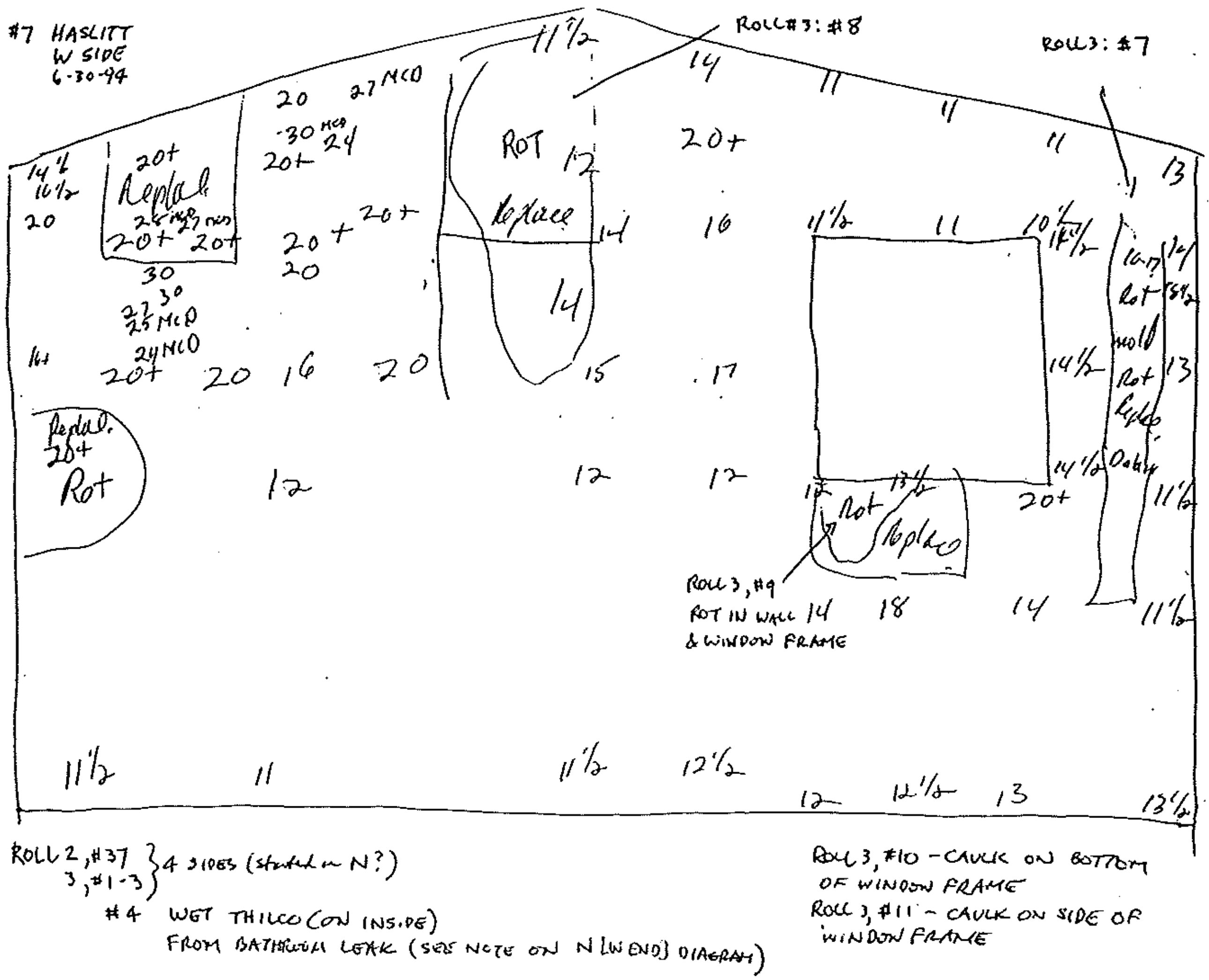

Figure 2 Wall field sketch with conditions noted.

The next step was to visually inspect for mold on the exterior surface of the plywood, for areas of plywood delamination, and for decayed plywood. If found, the locations were noted on the wall sketches. An example is shown in Figure 2. Findings also were recorded photographically and with a video camera. The complete siding removal, moisture measurement, and inspection process took about three hours per house..

Five of the 10 homes visited in the 1994 summer also were inspected during midwinter or early spring of 1994, along with four others. Generally speaking, siding was removed only in isolated locations during those earlier inspections. However, the moisture content of all regions of the siding was measured with a surface moisture meter. Where elevated levels were observed, the moisture contents of the plywood underneath were measured by driving the insulated pins of the probe-type moisture meter through the siding and into the plywood.

Indoor and outdoor relative humidities and temperatures were measured during the winter and spring using a digital hygrometer/temperature meter. Small pressure differentials were measured with a highly sensitive digital manometer (to within 0.1 Pa) to aid in understanding wall moisture migration characteristics. A blower door was used to perform depressurization tests to determine the airtightness of some of the homes (see the "Analysis of Results" section). Finally, infrared thermography was used to inspect walls for air leaks or thermal anomalies.

RESULTS AND FINDINGS

The salient results of the field inspections are presented in Table 1. Where blanks exist in the table, no observations were made one way or the other. The results are discussed in the following sections.

Elevated Plywood Moisture Contents

The MCmax values shown in Table 1 are the maximum values measured for any wall for each of the homes. The majority of those values are equal to or greater than the fiber saturation point for plywood (28%), with the highest being 80%. The >60 values were out of the range of the probe moisture meter and the plywood generally was wet to the touch, while the >20 values were above the upper range limit of the surface moisture meter. Many of the walls were relatively wet in many areas. Generally speaking, the walls were relatively drier on the bottom half and wettest near the top of the wall. They were especially wet on the upper portions of gable end walls. (See, for example, Figure 2.) They also were very wet on non-gable end walls outside of bedroom closets.

Three homes inspected in February-March 1994 had siding fully or partially replaced when wall damage was found prior to our inspections. In those cases the exterior vapor retarder usually was removed. When opening small areas of siding to check moisture levels of the plywood, the wood in all cases was much drier than in houses inspected the same week with an EVR in place. In none of these cases was the plywood ever more than 30% moisture content.

When siding was removed during the winter or early spring, liquid or frozen water often was noted between the plywood outer surface and the exterior building paper/retarder. However, it generally was not present between the siding and building paper/retarder.

Plywood Delamination, Decay, and Mold

Plywood delamination was noted in 8 of the 10 homes with siding completely removed and inspected during the summer. In some cases it was somewhat minor, but in many cases it was rather extensive. It was clearly caused by excess moisture levels in the plywood. In all cases the degree of delamination caused local surface bulging.

In no case was there any obvious indication of decay present within a wall by observing the wall from outside the siding. There were a few drip marks on the siding from between laps in a few cases (see Figure 3), but they were not always easily observable. However, upon removal of the siding and EVR, the plywood was found to be decayed in 10 of the 11 homes with all or most of the siding removed and 14 out of 15 overall (see Table 1). One of the 10 houses inspected during the summer did not have decay, but the summer plywood moisture content values were high enough (well above the fiber saturation point) that decay would likely occur in the future.

The degree of decay ranged from minor (wood soft in small areas) to major (wood disintegrated and easily punctured/broken apart by hand). All but 2 of the 14 test homes with decay exhibited major decay (see, for example, Figure 4). Both major and minor decay were noted about equally often on both the gable ends of the homes and the other sides. When major plywood decay was noted, the exterior building paper was often disintegrated as well. That may have allowed moisture to leave the wall cavity more easily and thus dry out the area and slow or stop the decay.

In addition to the decay found during the inspections of the 15 houses, there was previous or existing decay noted in 5 of 6 houses inspected by the defense (neither author was present but site inspection notes were reviewed; the inspection findings regarding decay were not clear for 1 of the 6 homes). Those 6 homes were part of the original 25 Tri State homes randomly selected for detailed inspections. Thus, of the total sample of Tri State homes randomly selected for inspection, overall 19 of 21 homes had plywood decay.

Site visits and inspections for a governor's task force prior to this study found decay in fewer than half the homes, based on partially removing siding in locations based on inspector preference and experience (Merrill and TenWolde 1989). However, this present study found decay in almost all homes when all the siding was removed.

Surprisingly, the siding was never decayed or otherwise affected. For example, the siding was almost never noted to be buckled. Moreover, in only one case was a stud or plate decayed, which agrees with the findings of Merrill and TenWolde (1989) of framing damage in 5% to 10% of the homes. By way of explanation, the studs were

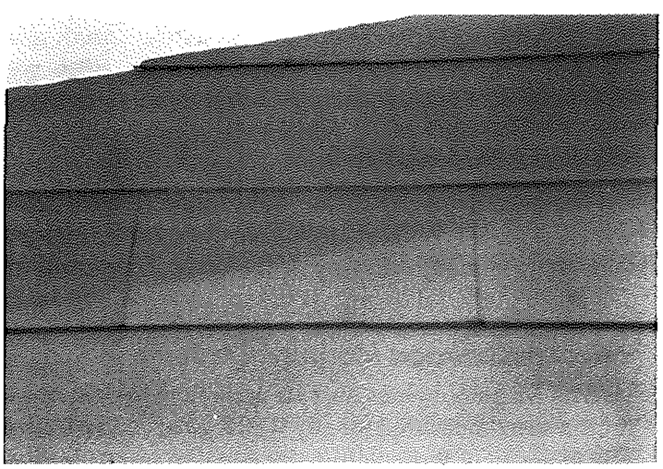

Figure 3 *Minor drip marks on siding between laps.*

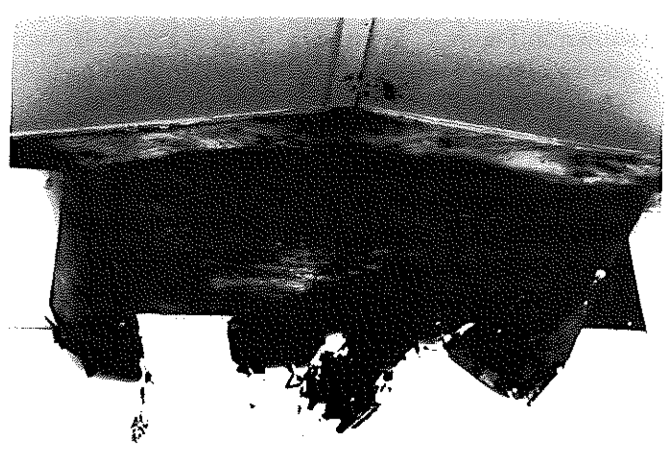

Figure 4 *Major plywood decay with disintegrated building paper.*

usually separated from the plywood with an asphalt-impregnated paper attached to the insulation batts and stapled to the outer face of the studs. Thus the plywood was fairly isolated, with asphalt-impregnated building paper or insulation backing on both sides in most cases.

Varying degrees of mold were often noted on the exterior surface of the moister sections of the plywood (and to a lesser extent on the inside surface). In a related lawsuit, mold in Tri State homes was shown to cause adverse health effects (Olson et al. 1993).

Indoor Conditions

The indoor relative humidity was measured in the eight homes inspected during late February and early March: the average was 31%, with a high of 41% and a low of 26% (the second highest was 33%). That average is almost exactly the same as the value predicted using MOIST software modified to calculate indoor relative humidity values (Tsongas et al. 1995) and assuming typical Tri State residence conditions.

The homes were inspected indoors for mold and mildew. It was sometimes found in localized small patches, typically in ceiling corners, and appeared to be due to cold surfaces caused by thermal short-circuiting. Slight mold also was noted on some window frames. However, the mold was not as bad as was seen in many other houses where decay did not occur.

While inspecting the bedrooms, a hole was regularly noted opening into the wall cavity in the inside gypsum board of the exterior walls above the flat ceiling (a removable partition) in the closet area. Wiring passed through it, and it had an area of about 10 to 16 in.^{2} (65 to 103 cm^2) (see Figure 5). In a few cases, mold was observed on the bottom of the closet ceiling near the opening.

Figure 5 Hole in gypsum board of exterior wall allowing exfiltration of moist indoor air into the wall cavity.

Blower Door Tests, Infrared Thermography, and Pressure Diagnostics

Blower door tests were run by the defense on houses 1 through 14, but the results have not been made available pending an appeal of a companion lawsuit. We ran a test on house 11 in conjunction with infrared thermography tests. The measured cfm50 value was 1,040. Using the national laboratory's methodology described in ASHRAE (1993), the natural infiltration rate was estimated to be 0.28 ACH.

Infrared thermography was used, both with and without a blower door operating, to scan the exterior walls to look for air leaks or thermal anomalies. A particular effort was made to examine the mid-wall area below the peak of the gable ends where elevated moisture levels, delamination, and decay of the plywood regularly were found. It was initially presumed that the plywood damage and/or elevated moisture levels high in the gable ends were due to substantial air leaks and exfiltration at that location. However, no large air leaks were found. In fact there was comparatively little air leakage through any part of the gable end walls. There were no leaks noted where the interior partition walls intersect the exterior walls. Moreover, there were far fewer anomalies than found in other thermographic inspections of homes in that region.

Measurements of pressure differentials were made to determine if any of the homes were pressurized such that moisture might be driven into the walls. In all cases the homes were negatively pressurized (typically about 2 to 3 Pa), if at all, except one house, which had very slight (+0.2 Pa) bedroom pressurization. Typically when they were depressurized, that was due to the stack effect or operation of the space-heating boiler. The lack of forced-air heating meant that most bedrooms were not pressurized.

ANALYSIS OF RESULTS AND FINDINGS

Elevated Plywood Moisture Contents

The plywood moisture contents were much higher than expected based on computer wall moisture simulation results for manufactured houses in Madison, Wis. (Burch and TenWolde 1993). Although wood components in walls can get rather wet (even well above the fiber saturation level) during winter months, walls typically dry out appreciably in the spring and by mid-summer are normally quite dry. In one house in Montana, wall moisture contents as high as 47% were measured in February but by April the same locations were below 18% and during mid-summer they were below 7% (Tsongas and Nelson 1991). In a study of 86 homes in the Pacific Northwest, winter moisture contents as high as 52% were measured in plywood sheathing, whereas no values above 23% were noted in the same plywood monitored during July and early August (Tsongas 1990).

Thus the moisture levels measured in these Wisconsin homes in late June and early July (see Table 1) are remarkably high and very atypical. Such high values would not be expected in conventionally constructed walls. In fact, one of the authors (Tsongas) has measured moisture contents in thousands of other wall cavities and has never measured plywood moisture levels above 52%, even in mid-winter, let alone July. Generally speaking, plywood moisture levels in July are less than 10% to 15%. In monitoring moisture levels in a number of 2-by-4 wall configurations in Madison, Wisconsin, where the indoor relative humidity was maintained at more than 40%, Sherwood (1987) found all moisture contents to be less than 16% by mid-April.

The plywood moisture contents of some of the walls were also measured during mid-winter or early spring of 1994. A number of readings were near or above 60% and the highest reading was 80%. That is the highest reading known to be measured in a U.S. wall without water leaks. Clearly such readings are atypical.

It is worth pointing out that the bottoms of all walls were considerably drier than the tops. In no case did they exceed the fiber saturation point (28%), nor were there any cases of decay there. There are three likely explanations for that. First, the continuous exterior vapor retarder typically did not cover the bottom foot or so of the plywood sheathing. Thus it could breathe and dry out better than the rest of the wall. Second, as will be discussed in more detail later, thermal convection looping within the wall cavities likely existed, and moisture in the cavity air preferentially condensed on the upper portion of the plywood sheathing in each stud cavity. In addition, any infiltration of cold, dry outdoor air in the winter would typically flow into the bottom of the wall cavity and lead to preferential drying of that lower portion of the wall.

There was another strong indication of the effect of the EVR. There were a number of places, such as on the exposed wall adjacent to the attached garage, where siding was routinely installed without an EVR since none was needed on the wall between the house and the garage. In none of those cases was the plywood moisture content even close to the fiber saturation point, nor was decay ever noted there. Nor was any decay ever noted in the wall that had no siding or EVR between the house and the garage. In one house, the vapor retarder was missing on one side of a corner but not on the other. On the side with it missing, the wood was dry (12%) and light in color, whereas right around the corner, where the retarder was in place, the wood was wetter (18% to 20%) and distinctly darker.

There is statistical evidence from a Pacific Northwest wall moisture field study that the highest wall moisture contents occur in bedroom and bedroom closet wall areas (Tsongas 1990). That may be caused at least in part by bedroom pressurization due to the operation of a forced-air furnace significantly increasing exfiltration of moist indoor air into the wall cavities. While Tri State bedroom walls often were exceedingly wet and generally wetter than other areas, that cannot be caused by forced-air furnace operation since forced-air heating systems were typically not installed.

Computer Simulation Results The moisture performance of the walls in the Tri State homes was modeled using software developed by Burch and Thomas (1992) and modified by Tsongas et al. (1995) to incorporate variable rather than constant indoor relative humidities. The model analyzes one-dimensional heat and moisture transfer in multilayer walls and accounts for moisture transfer by vapor diffusion, capillary flow, and one-dimensional air convection. It predicts moisture levels in any of the components of a wall cavity on an hourly basis, typically over a time span of one year. The results predicted by the model depend on the house construction and size, the occupants' life-style characteristics, the wall construction characteristics, and the local climate.

The purpose of the modeling was to compare the plywood sheathing and wood siding moisture contents with and without a relatively impermeable exterior vapor retarder. Predictions were made using Madison, Wisconsin, WYEC hourly weather data. The construction, building, and occupant characteristics of an average Tri State home were used as inputs to the model. From inside to outside the prototype wall construction consisted of 2-by-4 wood framing, 0.5-in. (13-mm) gypsum board with interior latex paint (12.0-perm primer and finish coat), R-11 (R-1.9) fiberglass batt insulation with a 4.1-perm inside facing and a 7.1-perm outside backing, 0.5-in. (13-mm) exterior-grade plywood sheathing, building paper (either 0.65 perms corresponding to the type actually used in the construction, 20.2 perms [ASHRAE 1993] corresponding to conventional construction, or 402 perms [Burch et al. 1992] corresponding to very permeable spin-bonded polyolefin), and 0.5-in. (13-mm) waferboard siding with exterior latex paint (5.5-perm primer and finish coat).

A 1,222-ft^2 (114-m^2) single-story home with an average room height of 9.5 ft (2.9 m) was assumed. The winter heating thermostat setpoint was 68°F (20°C), the space-heating balance point temperature was 56°F (13°C), there was no summer air conditioning, there was no mechanical ventilation (only natural infiltration), the effective leakage area was 50 in.^{2} (323 cm^2) (corresponding to an average natural infiltration rate of about 0.28 ACH), the indoor moisture generation rate was 24 lb/day (11 kg/day), there was a small amount of exfiltration assumed, and the sorption constant per unit floor area and corresponding thermal time constant were taken as 0.2×10^{-4} lb/h·ft^2 (0.27×10^{-6} kg/s·m^2) and 9 hours for manufactured homes (TenWolde 1994). Wind and stack coefficients were obtained from ASHRAE (1993). The moisture content predictions vs. time are shown in Figure 6. The results for the Tri State wall, but without an EVR (it was assumed the wall had a 20.2-perm building paper case typically used in conventional construction and labeled "Med Perm" in Figure 6), indicate that plywood sheath-

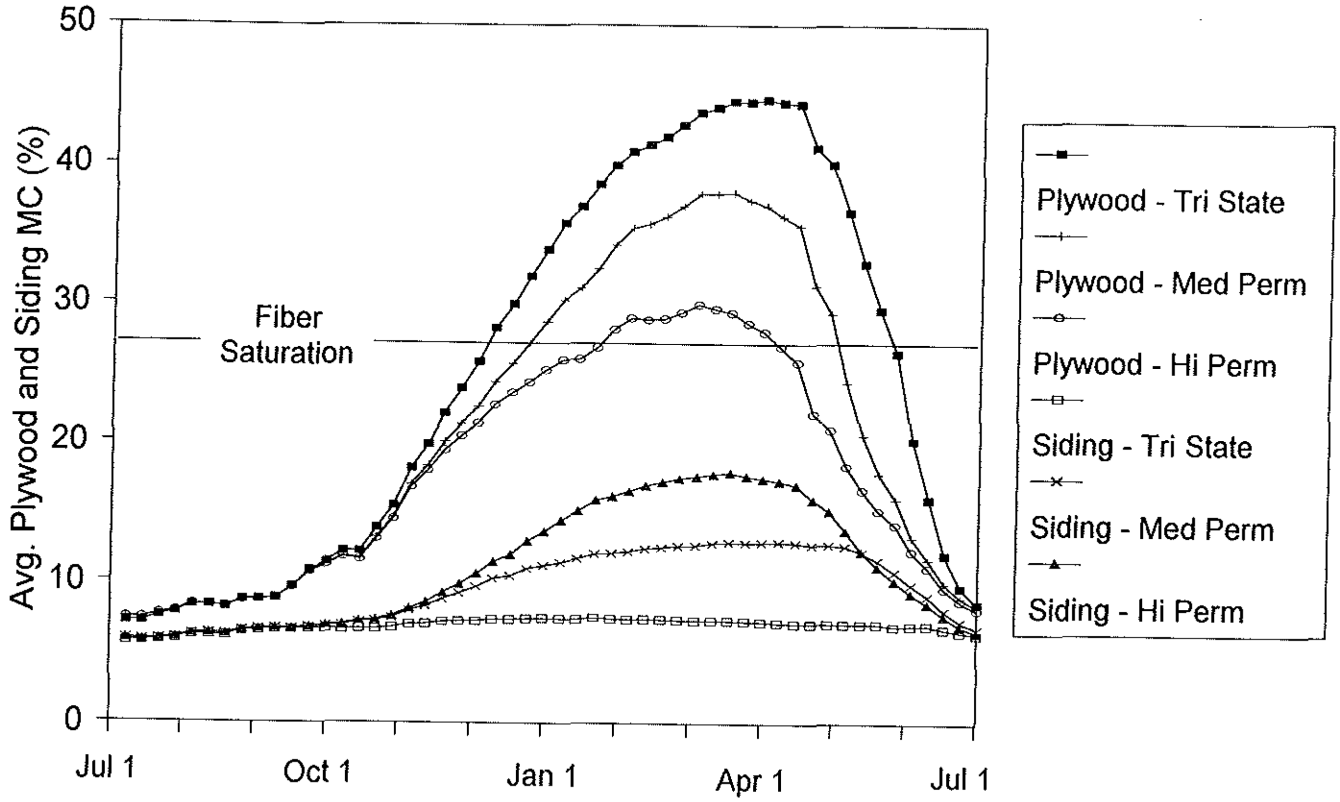

Figure 6 *MOIST simulation moisture content predicitons for the Tri State wall plywood and siding with building paper of different permeabilities.*

ing can get wetter than the fiber saturation condition during winter months when decay cannot occur. Nevertheless, the walls dry out rapidly in the spring so that decay is not possible. The same is true for the case with the very permeable building paper (labeled "Hi Perm"), except the moisture levels are even lower. These computer modeling results are in good agreement with field inspection results—both indicating that wood decay generally does not occur in plywood sheathing in northern heating climates.

However, in the same wall but with a 0.65-perm EVR in place (the actual Tri State wall construction, labeled "Tri State"), the peak winter sheathing moisture content is significantly higher. During the late spring and early summer months, the plywood moisture content with the EVR is about 10% higher than without the EVR, and that is a significant difference. More important, moisture contents above the fiber saturation point persist in the sheathing until late spring and early summer when decay can occur. Thus the sheathing probably got wet enough for some decay to occur. Then, as warm weather continued through the summer, it stopped. This reoccurred for many years until the plywood deteriorated. That is probably why it took more than 10 years for the first decay to be noticed. Incidently, even without any air leakage, the results were generally the same.

Infrared Thermography Results High plywood moisture contents have been shown to occur at the site of localized small air leaks in conventional 2-by-6 walls without an exterior vapor retarder (Tsongas and Nelson 1991). Moreover, one would expect some exfiltration at the top of the wall cavity. However, the infrared thermography results indicated that there was relatively little air leakage carrying warm, humid air into the wall cavities and exiting high in the gable ends. So that probably was not the only cause of the high moisture contents and decay often observed there, although it certainly could have been a contributing factor. In fact, there was little air leakage observable in any parts of the walls, including areas around electrical outlets and switches. Walls in stud cavity areas with electrical outlets or switches showed no greater decay than those without them.

The fact that the insulation batts were face stapled plus the exterior vapor retarder being continuous meant there was the equivalent of two continuous air barriers in place, one on each side of the wall cavity. That restricted air leakage. In addition, in comparison to site-built construction, there appeared to be few thermal anomalies such as thermal short circuits (e.g., poor insulation installation or missing insulation) that might cause cold spots where moisture might be more likely to condense. Moreover, there was no evidence of water leaks and there was a two-foot overhang all around the houses that kept bulk outdoor moisture away from the high outside sections of the gable end and other walls.

It would appear that while some moisture migrated into the wall cavities by air convection, moisture also diffused slowly through the gypsum board into the wall cavities, where it was trapped by the exterior vapor retarder. There was no upper plate in the gable end walls so the stud cavities were as high as 11 ft (3.4 m) at the peak. Thus these long wall cavities had the largest area for diffusion of water vapor and the greatest moisture entry per stud cavity. Natural air convection within the fiberglass insulation and any air spaces would cause the moist air to rise near the warm inner gypsum board surface until it reached the top of the wall cavity. It then turned and started to drop along the cold plywood outer surface. The moisture in the air condensed when it hit the cold plywood outer surface, and that resulted in the high moisture levels there. There was relatively less condensation at the bottom of the wall cavities, so they were drier. This hypothesis gained further credibility when it was noted that the long wall cavities near the ends of the gable end walls also had relatively elevated moisture levels, while the short wall cavities above and below the windows in between were relatively dry (they were much shorter and had much less moisture input by diffusion). Incidently, the exposed gable ends were adjacent to bedrooms. Of course, any air exfiltration out of the top of the wall cavities during cold weather would lead to condensation there and localized wetting. However, air leakage can only occur at cracks such as at the top of the wall cavities or between plywood panels. Yet the plywood decay was not limited just to crack areas but occurred over large areas, including many well away from the top of the wall cavities. Thus while moisture migration into the wall cavities by both diffusion and air leakage can lead to decay, it is believed that the diffusion mechanism is the dominant mechanism.

While diffusion is a slow wetting process, it nonetheless repeatedly wet the walls and kept them wet because drying also was by diffusion and slow. Apparently some decay occurred each year until the plywood deteriorated. The process was slow enough that it took more than 10 years for the first decay to be noticed and some was just noted after 20 years.

The other spot where walls regularly were found to be wet was high up on the non-gable end walls outside of the bedroom closets, where a relatively large hole allowed moist, warm indoor air to leak into the top of the wall cavity. When it hit the outside wall surface it condensed and caused elevated moisture levels. Once wet, the exterior vapor retarder kept the walls from drying out as quickly as conventionally constructed walls. Clearly, decay in that spot was caused by air leakage rather than diffusion.

In this study the vast majority of moisture problems and associated decay occurred in bedroom walls for the reasons noted above. Merrill and TenWolde (1989) also found that the most damage occurred in bedroom walls.

Plywood Delamination and Decay

While delamination of exposed plywood siding such as T1-11 siding is not uncommon, especially if not well protected with paint or stain, delamination of plywood sheathing inside a wall and protected from the weather is quite rare. It can only occur if the plywood has gotten soaking wet as a result of a leak or some other unusual cause. Clearly the latter is the case in the affected walls. Leaks generally were not observed, especially on gable ends where delamination was regularly observed. For one thing, the decay usually occurred high up on the walls in areas protected from the weather by the large roof overhang.

In terms of the decay observed in the Tri State homes, there is no other documented case of such severe and widespread plywood decay. It has been suggested that the decay was caused by elevated indoor relative humidities and lack of sufficient indoor moisture control (Merrill and TenWolde 1989). It has been presumed that the elevated indoor moisture levels were caused by a combination of relatively tight construction, lack of bathroom or other ventilation, damp basements, relatively small home size, and high occupancy levels.

It is true that elevated wall moisture levels are statistically correlated to high indoor relative humidities (Tsongas 1990). However, the average winter indoor relative humidity of 31% measured in this study is not particularly high. For example, the average indoor relative humidity of 20 Montana homes whose walls were much drier and without any decay was 40% (Tsongas 1990). Yet those homes were much larger and generally in a more severe winter climate than that in Wisconsin. Moreover, the Tri State homes were tight, but not overly tight, and generally had bathroom ventilation. A number of the homes with moisture problems had relatively low occupancy levels. As noted earlier, there simply has to be a reason other than high indoor relative humidities for the extremely elevated wall moisture levels and the associated decay. None of the factors about the Tri State homes or their occupant life-style characteristics was that unusual. The only plausible explanation for the exceedingly high plywood moisture contents and the surprisingly high percentage of Tri State homes with plywood decay is the existence of the exterior vapor retarder.

It should be noted that an attempt was made to determine whether plywood decay had occurred using surface or probe-type moisture meters and/or infrared thermography. It was hoped that actual removal of the siding could be avoided. Unfortunately, no noninvasive method was found that would predict the condition of the interior wall structures, short of siding removal.

CONCLUSIONS

Detailed field inspections plus computer simulations have conclusively shown that the installation of a low-permeability vapor retarder on the outside of the plywood sheathing has led to relatively elevated moisture contents in the plywood sheathing, substantial deterioration and decay of the plywood sheathing and the building paper itself, and the growth of large amounts of mold within the wall cavities of a majority of the Tri State homes inspected. In our opinion, these unsatisfactory conditions will occur in almost all the Tri State homes, if they have not already, given enough time. Therefore, even if plywood decay has not yet occurred in some of the homes, it is inevitable that it will at some point in the future. Thus, all the exterior building paper needs to be removed. If the homes had been constructed without an exterior vapor retarder, there would be little or no damage and significantly less mold growth. While any decay has obvious structural effects on the dwelling, the presence of mold can have significant health effects on the occupants, as has been shown in a previous Tri State Homes case (Olson et al. 1993).

There appears to be no nondestructive or nonintrusive way to determine the extent or location of the damage to the walls of any Tri State home. Thus the only remedy to this situation is to remove all the siding, remove the building paper, fix the deteriorated plywood, clean as much mold as possible, replace the relatively impermeable vapor retarder with a permeable retarder, and re-side the walls. Then the walls should be relatively free of problems for the life of the buildings.

It should be noted that it was well known within the building community prior to the construction of these Tri State homes that the permeance or perm rating of materials on the cold side of exterior walls should be much greater than those on the warm side. A ratio of at least 5 to 1 for the permeance of the outside materials relative to the inside materials was widely recommended at the time (see Anderson and Sherwood [1974]). The recommendation was made to help prevent condensation problems in walls. Thus it was fairly common knowledge that a low-permeance vapor barrier should not be put on the cold side of the wall. In fact, we know of no other cases where that was done at the time. Clearly, incorporating such an EVR in the Tri State homes was a huge mistake with disastrous consequences. It should never have happened.

Obviously one would like to avoid similar problems in the future with presently available or future building products, such as sheathing and siding that act as an exterior vapor retarder, that are used in northern heating climates. Problems with at least one such product have been observed by one of the authors (Tsongas). Based on the results of this study, their use should be avoided until it has been shown that they will not create wall moisture problems, preferably by a combination of computer simulation of wall moisture performance with those products in the walls and side-by-side comparative testing with similar products that do not incorporate an exterior vapor retarder. Then and only then can one be reasonably sure that the products are safe for widespread use.

Finally, it has been suggested that the decay that occurred was caused by elevated indoor relative humidities associated with tight construction and other factors. The essence of that argument is that the elevated indoor relative humidities caused excessive condensation in the walls that led to decay. It is true that increasing indoor relative humidity levels leads to higher moisture levels in walls (Tsongas 1990). However, while higher moisture contents may occur *during the winter*, the wood components in conventionally constructed walls still dry out sufficiently in the spring prior to warm weather such that decay does not occur. There are numerous examples of similar poorly ventilated, airtight homes with even higher relative humidities (often in multifamily housing), and yet decay in such walls is seldom observed in any other northern U.S. cold winter climate location. The Tri State homes may have had a high wetting potential, but the key is they also had a rather poor drying potential. The exterior vapor retarder trapped moisture within the plywood and also prevented it from drying out as quickly as with a breathable exterior building paper or none. Thus the primary cause of the damage was not the conditions inside the houses but rather the unusual wall construction.

RECOMMENDATIONS FOR FURTHER STUDY

It is recommended that the moisture performance of existing noninsulating siding products or sheathing materials that act as an exterior vapor retarder be explored by a combination of computer simulation using the modified model (Tsongas et al. 1995) and field tests. Computer simulations could be run to determine what conditions and materials should be tested. Side-by-side field tests in actual homes comparing similar materials with and without vapor retarder properties should then be undertaken to determine if the vapor retarder materials actually produce problems.

It is also suggested that further computer simulation be undertaken to examine the relative humidity conditions in conventional walls in northern heating climates to determine if conditions conducive to the growth of mold exist. The presence of mold has been noted both in this study and others in the Pacific Northwest (Tsongas 1980, 1986, 1990). It also would be worthwhile to repeat such a study for southern hot and humid climates using the modified software. That should lead to a better understanding of ways to prevent its growth. Recent litigation results (Olson et al. 1993) and an increased emphasis on indoor air quality as related to health issues suggest that questions regarding the performance of walls from a mold growth point of view will likely receive increased emphasis in the future.

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