#3369

Overview of Moisture-Related Damage in One Group of Wisconsin Manufactured Homes

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ABSTRACT

In July 1986, reports surfaced of widespread moisture damage in walls of manufactured single-family homes in Wisconsin. The homes were manufactured by a company that declared bankruptcy and was liquidated just before the reports of moisture damage surfaced. This paper presents information about the nature and extent of the damage and summarizes the results of a health study of residents of the homes and air quality measurements of the homes.

Site visits and a home inspection program revealed decay in fewer than half the homes. Most decay was in the sheathing, with far less damage to the wall framing. A survey of homeowners and airtightness measurements further confirmed that the damage was primarily due to excessively high indoor humidities, which led to condensation in the walls during winter. The homes were very airtight, leading to very low ventilation rates during winter. Insufficient ventilation, combined with a relatively large number of occupants, appeared to have led to high-humidity conditions; the authors found a direct relationship between occupant density and the incidence of moisture problems. Other features, such as the type of heating system, were not found to have a significant influence.

Medical evaluation showed that the residents of these homes suffered more often from respiratory problems than residents of similar site-built homes included in the study. This appears to be related more to the high level of several pollutants in the homes than to the presence of fungal spores. However, no single individual contaminant could be identified as responsible for the irritant effect.

INTRODUCTION

Between 1970 and 1982, a company in Mercer, WI, manufactured more than 5000 modular homes. Approximately 3400 of these homes were erected in Wisconsin. In July 1986, public attention was drawn to the homes by reports of serious damage caused by condensation of moisture in wall cavities. The reported damage raised sufficient public concern that the governor of Wisconsin appointed a task force to investigate the situation and recommend corrective action. The task force published a manual for homeowners (Merrill et al. 1986). The authors of this paper were members of that task force. In 1986, prior to the initiation of the task force investigation, the company completed bankruptcy proceedings and its assets were sold at auction.

There have been persistent concerns in the construction industry that construction practices that drastically reduce natural air exchange will result in decay and other moisture-related structural damage. However, published results from previous research have not unequivocally supported this concern. Prior to the case discussed in this paper, there had been only isolated reports of wall decay from winter condensation. Moisture damage has generally been traced to sources other than condensation (Tsongas 1980, 1986). A survey of 201 homes with moisture damage in Canada revealed that these homes had a much higher than average indoor relative humidity. The damaged homes also had a larger number of occupants than the average Canadian home (Canada Mortgage and Housing Corp. 1983). Nevertheless, the report concluded that siding and sheathing moisture damage appeared to be more strongly related to weather conditions than to indoor humidity conditions.

Controlled laboratory and field exposure tests have demonstrated the possibility of severe condensation in walls in cold climates but have not established a clear link with significant decay (Burch and Treado 1978; Burch et al. 1979; Sherwood 1983).

This paper presents information about a sample of homes in which instances of condensation-related structural damage have been confirmed. Information about the frequency and nature of the damage is presented as well as pertinent data on occupancy and other factors. This is followed by an analysis of the differences between homes that evidenced damage and those that did not. The relationship of air quality to health is discussed as well. The data were derived from site visits by the authors, a survey of homeowners, and sample studies of structural damage, resident health, and air quality. Conclusions are based on these data as well as the authors' professional judgment.

CONSTRUCTION DETAILS

The majority of the homes studied were in the rural northern parts of Wisconsin where the number of heating-degree days exceeds 8500 per year. The homes consisted

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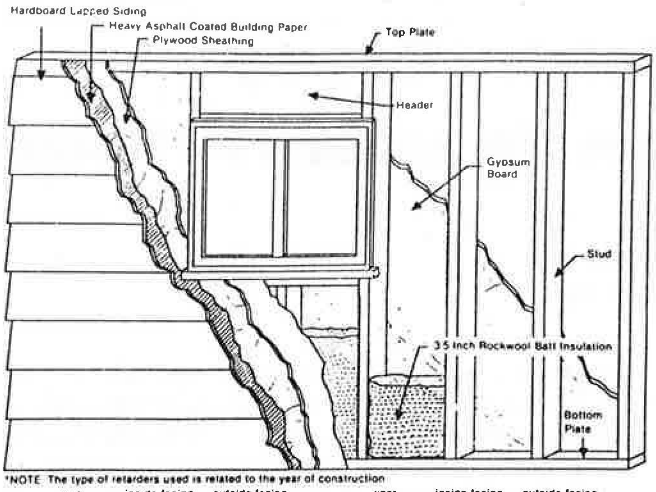

*NOTE The type of retarders used is related to the year of construction

year	inside facing	outside facing	year	inside facing	outside facing
1970-1974	kraft paper	kraft paper	1975-1976	kraft paper	kraft paper
1974-1975	polyethylene	kraft paper	from 1977	aluminum	kraft paper

Figure 1 *Wall construction of tri-state homes (ML87 5395)*

of a combination of factory-built panels and modules erected on an owner-prepared foundation.

A sketch of typical wall construction is shown in Figure 1. The interior surface material was 1/2 in (13 mm) sheet rock nailed to nominal 2- by 4-in (50 by 100 mm) studs. Mineral fiber insulation was installed between the studs. The insulation had an exterior kraft paper facing. The interior facing material was polyethylene, kraft paper, or aluminum, depending on the year of construction. The interior facing on the insulation was secured to the studs on the exterior side. The 1/2 in (13 mm) plywood sheathing was installed on the outside of the studs. For many homes, a layer of asphalt-coated building paper was installed over the sheathing. This was covered with hardboard lapped siding.

Insulated roof panels were supported by exterior walls and a center ridge beam to form a cathedral ceiling in most parts of the house. The roof framing usually consisted of 2- by 6-in (50 by 150 mm) lumber with the cavity completely filled with mineral fiber insulation. Soffit vents were present, with ridge vents less common.

It is impossible to be more specific because suppliers of the materials varied from year to year, and this resulted in variation in the exact materials used. The bankruptcy and sale of company assets also made it difficult to develop a complete and accurate picture of its construction practices.

SITE VISITS

Members of the task force visited a total of 12 homes in August 1986. Several of these homes had been reported as having the most severe damage. Homes that had not been the subject of previous damage reports were also inspected. In most cases, at least part of the siding had been removed, allowing observation of the sheathing. There had been claims that moisture was condensing in the roof sections and running down into the walls. The fact that ice dams had been reported by owners was cited to support this contention. Therefore, in several cases the cavities between the roof and ceiling were inspected for damage.

TABLE 1
Responses to Survey According to Year of House Construction

Year of construction	Responses	
	Number	Percent
1970	20	1.5
1971	45	3.3
1972	89	6.6
1973	111	8.2
1974	175	12.9
1975	142	10.5
1976	189	13.9
1977	195	14.4
1978	165	12.2
1979	87	6.4
1980	43	3.2
1981	15	1.1
1982-86	56	4.1
Unknown	24	1.8
Total	1356	100.0

The degree of damage varied. Several homes exhibited no significant damage, and the occupants did not report severe winter condensation problems. In several other homes, the sheathing was stained in limited areas. In other homes, the sheathing exhibited severe deterioration in isolated areas. In the areas of most severe damage, partial decay of studs was sometimes evident. In one home, there was significant damage to the top plate. This house was the only one in which studs had sufficiently deteriorated to warrant replacement.

The only evidence of damage in roof panels was associated with roof penetrations, such as vent stacks and chimneys. Damage most often appeared in the lower half of the exterior wall adjacent to the bathroom. There was also limited damage at the exterior corner of bedrooms and at the upper portion of gable end walls. Substantial interior damage was evident in only one home, where sheet rock on the cathedral ceilings of the bedrooms was bowed and corners of the bedrooms were severely stained. This house also exhibited the most severe exterior damage. Its construction was different from the other homes inspected in that it had electric baseboard heat, and a plastic (polyethylene) vapor retarder had been used under the

TABLE 2
Responses to Survey According to Floor Area of House

Floor area (ft^2)	Responses	
	Number	Percent
(Unknown)	128	9.4
<900	58	4.3
900-999	103	7.6
1000-1099	180	13.3
1100-1199	189	13.9
1200-1299	350	25.8
1300-1399	98	7.2
1400-1499	54	4.0
1500-1599	31	2.3
>1600	165	12.2

TABLE 3
Responses to Survey According to Occupancy

Occupants per household (No.)	Responses	
	Number	Percent
1	113	8.3
2	436	32.2
3	197	14.5
4	326	24.0
5	173	12.8
6 or more	90	6.6
(Unknown)	21	1.5
Total	1356	100.0

TABLE 4
Primary Heating System and Fuel in Homes

Heating system and heating source	Responses	
	Number	Percent[1]
Heating system		
Forced air	119	9
Hot water	1031	76
Wood stove[2]	282	21
Heat source		
Electricity	58	4
Wood	437	32
Gas	673	50
Oil	261	19

[1] Percentage of total number of responses (1356).
[2] Located in living space.

sheet rock. More detailed information on the damage and possible causes can be found in a recent article (TenWolde 1988).

SURVEY OF HOMEOWNERS

Survey Methodology

The task force mailed a survey to all known homeowners to assess the extent of the problem and gain additional information about potential causes of the damage. A cover letter from the governor's office accompanied the survey. Appendix A contains a copy of the survey and cover letter.

The survey included questions about the house, the household, and the health of household members. Questions were designed so that they could be answered without requiring the removal of any building component, such as siding. The questionnaire was developed under severe time constraints, which precluded pilot testing. The survey was mailed to more than 2500 addresses of original owners furnished by the company to the bankruptcy court. As a result of the inadequacy of the mailing list, more than 500 letters were returned as undeliverable. However, 1356 usable responses were received and analyzed.

Survey Findings

Tables 1, 2, and 3 show selected statistics about the homes and their occupants. More than half (63.9%) of the respondents lived in homes built between 1974 and 1978 (Table 1). Table 2 shows that the estimated floor area of more than half the homes was between 1000 and 1300 ft^2 (93 and 120 m^2). The average floor area was approximately 1200 ft^2 (110 m^2). Table 3 illustrates the distribution of family size among the respondents. Almost 58% of the homes had three or more occupants, and more than 43% had more than four. The average household size was 3.2 persons.

Statistics concerning the heating systems in the homes are displayed in Table 4. The majority of respondents had water distribution systems; few homes had a forced-air distribution system. Gas was the principal fuel. The questionnaire did not distinguish between natural gas and liquid propane gas. Almost one-third of the homes were heated primarily with wood. More than 68% of the respondents reported having a fireplace or wood stove, which was usually (73% of the time) located in the basement. Only 4% relied exclusively on electricity for heat.

Respondents were provided with a list of moisture problems and asked to indicate which, if any, they had noticed in their home. Almost 56% reported one or more current problems. Table 5 shows the relative frequency of the various problems. Caution must be used when drawing conclusions from these figures because, for each problem, between 25% and 32% of the respondents made no response.

Nearly two-thirds (63.3%) of the respondents reported using dehumidifiers in their home during the previous two

TABLE 5
Past and Current Moisture Problems

Moisture problem	Incidence of problem (number (%))[1]			No response (number (%))[1]
	Current	Past only	None	
Mold or mildew on walls or ceilings	365 (27)	56 (4)	586 (43)	349 (26)
Heavy condensation on windows	581 (43)	85 (6)	354 (26)	336 (25)
Warping, staining, or streaking of siding	357 (26)	44 (3)	556 (41)	399 (29)
Bowing or crumbling of walls or roof	195 (14)	19 (1)	709 (52)	433 (32)
Wet or damp basement	549 (40)	39 (3)	408 (30)	360 (27)
Ice buildup on roof	413 (30)	44 (3)	511 (38)	388 (29)

[1] Values in parentheses are percentage of questionnaires returned (1356).

years, but they did not indicate when (which season) they were used. Despite the high incidence of moisture problems, almost one-third (32.3%) of the respondents reported using a humidifier during the previous two years.

Survey Analysis

The analysis was designed to answer two questions:

1. Are signs of severe condensation on windows good predictors of other moisture problems?

2. Do occupancy, the type of heating system, or construction details affect the potential for condensation and decay?

Visual Indicators. To establish if signs of condensation on windows give a reliable indication of other moisture problems, we determined how often those problems were reported concurrently with heavy condensation on the windows. This, of course, does not prove any causal relationship, but it does indicate how likely one symptom is associated with another. Figure 2 shows the results. The moisture problem categories such as condensation or mold only include positive responses to that specific question. Thus, for this analysis, we assumed that those who failed to respond to a specific question did not experience that particular problem, along with those who specifically

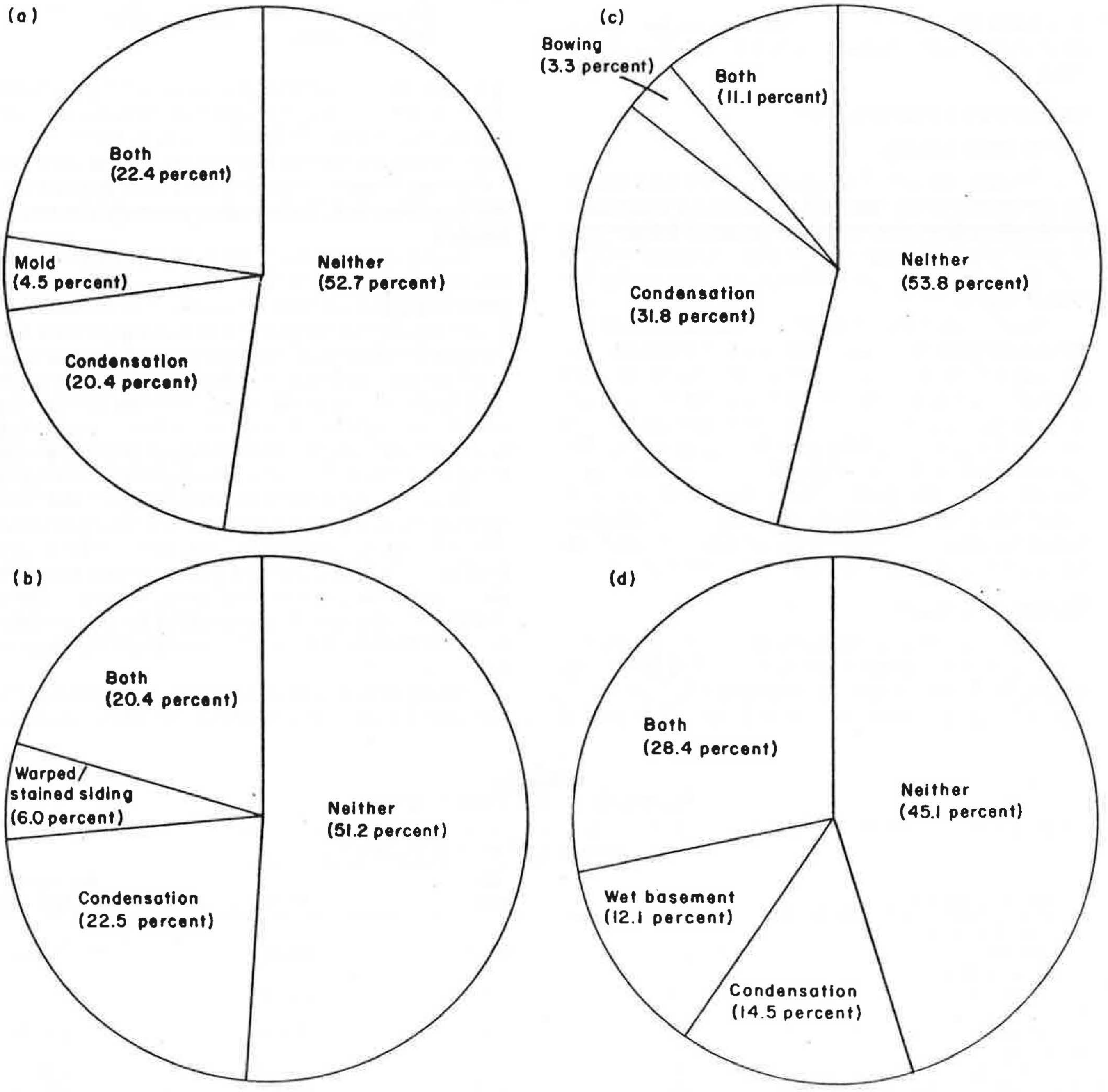

Figure 2 *Reported concurrent moisture problems: (a) current condensation on windows and mold or mildew on walls or ceilings, (b) warped or stained siding, (c) bowing or crumbling of walls or ceiling, and (d) damp or wet basement (ML88 5610)*

stated that they did not. Table 5 shows how many did not respond to each question.

Figure 2a shows that 42.8% of the respondents reported condensation and 26.9% reported mold. Only 4.5% reported mold without reporting condensation as well. This means that 83% of those who reported mold also had problems with heavy condensation. Conversely, of those with a condensation problem, 52% also reported mold. Condensation without mold was reported by 20.4%. These results suggest that mold indicates a more severe humidity problem than heavy condensation and that heavy condensation on windows may serve as an early warning of excessive indoor humidity.

Figure 2b relates the incidence of heavy condensation with reports of warped or stained siding. Of those reporting condensation, almost half (47%) mentioned siding problems. Only 6% reported siding problems without condensation (23% of respondents with siding problems). This suggests that the majority of siding problems were related to indoor humidity problems and that heavy condensation apparently is associated with an increased risk of damage to the siding.

The incidence of current condensation and bowing of walls or ceiling is shown in Figure 2c. A relatively small number of respondents (14%) reported bowing of walls or ceiling. Of these, 77% also reported heavy condensation on the windows. A stronger correlation was expected because a causal relationship was anticipated between condensation (indoor relative humidity) and bowing of the gypsum board. This suggests that other reasons for wetting of the gypsum board, such as voids in the insulation, roof leaks, or leaking from ice dams, may play a significant role. However, as with the siding, heavy condensation does raise the probability of bowing of the gypsum board on the walls or ceiling.

Figure 2d presents the concurrent incidence of condensation and damp or wet basements. Wet basements are reportedly often the cause of high indoor humidity and condensation. Forty percent of all respondents reported damp or wet basements. However, a substantial number of respondents (14.5%) reported condensation without a wet basement. This suggests that wet basements may help create indoor humidity problems but are by no means the only contributing factor. It may also be argued that a damp basement during winter is the result of a low ventilation rate and high indoor humidity; the basement is not allowed to dry out from high moisture conditions in the summer.

In summary, the responses indicate that heavy condensation on windows is a reasonably good indicator of the potential for other moisture problems, including staining and warping of the siding. Because heavy condensation is primarily related to high indoor humidity, this finding also supports the initial conclusion that the decay of the plywood sheathing in many of these homes was most likely caused by excessive indoor humidity during the winter, resulting in condensation in the walls. Conversely, the responses also suggest that when no heavy condensation occurred, other moisture problems were much less likely to exist. This implies that lowering indoor humidity is likely to be effective in eliminating most moisture problems. Usually, the most convenient and economic way to lower indoor humidity is through increased ventilation.

Factors Contributing to Moisture Damage. Using condensation as an indicator of other moisture problems, we correlated the incidence of condensation with other parameters such as the heating system, fuel used, and the number of occupants. We expected to see a lower incidence of condensation in homes with a forced air distribution system, due to a more even distribution of heat and moisture throughout the house and basement. However, Table 6 shows that forced air did not decrease the incidence of condensation on the windows. None of the heating systems seems to have a significant influence on condensation on windows. We expected that a wood stove in the living space or a fireplace would increase ventilation and therefore lower humidity and the chance of condensation. However, the responses indicate that homes with wood stoves or fireplaces had an average frequency of condensation. During our site visits, we noticed that the basement often served as a wood storage area. Storing wet wood in the house may explain the fact that we found no apparent decrease in relative humidity with wood stoves and fireplaces. Electrically heated homes tend to have lower ventilation rates than homes with chimneys, and in the past they have been reported to be more prone to moisture problems (for example, see Platts 1983). However, Table 6 does not show a markedly greater incidence of condensation in homes that relied solely on electric heat (many electrically heated homes also had a wood stove or fireplace).

Of those who reported condensation, 27% had used a humidifier during the previous two years. Undoubtedly, humidification contributed to any moisture problems in

TABLE 6
Incidence of Condensation with Different Types of Heating Systems

Heating system	Incidence of condensation (number (%))		
	Current	None	Total
Forced air	54 (45)	65 (55)	119
Hot water	436 (42)	595 (58)	1031
Wood stove in living space	118 (51)	115 (49)	233
Fireplace or wood stove	426 (46)	505 (54)	931
Electricity[1]	95 (45)	116 (55)	211
Electricity only	28 (48)	30 (52)	58

[1] Total number of households using electricity as the primary source. Some households supplemented electricity with a wood stove or fireplace

TABLE 7
Distribution of Occupancy Load Among Responses to Survey

Occupancy load[1]	Responses Number	Responses Percent
0-1	64	6.5
1-2	276	28.0
2-3	195	19.8
3-4	269	27.3
4-5	132	13.4
5-8	48	4.9
Total	984	100.0

[1] Number of occupants per 1000 ft^2 (93 m^2) of floor space.

those homes, but humidification was not a factor in the majority of homes with condensation.

One factor that proved to have a profound effect on condensation potential is occupancy load, the number of persons living in the household per square foot of living area as reported by the respondent. A number of respondents provided square footage responses that were outside the expected range of values. We excluded these values from the analysis by including only cases where the square footage value was between 800 and 1400. This included 80% of the cases in which data on square footage were available (see Table 2). Table 7 shows the distribution of occupancy load, and Figure 3 shows the incidence of moisture problems as a function of occupancy load; the problems included condensation on windows, warping of siding, bowing of sheet rock, mold, and condensation. Calculations confirm that with extremely low ventilation rates, indoor humidity can be very high from normal activities, with moderate occupancy load and without unusual sources of moisture. Nevertheless, Figure 3 also shows a significant number of moisture problems in homes with a relatively low occupancy load, indicating other causes for condensation.

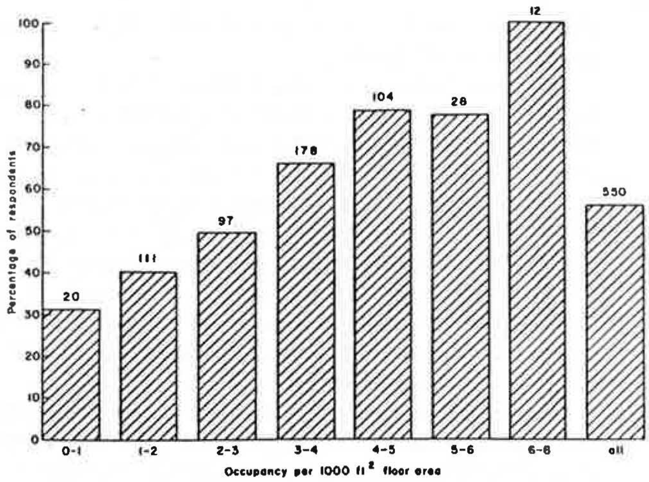

Figure 3 *Incidence of moisture problems as a function of occupancy load, expressed as percentage of total respondents in each occupancy load class. Numbers above bar are numbers of respondents reporting problems (ML99 5609)*

INSPECTION PROGRAM

Inspection Methodology

To gain a more reliable measure of the extent and nature of damage, a program was established to provide a free inspection for homeowners who completed a

TABLE 8
Estimated Degree of Damage in Initial Inspections

Percentage of inspected homes[1]	Degree of damage[2]
25	None No interior problems No symptoms of problems or damage to wall components
40	Symptoms but no damage Building paper and sheathing show symptoms of being wet at some time Materials not damaged
20	Minor damage Siding and sheathing only Small, spotty locations Up to 100 ft^2 (9 m^2) of damage
10	Moderate damage Mainly sheathing decay and delamination Little if any decay of studs or insulation but materials sometimes moist Most common at gable end and bath wall Typically 100 to 250 ft^2 (9 to 23 m^2) of damage
5	Severe damage Sheathing damage worst with some stud and insulation damage More locations of damage, including gable ends, bath walls, bedroom window area, outside walls of closets, and a few cases of lower roof damage Typically 250 to 400 ft^2 (23 to 37 m^2) of damage, with a few homes over 400 ft^2 (37 m^2) of damage

[1] Based on 533 inspections.
[2] Damage classifications are based on a consensus among inspectors on the typical area of damage associated with the listed problems.

TABLE 9
Location and Type of Damage in All 694 Inspected Homes

Building component	Incidence of damage by location (%) Bedroom	Bathroom	Kitchen	Dining and living rooms	None reported
Siding	14	12	7	8	72
Sheathing	13	10	6	7	70
Framing	2	4	1	2	85[1]
Insulation	6	7	3	4	78[1]
Windows	6	7	5	8	80
Roof	1	1	1	1	91[1]
Interior drywall	3	4	2	2	86[1]

[1] Percentages are lower than would be expected from the damage reports (that is, the sum of all reported percentages is less than 100%). This reflects the level of uncertainty or ambiguity about the actual condition.

postcard request form. The request form, together with information about the inspection program, was sent to all known Wisconsin owners of the homes. The inspections were performed under the direction of the state's uniform dwelling code coordinator, using experienced building professionals who were specially trained for this inspection program. In February 1987, a report on the first 533 inspections was published (Marx 1987), and some statistics in our article are based on this report. Eventually, 694 inspections were completed.

The inspection program did not provide a random sampling of the homes; therefore, conclusions about the extent and nature of damage in the entire population of the homes must be considered with caution. The inspection did not require that siding be removed before the inspection, and the inspector only removed siding in areas typically prone to damage. In those cases where the siding was not removed, it was impossible to determine with certainty whether there was hidden damage. However, siding was at least partially removed in 70% of the cases, either during or before inspection. Damage to the sheathing could be assessed with much more certainty with the siding removed. Damage to framing and insulation could be determined only if the sheathing was removed or severely decayed. In some cases, inspectors estimated the extent of damage from visual symptoms on the basis of their experience with other home inspections. Many homeowners preferred that the siding not be removed.

Inspection Findings

The inspectors estimated the extent of the damage from visual inspection and spot removal of the siding. Table 8 summarizes this assessment for the first 533 inspections. An estimated 25% of the homes inspected showed no signs of damage or interior problems. Only about 15% showed damage that involved more than scattered spots of siding or sheathing. These homes had from 100 to 400 ft^2 (9 to 37 m^2) of estimated sheathing damage as well as some deterioration of structural members and insulation. Significant framing decay was found only in the estimated 5% of homes with severe damage. A similar assessment is not available for the additional 161 inspections, but indications are that those inspections yielded very similar results.

Tables 9 and 10 show the locations of damage. Percentages in Table 9 are based on all 694 inspections and in Table 10 on the 485 homes from which siding was removed. The percentages in both tables are not very far apart, indicating that the inspectors were able to estimate damage from visual signs. Very few complaints about the accuracy of the damage assessments have been received from homeowners since the inspections. The tables confirm that siding and sheathing damage was most prevalent in bedrooms and bathrooms. Decay of the framing or insulation damage was unusual. The inspectors reported no damage in 78% to 87% of the homes, but it does not follow that the other 13% to 15% actually had

TABLE 10
Location and Type of Damage in All 485 Inspected Homes with Siding Removed

Building component	Incidence of damage by location (%) Bedroom	Bathroom	Kitchen	Dining and living rooms	None reported
Siding	18	15	9	11	69
Sheathing	17	12	8	7	69
Framing	3	5	1	2	87[1]
Insulation	8	9	4	4	79[1]
Windows	8	9	7	9	80
Roof	1	1	1	1	90[1]
Interior drywall	3	4	2	2	87[1]

[1] Percentages are lower than would be expected from the damage reports (that is, the sum of all reported percentages is less than 100%). This reflects the level of uncertainty or ambiguity about the actual condition.

framing damage. Reported framing damage in individual rooms indicates that a maximum of 9% to 11% of the homes sustained damage to the framing, but many of these homes had framing damage in several rooms. With severe damage estimated at 5% (Table 8), framing damage can be estimated at between 5% and 10%. Roof damage was also rare, probably less than 4%, although only 90% of roofs were reported as positively undamaged.

Of all the homes inspected, only 38% had any exhaust ventilation equipment. We believe that this factor, combined with the airtightness of the homes, contributed greatly to the excessive humidity levels in many of these homes.

AIRTIGHTNESS MEASUREMENTS

Methodology

Many of the recommendations of the Wisconsin task force, which were published in their homeowner's manual, were based on the hypothesis that these homes were unusually airtight and, therefore, experienced very low ventilation rates during the winter (Merrill et al. 1986; TenWolde 1988). This, in turn, led to the high indoor humidity levels reported by the homeowners. However, at the time of publication of the manual no actual measurements had been made to confirm this hypothesis.

The Wisconsin Division of Health had fan pressurization tests performed on randomly selected homes of this manufacturer as well as other homes of similar size in the same geographical area. In contrast to the manufactured homes, the comparison homes were generally constructed onsite, using conventional construction methods. The fan pressurization test yields information on the relative airtightness of a building, but it does not directly measure actual ventilation rates under normal air pressures experienced in service. Measurements were made in 73 of the manufactured homes and in 49 other homes. A fan pressurization technique was used as described in the ASTM E 779-87 Standard Test for determining air leakage rate by fan pressurization. The homes were tested with doors and windows closed, storm windows and doors in place and closed, and doors to unheated areas closed. Measurements were made with the homes pressurized as well as depressurized.

Findings

The manufactured homes appeared to be considerably more airtight than the other homes measured. The average air exchange rates for the sample of manufactured homes was 4.7 air changes per hour (ach) at 50 Pa of pressure. The average rate for the comparison homes was 9.3 ach. The range for the manufactured homes was also considerably smaller—2.4 to 6 ach for them and 2.6 to 31.2 ach for the other homes, at 50 Pa of pressure. Although ventilation rates cannot be directly calculated from these results, ventilation rates in the manufactured homes are likely to be substantially below those of other homes under similar conditions.

HEALTH AND AIR QUALITY STUDY

Methodology

One major concern of homeowners was that the presence of high levels of fungal spores was causing health problems for them. Spurred by these concerns, the Wisconsin Division of Health undertook an epidemiological study to evaluate the health of residents and the indoor air quality of the homes. A sample of 110 homes from this manufacturer was randomly selected. In addition, a control sample of 85 site-built homes matched by township with the 110-home sample was selected. Both groups of houses were similar in average floor area and occupancy. Residents of all homes underwent an extensive clinical evaluation, and a variety of environmental measurements were taken in the homes. The indoor air quality sampling took place from November 1986 through March 1987.

Findings

The results of the air quality measurements are summarized in Table 11. The mean level of fungal spores in the air of the manufactured homes was 314 colony-forming units (cfu) per cubic meter of air, while the mean for the comparison homes was 238. Both of these means are well below 1000 cfu/m³ of air; previous investigations into building-related illness have suggested that the airborne fungal concentration must exceed this level to be associated with health effects (Sieger et al. 1987a, 1987b). These test levels are consistent with the fact that allergen skin tests on residents showed no significant increase in

TABLE 11
Air Quality Tests of Manufactured and Comparison Homes[1]

Type of home	Airborne fungal spores (cfu/m³)[2]	Relative humidity (%)	Carbon dioxide (ppm)	Nitrogen dioxide (μg/m³)	Suspended particulates (μg/m³)	Formaldehyde (ppm)
Tri-State (n = 108)	314[3]	42*	1121**	22.7[3]	156*	0.017**
Comparison (n = 87)	238[3]	39*	847**	17.7[3]	85*	0.011**

[1] Source is Sieger et al. (1987a, 1987b). Values are expressed as means. Asterisks indicate statistical level of significance as determined by Student's t test: $^{*}p = .001$, $^{**}p = 0.001$

[2] Colony-forming units per cubic meter

[3] No significant difference between manufactured and comparison homes

sensitivity to a variety of common allergens, including four fungi.

The clinical evaluations of residents of the manufactured homes were significantly different from those of residents of the comparison homes. The former reported 11 times more colds, 50% to 100% more chronic coughs and other respiratory problems, and a four times greater incidence of burning eyes. Physical examinations confirmed the greater prevalence of various respiratory abnormalities among them. This increase in respiratory irritant symptoms may be partially explained by differences found in some of the air quality measurements. Mean relative humidity was 42% for the manufactured homes and 39% for the comparison homes, which is not a statistically significant difference. We consider 40% relative humidity as the upper limit for sustainable indoor humidity in northern Wisconsin. However, 19% of the manufactured homes had humidity readings above 50%, which is commonly considered excessive for cold winter conditions. Only 5% of the comparison homes had a comparably high level of humidity.

There was a much greater difference in mean carbon dioxide levels. The comparison homes had levels of 847 parts per million (ppm). The manufactured homes had mean levels of 1121 ppm. This is above the indoor air quality guideline of 1000 ppm set by the World Health Organization. The level of suspended particulates in the manufactured homes was also significantly higher (156 $\mu g/m^2$) than in the comparison homes (85 $\mu g/m^2$). Levels of nitrogen dioxide and formaldehyde were also higher. However, the levels were sufficiently low that irritant effects would not be expected. The fact that all the environmental measures were higher in the manufactured homes suggests that these homes had a much lower air exchange rate than that of the comparison homes.

CONCLUSIONS

Some of the following conclusions drawn from the results of the survey, site visits, inspection program, and health and air quality tests are by necessity limited to the specific group of homes and cold winter climate in this study. Other conclusions apply more broadly to moisture problems in general.

1. The evidence presented in this study demonstrates that winter condensation in walls can cause severe structural damage.

2. Winter wall condensation is more likely to damage the wall sheathing than the wall framing. Site visits and inspections revealed that decay of the wood wall framing occurred only if there was severe damage to the wall sheathing. Framing damage occurred in only an estimated 5% to 10% of the homes. Roof damage was found to be even less common.

3. Condensation and decay of the sheathing in the manufactured homes were primarily caused by an unfortunate combination of high indoor humidity and cold weather.

4. The manufactured homes were generally exceptionally airtight. This conclusion is based on the results of fan pressurization measurements.

5. Heavy condensation on windows appears to be a reasonably good indicator of other moisture problems. The presence of mold may be an indicator of more severe problems, such as structural damage. The majority of the problems with the exterior siding seem to be related to excessive indoor humidity, rather than moisture from the outside.

6. The type of heating and heat distribution system in the homes showed no correlation with the incidence of condensation. There was no evidence that houses exclusively heated with electricity suffered more damage than others.

7. The number of occupants per unit of floor area showed a strong correlation with the incidence of condensation and other moisture problems. The larger the number of occupants per unit of floor area, the greater the chance of moisture problems. More than 78% of households with more than four persons per 1000 ft^2 (93 m^2) of floor area reported one or more symptoms of moisture problems.

8. Residents of the homes suffered more often from respiratory problems. This appears to be related more to the higher level of several pollutants in the homes than to the presence of fungal spores. However, no single individual contaminant could be identified as responsible for the irritant effect.

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