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Analysis of Moisture Findings in the Interior Spaces of Finnish Housing Stock

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ABSTRACT
A grading system was developed to rate the moisture damage profile of dwellings and to study the relationship between moisture-induced indoor air problems and occupant health. A total of 630 randomly selected houses and apartments, built between 1950 and 1989, were visually inspected. Moisture observations were standardized into three damage levels. Thus, a system to classify the homes into three grades was devised. The two grades of homes associated with the highest levels of damage were graded as index homes.

Overall, 51% of the sample had some kind of moisture fault in them and one in every three homes (33%) was classified as an index home. The mean number of damage incidents in the index dwellings varied from 1.4 to 2.6. The mean number of damage incidents in the reference homes was 0.28. Prevalence of index dwellings was significantly higher ($p < 0.01$) in houses (38%) than in apartments (26%). There was no major difference in the prevalence of index buildings in houses built in any particular decade (30–35%). Moisture was observed in 28% of bathrooms, in 10% of kitchens, and in 17% of other spaces. Indoor relative humidity (RH) levels were low in most homes.

IMPLICATIONS
The grading system developed in this study provides a method of analyzing moisture findings and their intensity in dwellings. This knowledge is needed both for understanding the profile of existing moisture damage, particularly in cold climates, and for assessing how different levels of moisture damage relate to mold exposure and on occupant health. Therefore, the grading system may be useful both in assessing the condition of a building as a surrogate of exposure in epidemiologic studies, and as a decision-making instrument in assessing need for repair.

INTRODUCTION
Epidemiologic studies have linked exposure to mold in homes to respiratory illnesses and symptoms of the occupants living in these houses.[1-4] Mold growth can develop when moisture is allowed to accumulate on interior surfaces or in construction materials, for example, due to condensation or water leaks. The presence of excess moisture in structures has been used in the epidemiologic literature as a determinant of exposure[5] since it is the primary factor that leads to growth of microorganisms. In general, microbes may grow on any surface provided there is enough moisture and nutrients available. Therefore, such a moisture observation in an indoor environment can be used as an indicator of a potential microbial problem that may subsequently lead to exposure to microbial emissions.[6]

In Finland, the climate is cold for most of the year. Mean temperatures at the height of winter, February, vary from –6 °C in the south to –14 °C in the mid-interior and –10 °C in the north. The entire country experiences average monthly temperatures of 13–17 °C in the summer and less than 650-mm annual precipitation.[7]

In cold climates, transfer of heat, air, and moisture across a building envelope in response to a difference in thermal and moisture conditions can lead to accumulation of moisture on building parts, deposition of moisture on cold interior surfaces, and subsequently, may threaten their durability and functionality. However, the level of indoor air humidity during cold seasons is generally low because of the low moisture content in supported outdoor air. Therefore, problems related to condensation due to moisture migration across a building enclosure can be minimized by employing proper insulation with vapor and moisture barriers.

However, the absence of high indoor humidity does not exclude risks of moisture problems in a home. For instance, water leaks can occur due to defects in roofs, walls, foundations, balconies, and windows. Frost can also damage the building enclosure and increase the risk of leaks. Such defects could lead to moisture being introduced into heated spaces or locations within the enclosure that are difficult to detect, for example, in wall cavities of an external wall, and this could subsequently result in molds growing in hidden spaces.[8,9]

Liquid water originating from interior plumbing leaks, faulty washing machines, and the use of bathrooms and kitchens also pose potential moisture problems.[10] Building materials in spaces where there is a high water usage may retain high moisture contents even after the surrounding air humidity has returned to normal levels. This is also a crucial factor favoring microbial growth within interior materials.

The prevalence of moisture problems in private houses has been previously reported by Nevalainen et al.[11] The paper described both observations of moisture and moisture repairs. These analyses, however, were based on dichotomous groupings and did not take into account the number and severity of the observed moisture faults. The present paper quantifies these moisture problems in both private houses and apartments. The material is predominantly based on information collected during a survey, that is, only that damage in existence at the time of the survey was included. The aim of the study was to develop a grading system of dwellings that would provide a method of analyzing moisture findings in sequence. This knowledge is needed for understanding the profile of existing damage and for classifying residences in epidemiologic studies.

METHODS

Random Sample

Between 1993 and 1996, several surveys were conducted to assess the extent of moisture-related damage in the current national housing stock and to investigate the association between the presence of moisture and occupant health. A total of 630 private homes were randomly selected for inspection for signs of current or previous moisture-induced damage in their interior spaces. The selection comprised 390 houses and 240 apartments, which were drawn from 120 blocks of flats.

The sample was chosen to represent a cross section of the current Finnish housing stock. It was drawn from three large cities in three different regions: Oulu, Kuopio, and Helsinki. In all, 54% of the houses came from the Kuopio district (Kuopio and Kiuruvesi), and the remaining sample was drawn in equal proportions (23% each) from Helsinki and Oulu. All the apartments were drawn in equal proportions from all three cities: Helsinki, Kuopio, and Oulu. The regions represent the southern, central, and northern populated zones, respectively. The zones are not only geographically distinct, but also represent local variations with respect to the harshness of the winter.

Approximately three-fourths of the residential buildings in Finland were built after the 1950s.[12] Therefore, houses and apartments were randomly selected from building permits issued across four decades, from the 1950s through the 1980s. In each city, 30 houses from each decade were selected. An extra set of 30 houses from the 1970s and only one sample of 30 houses representing the 1950s were drawn from Kuopio. In each town, 20 apartments from 10 block units were randomly selected from each of the four decades. Each decade not only tells the age of the building but also represents a construction style, which in Finland has changed extensively since the 1950s.

On-Site Inspection

The field crew were civil engineers who were all given similar guidelines on how to seek out and identify signs of moisture condensation or water damage in locations within a home such as walls, roofs, floors, windows, ventilation, and plumbing systems. They recorded signs of water leaks, condensation on cold surfaces, detached interior coverings (e.g., linoleum and tiles), blistered painted walls, detached interior surfaces or wallboards, and any other signs that could be interpreted as moisture damage. No structural components were dismantled. A checklist was used to standardize the results based on the type and severity of the damage and to pinpoint the locations on which they were found.[11] Surface moisture recorders were used to identify moist spots. Temperatures and humidity levels, both indoors and outdoors, were recorded at the time of inspection.

Homeowners were asked questions about signs of current or previous moisture-related damage and repair actions taken to repair them. They were also asked about their indoor moisture-producing activities, such as the use of humidifiers, how they dry their laundry, and the number of people living in the dwelling. These data were recorded according to a checklist in an interview before the inspection.

Criteria for Grading Homes

The home spaces were classified into three domains: bathrooms, kitchens, and other spaces. All damage was tagged according to the domain. Furthermore, the damage in each domain was tagged with the surface on which it was found or the equipment that had induced the damage (e.g., vents). Interior materials were similarly registered with the type of damage associated with them. Finally, all of this information was coded and processed using SAS statistical software.

The degree of damage in a home was estimated by the severity of each damage incident according to the scale of the predesigned checklist,[11] including all signs of moisture damage. The damage could be located anywhere within the three space domains. Three groups of damage patterns were created as indicators of the degree of moisture damage within a home. The criteria were based on the most severe damage in the home, taking into account other observed damage incidents. The level of damage in a home was established by organizing incidents according to one of these three sets of damage patterns. Samples without any moisture observation and those with only minor observations were pooled together and classified as grade I. Samples identified with notable moisture patterns were classified as grade II, and those with significant problems were classified as grade III.

A home was classified into grade I if it fulfilled one of the following conditions during the inspection:

- No visible moisture damage was recorded.
- Minor moisture damage, such as colored stains on interior coverings that were caused by faulty appliances (e.g., washing and dishwashing machines) or pipe leaks, was observed, and no further consequences would be anticipated.
- Only one patch of deteriorated interior finish or covering, which needed drying, re-gluing, or fixing, was observed.

A grade II home met one of the following conditions:

- A single observation of a damaged interior structural component that needed opening, drying and renewal, or minor repair, was recorded.
- A single patch of deteriorated interior finishing or covering (as defined in grade I) was observed, along with other damage of similar severity. The other damage could be of the same level of severity or lower, but not worse.

A grade III home met one of the following conditions:

- A damaged interior structural component (as defined in grade II) was observed, together with other damage. The other damage could be of the same level of severity or less.
- A functional element that needed partial or total renewal was observed, with or without the presence of other damage. The severity of damage in this category had to be more significant than any damage appearing in grades I and II.

This grading system was designed to classify homes into a spectrum of grades, with grade I representing homes with no significant moisture problems, grade II homes with notable moisture problems, and grade III homes with significant moisture problems. Moisture findings in grade II and III samples were considered important, and therefore these homes were collectively referred to as index homes (index apartments and index houses). Grade I samples were considered as reference homes, that is, samples predominately free of moisture problems.

RESULTS

Prevalence of Moisture Observations

At least one moisture observation was made in 54% of the houses and 45% of the apartments. Relatively more houses than apartments had signs of moisture. Table 1 shows the results of houses and apartments divided into the grades separately.

The overall distribution of homes for index (grades II and III) and reference (grade I) homes are presented in Figure 1. These findings indicate that grade II and III homes made up 33% of the dwellings inspected by our crew, and that 38% of the houses and 26% of the apartments were in the index category. A statistically significant difference ($p < 0.01$) was observed between the distribution of houses and apartments into the index and reference groups.

Figure 2 shows the distribution of each grade of houses and apartments according to which decade they were built. The results indicate that houses with the most moisture observations were built in the 1960s and 1970s, while apartments built in the 1950s and 1980s had the most moisture observations. In general, about one in every two homes built between 1950 and 1989 had a sign of moisture, and the percentage of index homes among the samples ranged from 30 to 35%.

Number of Damage Sites in Different Grades of Homes

The mean number of damage sites in graded houses and apartments is shown in Figure 3. The mean number of damage sites in grade I houses and apartments was 0.28, collectively. The mean number of damage sites in grade II houses and apartments was 1.4 and 1.7, respectively, whereas in grade III it was 2.4 and 2.6, respectivly. The mean number of damage sites in grade II and III homes according to when they were built is presented in Figure 4. Moisture observations were spread in relatively equal proportions among homes built throughout study period, although the 1960s and 1970s had slightly less than the average values.

Table 1. Distribution of graded houses and apartments and 95% CI for an observation of grade II or III (index) homes.

	Reference Homes	Index Homes			
	Grade I	Grade II	Grade III	Index Homes	
	N(%)	N(%)	N(%)	N(%)	95% CI
Houses	243 (62)	89 (23)	58 (15)	147 (38)	33–43
Apartments	177 (74)	28 (11.5)	35 (14.5)	63 (26)	21–32

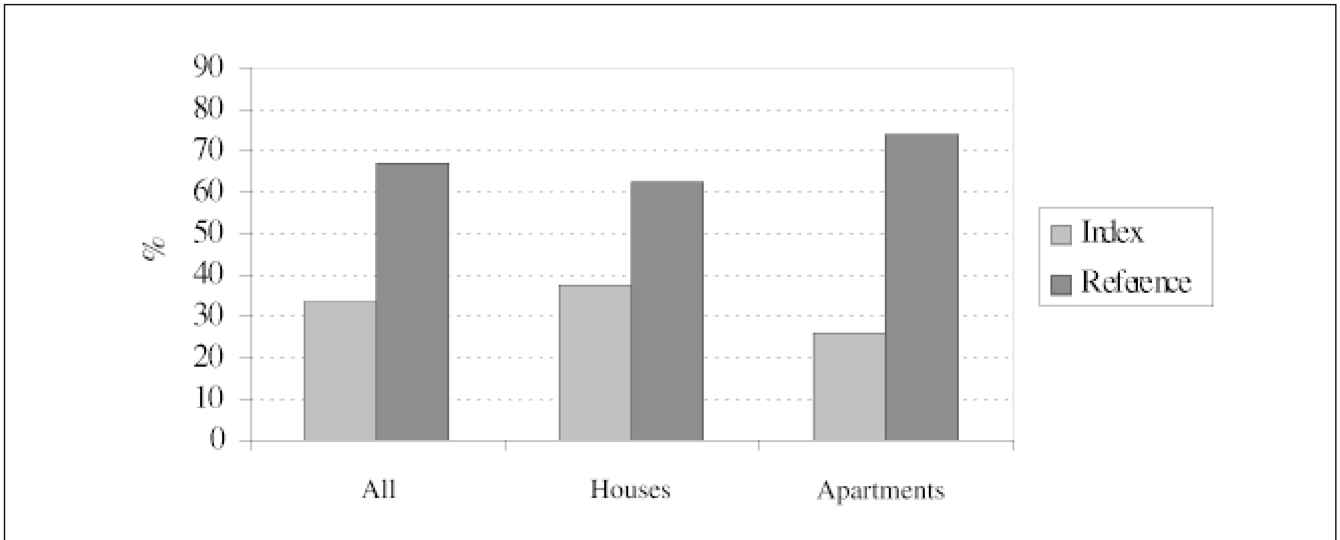

Figure 1. Percentage of reference and index homes in the Finnish housing stock according to dwelling type.

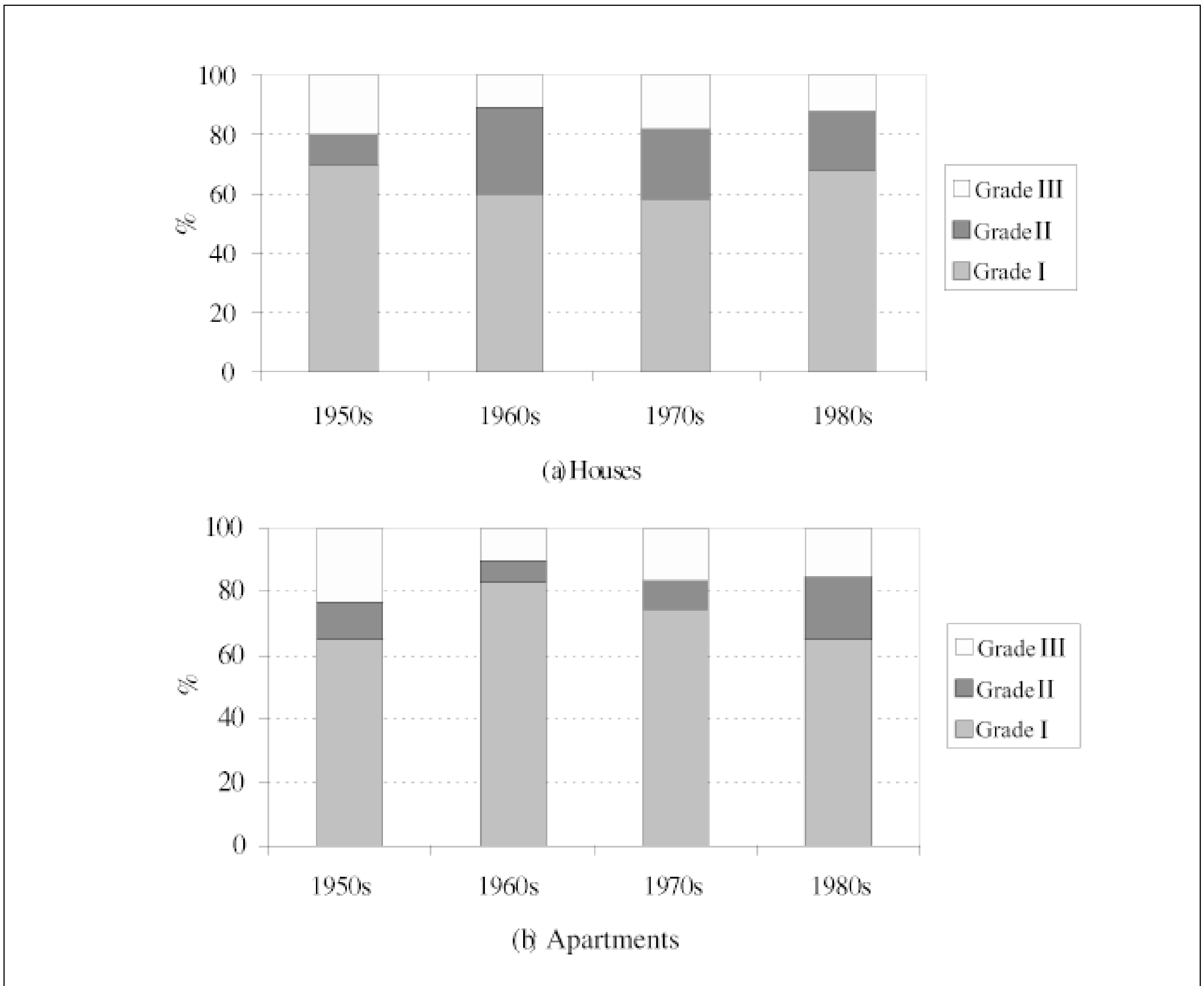

Figure 2. Distributions of graded (a) houses and (b) apartments into the decades during which they were built.

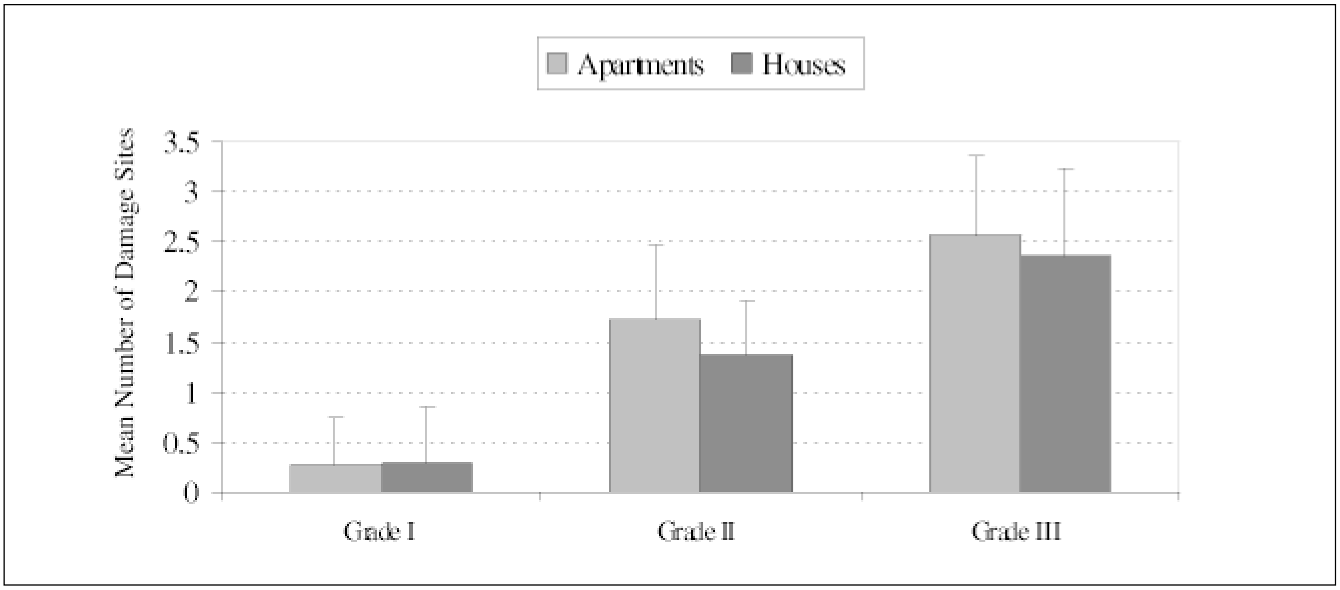

Figure 3. Mean number of damage sites in each grade of houses and apartments.

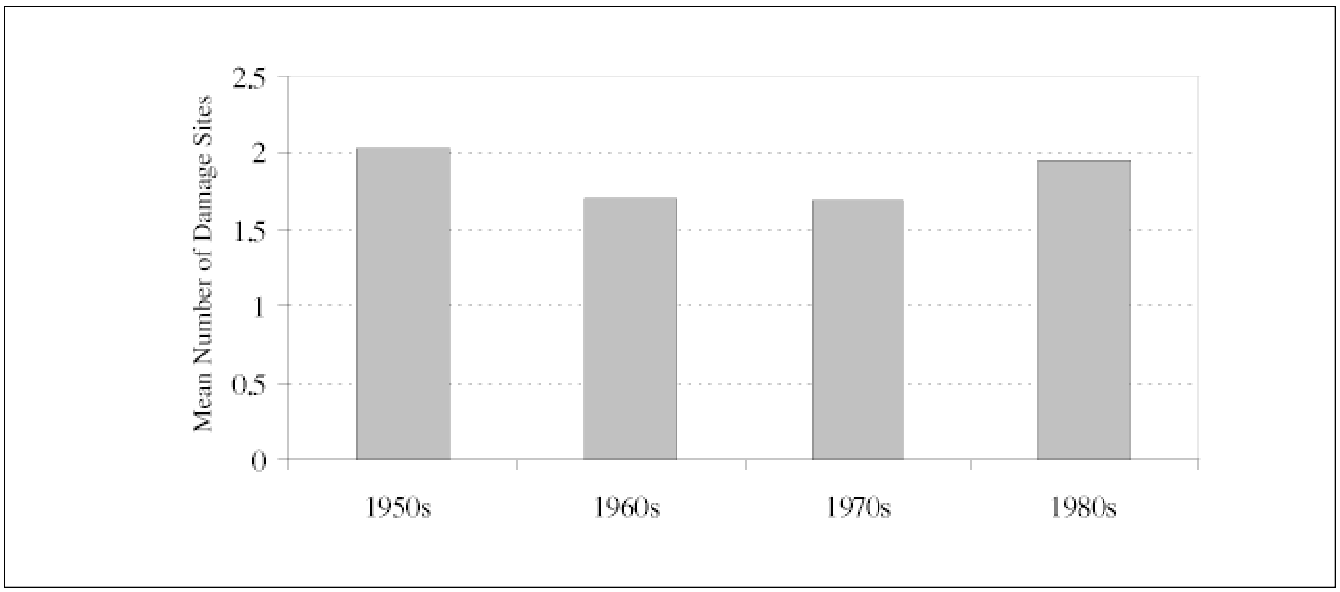

Figure 4. Mean number of damage sites in homes in grades II and III according to the decade in which they were constructed.

Distribution of Damage According to Domain Spaces and Structural Assemblies

The presence of moisture observations in interior spaces and structural components is presented in Table 2. About half of the grade III homes showed signs of moisture damage in both the floor and roof structures. Moisture problems in bathrooms or toilets were prevalent in the homes. Overall, 28% of the inspected dwellings had some sign of inappropriate moisture in the bathroom. The grading system filtered samples so that the percentage of the homes with moisture observations in bathrooms in grades I, II, and III were 12, 51, and 73%, respectively. Moisture-induced damage in the bathrooms was found in 74% of the index apartments and in 55% of the index houses. This figure of index homes with moisture observations in the bathrooms accounted for 20% of the overall sample of the apartments and 20% of the houses. Furthermore, 20% of the apartments had an extra bathroom or toilet, and the proportion of moisture observations was 10% higher in these homes.

Observations in the bathrooms of apartments were almost exclusively restricted to damage on the floor and wall covering. Problems on walls and floors of the overall apartment sample were seen in 15 and 18% of the apartments, respectively. Plumbing leaks were not common in the bathrooms. We also checked if the materials used in

Table 2. Distributions of moisture observations into different locations and spaces of the homes.

Location: Category (*N*)	Floors %[a]	Walls %[a]	Plum %[a]	Roofs %[a]	Wind %[a]	Vents %[a]	Bath %[a]	Kitch %[a]	Other %[a]
Grade I (420)	5	7	4	4	2	1	12	2	7
Grade II (117)	22	29	11	33	11	8	51	22	26
Grade III (93)	48	53	27	42	19	16	73	26	48
Houses (390)	12	18	10	21	4	6	28	9	14
Apartments (240)	19	18	7	-	11	2	29	10	21
1950s (90)	28	11	10	8	3	13	26	14	20
1960s (150)	8	19	8	12	1	5	30	9	20
1970s (220)	12	15	10	23	7	6	26	8	13
1980s (170)	18	24	7	11	6	6	31	10	17
All (630)	15	18	9	15	7	5	28	10	17

Note: *N* is the sample size; Plum = plumbing, Wind = window frame, Vents = exhaust vents, Bath = bathroom, Kitch = kitchen, and Other = spaces other than kitchens and bathrooms; [a]Homes (%) with moisture fault in this location/facility.

the bathrooms of apartments contributed to the number of moisture observations, but this was not conclusive because such a high proportion of apartments used the same kind of covering materials (wall and floor tiles). However, a small portion of apartments that used plastic wall and floor linoleum usually showed no visible moisture damage.

The most common wall materials near the water tab in the bathrooms of the apartments were concrete (61%) and brick (24%). Unusual moisture was observed in 12% of the bathrooms with concrete walls, in 9% with brick walls, and in 20% with building board covering. A few apartments had bathrooms made of prefabricated metallic sheathings, and they did not appear to have any problems.

About 10% of the homes were reported to have a moisture problem in the kitchen. The occurrence of moisture damage in the kitchens was 33% in index apartments, 20% in index houses, and 4% in reference homes. Plumbing leaks caused almost all problems in kitchens. There was little damage on kitchen walls or windows, or damage that could be attributed to appliances. There was no damage found on kitchen floors, ceilings, or exhaust ducts situated in kitchens.

The final domain was made up of spaces such as living rooms, bedrooms, closets, porches, and basements. Damage in this domain was found in 17% of the homes. Half of grade III homes and one-fourth of grade II homes were found to have at least one spot of damage in spaces other than bathrooms or kitchens. Apartments had a higher percentage of this kind of damage than houses in each grade of homes had. The overall frequency of moisture observations in this domain was higher than the observations reported in kitchens, but less than that encountered in bathrooms (see Table 2).

Relative Humidity Measurements and Moisture Content

Figure 5 shows plots of calculated indoor moisture content (g/m^3) against outdoor temperatures in 480 homes. The recordings are based on relative humidity (RH) measurements during the inspection visit. RH recordings in these homes at the time when outdoor temperatures varied from –30 °C to +30 °C showed that ~85% of the houses and 60% of the apartments had an RH between 20 and 45%. In all, 20% of the homes had an RH higher than 45%, but only 3% of them showed levels higher than 60%.

Twenty-five percent of homeowners reported frost or condensation on windowpanes. One-third of the reported cases occurred between the windowpanes; otherwise, they were on the inside pane. Occupants of homes in the two coastal cities, Helsinki and Oulu, reported 10% more condensation or frost on windowpanes than those living in the inland town of Kuopio reported. In grade II and III homes, condensation was reported 10% more frequently than it was in grade I homes.

DISCUSSION

Analysis of Moisture Observations

Our grading system screened and sorted the sample of homes according to the number and estimated severity of moisture damage found. The homes were allocated into grades I, II, and III, so that grade I contained no or minimal moisture problems while grade III contained the most significant accumulation of damage. Even though 54% of the houses and 45% of the apartments were found to have some sign of unusual moisture, only 38% of the houses and 26% of the apartments were graded into the category of index homes with significant moisture damage. The grading system in effect classifies the homes so that the risk of moisture damage-induced

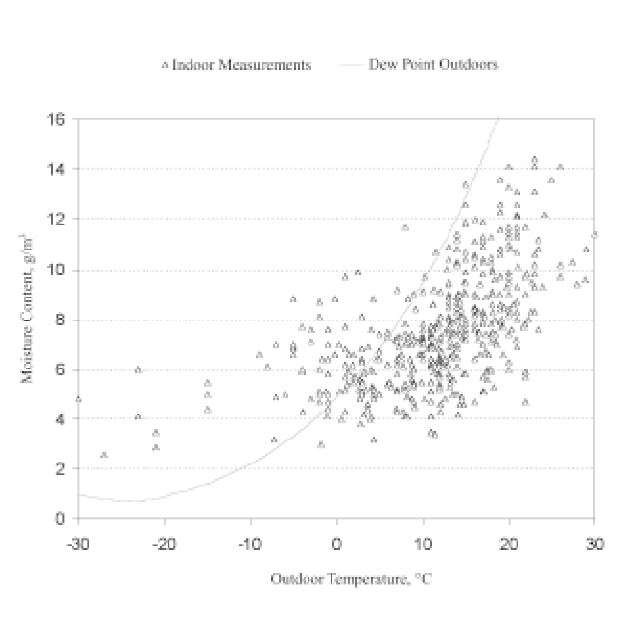

Figure 5. Indoor moisture content vs. outdoor saturation temperature curve based on indoor humidity recorded in 480 homes at the time of inspection. The curve indicates a border along which moisture would condense if it came into contact with a cold surface with temperature equal to the outdoor temperature.

exposure increases with grade. Therefore, grade II and III homes represent a set of homes with observations of moisture sufficient to cause concern. These homes were identified in all types of dwellings drawn from all regions and built in all postwar decades. Thus, they are representative of current Finnish housing stock, construction styles, and climate.

The proportion of index houses was significantly higher than the corresponding proportion of apartments. However, index apartments had more cases of damage per home than index houses had. Thus, the lower percentage of index homes among apartments did not mean that apartments were free of moisture problems. It may indicate that moisture problems were present in both houses and apartments, but much of the damage in apartments was not considered as serious. In addition, potential risk locations of moisture problems in buildings' indoor-outdoor contact areas (e.g., roof, outer walls, and basement floors) occur more frequently in houses than in apartments.

Between 49 and 52% of all the homes in the four decades had at least one sign of moisture. Our grading system showed that index homes were rather uniformly dispersed (30–35%) over these decades and that even though there were more index observations among houses from the 1960s and 1970s, the mean numbers of damage sites in that set of samples were, nevertheless, lower than in other decades. One factor that could explain this finding is differences in constructional styles taking place with time. In addition, buildings of different ages are in different phases of the renovation cycle.

Apartments were drawn from blocks of flats that contain a number of small apartments (30–100 m^2), while the sample of houses had bigger dwelling spaces (70–200 m^2). It should be pointed out that moisture damage was observed in only 17% of dwellings in locations other than bathrooms and kitchens, so the effect of room size seems to be minimal compared with the effect of the water load. On the other hand, once a material has been contaminated by microbial growth, the distribution and extent of the exposure may be influenced by the size of the facility and other factors, such as the efficiency of ventilation.

Moisture observations on walls were detected from both houses and apartments. They were particularly prevalent in homes built in the 1960s and 1980s. External wall structures in ~85% of apartments were made of concrete materials, while ~90% of the corresponding houses consisted of a timber structure. It is possible that these two types of materials disintegrate over the years in different ways due to moisture-related stresses, thus affecting their ability to withstand the elements of external moisture.

Only 12% of the homes in this study had basements; most of the below-grade moisture problems associated with basement structures were avoided. Many of the houses drawn from the 1950s and a few from the 1960s had basements that were converted into living spaces. Water could have penetrated through the walls of these basements from the ground, damaging interior wall finishes and fasteners, since the basements were originally not designed as living spaces and, therefore, appropriate waterproofing and other structures may not have been incorporated.

The observations associated with external sources were, in general, serious and identified in all types of homes, decades, and regions. Equally widespread were homes with damage caused by occupants' activities, plumbing leaks, or faulty equipments. Most of these problems were observed on floors, particularly in bathrooms.

Construction defects or errors were found on the building envelope that allowed water to penetrate into the interior, for example, damage on the roofs, broken-down gutters, faulty downspouts, poorly constructed roof overhangs, and poorly shaped ground surfaces that allowed water to pool toward the foundation of the building. Other problems were due to aging or corrosion of building materials and lack of maintenance. External leaks appeared on the inside on sites including ceilings, wall joints, window frames, and joints to vents extending through the envelope.

The material included only visible moisture observations, that is, visible changes or signs on materials without any dismantling of structures. Damage in hidden locations, for example, due to condensation or leakage inside structures, may not have been visible. Moreover, these observations represent only the figures reported by inspectors and do not take into account those cases where the damage was repaired. Therefore, this grading system excludes exposure from previously repaired structural damage. It also fails to take into account the time factor of exposure. The subjectivity of the method and the fact that repairs may or may not have eliminated the exposure mean that the estimates obtained in this study may be conservative.

Since different people from each of the cities carried out the investigations, it could be expected that there would be differences in the way each team judged the severity of similar damage. Such a difference could eventually affect the distribution of homes into grades. Nevertheless, it can be concluded that moisture problems in homes, when the index homes were taken as problem indicators, were currently found from both houses and apartments. This concept is further reinforced by statistical tests [95% confidence interval (CI)] that showed the spread of index homes throughout the country to be within a range of 21–32% for apartments and 33–43% for houses.

Findings of Air Moisture and Relative Humidity

This topic was evaluated because the characteristics of damp housing are often associated with high levels of humidity in the indoor environment.[13] According to our findings, this does not apply in the northern climate of Finland. Data of current humidity were gathered in all the dwellings, but without performing any long-term monitoring. These data were used to calculate the actual moisture content in both indoor and outdoor environments, as well as critical values.

Only 12% of the houses had higher than 45% humidity, and in none of the houses did the humidity exceed 60%. Thirty-three percent of the inspected apartments had higher than 45% RH, and in only 8% did it exceed 60%. These findings indicate that it is uncommon to have moist air indoors in Finland. However, variations might have existed if a long-term measuring system had been adopted or if special cases like the amount of moisture generated by the occupants had been considered.

A total of 25% of the occupants reported surface condensation on their windows. Windows are generally the first cold surfaces indoors where condensation appears when the RH rises or when the surface temperature drops sufficiently. Such condensation may also imply poor air circulation, especially if it occurs between window glazing, and it can cause deterioration of wooden window frames.

Even though outdoor air may approach 100% RH during the cold season, its moisture content is usually very low. When cold outdoor air replaces indoor air, it warms up and its RH drops significantly. Condensation between windowpanes implies that indoor air, containing higher moisture content than outdoor air, can penetrate into the window compartments and condense on cold windowpanes. Thus, thermal bridges and the air exfiltration through other leakage paths in the building enclosure are more likely to cause both surface and hidden condensation on windows, wall cavities, exhaust ducts, and attic spaces. However, newer dwellings in Finland are often insulated from inside with vapor barriers along the heated space. Good construction workmanship is crucial in avoiding air leakage across the envelope that could result in concealed condensation, a promoter of hidden mold growth.

The findings of this study indicated that most moisture problems occurred in bathrooms or as leakage through the envelope in both newer and older buildings. This emphasizes the importance of good design, maintenance, and housekeeping as prerequisites for attaining a good indoor environment. These findings also indicate that even though moisture preventive measures are generally incorporated into the building code in Finland, they do not invariably prevent moisture from entering the building, regardless of its age. Although RH levels in most homes were low, there is a need for further research to establish the major sources of moisture in indoor environments and the behavior of heat, air, and moisture indoors in response to climatic changes and/or mechanical systems that regulate the indoor climate. Further investigations are also needed to study moisture condensation within structural assemblies and in attic spaces where structural ventilation is important, and to verify the moisture load that structures should be able to tolerate.

CONCLUSIONS

The grading system introduced in this study demonstrated that most homes had been subjected to different levels of moisture damage, the levels of which varied in severity and according to the number of places where moisture damage was observed. Therefore, there is a need to assess how different levels of moisture relate to mold exposure and their effects on occupant health. In this respect, the grading system can be used (1) to assess the relationships among degree of damage in a home, exposure, and health of the occupants; (2) to identify spaces or rooms with high risks of moisture damage; and (3) as a statistical tool in assessing risks of exposure to moisture-induced problems in buildings.

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