# Case Studies of Moisture Problems in Residences

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*by George Tsongas[1]*



## Purpose of the Chapter

The purpose of this chapter is to provide a survey and overview of the results and findings of case studies of moisture problems in buildings. By case studies is meant any field study or pertinent and realistic laboratory study dealing with some aspect of actual moisture problems in buildings. Moisture modeling studies are not included. The chapter describes both research and studies published in the open literature as well as studies conducted by the author. An effort has been made to avoid hearsay, 'conventional wisdom and other noncredible evidence with no factual basis. Most of the emphasis is on relevant U.S. and Canadian studies or experience.

## Types of Case Studies Reviewed

The focus is on case studies of shell-dominated residential-type buildings because relatively little published information is available on moisture problems in other types of buildings. The findings for residences may be appropriate for light commercial buildings that act like residences but probably not for heavy commercial or industrial buildings. A distinction is made between older existing buildings and newly constructed buildings. Another distinction is made between studies of buildings in northern climates where the major emphasis is on winter heating and buildings in southern climates where the emphasis is on summer cooling. There are fewer published studies related to summer cooling moisture problems. There are also fewer unpublished case studies cited, in part because the author is more familiar with northern climates. While both laboratory and field studies have been surveyed, the emphasis is on field results of actual buildings. Relevant field tests of unoccupied test huts also have been included. Finally, studies are presented that identify excess moisture problems as well as those that deal with moisture control strategies.

## Classification of Moisture Problem Case Studies

For organizational purposes, moisture problem case studies have been broken down into three separate categories: (1) indoor excess moisture problems, (2) exterior excess moisture problems, and (3) excess moisture problems inside exterior walls. Moisture is always present in buildings, but the levels may be low enough so that there are no associated problems. The term excess moisture refers to situations where moisture levels are high enough for problems to occur.

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When and if they exist, moisture problems within walls usually have the most serious effect on the structure, although they tend to occur relatively infrequently. On the other hand, excess moisture problems and associated biological contaminants inside homes can dramatically affect the health of the occupants, and such problems are rather commonplace. However, until the recent concern over indoor air quality, indoor moisture problems had not received much serious research attention.

*Indoor Moisture Problems*

Moisture problems that occur within the heated indoor space include: mustiness, dampness, and odors; condensation on windows and sweaty pipes and toilets; window sill staining and damage from excess window condensation; mold, mildew, and stains on surfaces; and basement dampness and leakage Water vapor in indoor air will condense on surfaces whose temperature is below the dew point temperature of the indoor air. For indoor air at 70$^{o}$F (21$^{o}$C) and 50% relative humidity, the dew point temperature is about 50$^{o}$F (10$^{o}$C). During the winter, surfaces such as windows are often cooler than the dew point temperature of the indoor air such that condensation will occur. Surface condensation such as window condensation is most prevalent during the coldest outdoor weather.

There is a definite influence of weatherization on the incidence of surface condensation. Adding insulation or storm windows helps reduce condensation because surface temperatures are warmed, whereas house tightening hurts because it increases the indoor moisture levels. In fact, weatherizers have become so good at house airtightening that the incidence of moisture problems is dramatically increasing in weatherized homes.

In order for mold and mildew growth to occur, the mean monthly relative humidity of the air next to the surface must be about 80% or greater [1]. This means the local indoor air must be fairly humid, with a relative humidity value generally greater than about 60 to 70%. The latter value is somewhat lower because indoor air is usually warmer than the surface temperature. Mold and mildew occur on cold surfaces where the relative humidity is highest, such as those caused by missing insulation or thermal bridges (local areas that are poorly insulated). It is typically noted on inside surfaces of window frames and exterior walls and ceilings.

The incidence of mold and mildew and other problems related to excessively high indoor relative humidities is extremely important because it has recently been connected to biological contaminants that are just now being recognized as causing significant health problems [2,3]. Moisture-related contaminants, including allergens that cause allergic reactions and pathogens that cause respiratory infections, are apparently on the rise, in part because of increased emphasis on house tightening and in part because of better recent recognition of the health problems along with improved diagnosis. There is a range of indoor relative humidities that promote optimum health of the occupants. One study [3] suggests 40 to 60%, but many building science and health professionals believe the range perhaps should be slightly lower (say 30 to 50%) to avoid the growth of biologicals (such as dust mites) and associated health problems (such as asthma).

Basements are included in the 'indoor' category because they often are intentionally heated and many times are unintentionally heated. Furthermore, they often are well connected to the main living space from an air movement (and hence moisture) point of view. Basement dampness and leakage is usually caused by improper ground grading near the foundation, inadequate foundation drainage, leaky foundation walls, or poor flashing details. Often moisture in the ground around a basement is absorbed into the concrete and wicked by capillary action to the inside surfaces of the basement walls where it evaporates into the interior air space the concrete surfaces often appear dry because of the evaporation I. This situation is exacerbated by collection of rainwater next to foundations where downspouts do not drain into a sewer or other suitable outfall.

### Exterior Moisture Problems

Exterior parts of the house include all areas outside of the heated living space, except for walls which are classified as a special category because of the considerable interest in them. Exterior problems that can be moisture-related include: roofing and/or attic condensation and frost; roof wood decay-; blistering and peeling paint: wood siding shrinkage, cupping, and cracking; hardboard siding buckling; plywood siding delamination: condensation and decay in crawl spaces; and basement leakage due to improper grading or inadequate drainage.

Roofing and attic moisture problems are typically caused either by leaks or because moist indoor air is leaking into the attic. The major cause of some of these problems is often not related to excess moisture. For example, peeling paint is often caused by improper surface preparation or painting when it is too cold, and hardboard siding buckling is often caused by improper nailing.

### Moisture Problems Inside Exterior Walls

Excess moisture problems inside exterior walls include high wood moisture contents (which by itself may not be a problem) and wood decay (sometimes called dry rot) and subsequent structural damage. Wood decay is caused by a fungal growth. The conditions required for the fungal growth are warm temperatures (24 to 33$^{o}$C [75 to 90$^{o}$F] is optimum, and there is no growth below 10$^{o}$C [50"F]). high wood moisture content (greater than 30%, with no growth below 20%), and exposure to air [41. Wood normally will not decay in winter because the conditions are not met In the summer, wood normally dries out except when leaks exist such as roof or siding leaks that wet the wood.

## FIELD STUDIES OF INDOOR EXCESS MOISTURE PROBLEMS

### Older Existing Homes in Northern Climates

*The Iowa Moisture Problem Survey*

A survey of 334 Iowa households was conducted during 1988 to obtain baseline data on housing characteristics and energy efficiency to assess the incidence of moisture problems and to identify any relationships between the occurrence of moisture problems and house or energy characteristics [5]. Residents typically did not recognize problems caused by excess moisture in their homes (only 17% did). After definition (once prompted about specific types of problems), 98% of the residents reported at least one type of moisture problem. That is a higher incidence of moisture problems than ever seen elsewhere.

The most common types of moisture problems were: moisture condensation on windows (62%). exterior paint peeling (4 1%), staining of interior window frames and sills (3 1%), and mildew on walls/ceilings or in basements/closets (23%). Other problems identified were: decay/rotting of interior window frames/sills (20%), moisture/mildew problems in summer (18%). frost/condensation on walls/ceilings (13%), and interior paint peeling (10%). Moisture problems occurred particularly in energy "efficient houses. It was concluded that residents of single-family homes should continue to receive information on how to identify and correct any problems related to excess moisture.

The key finding is the very high percentage of reported moisture problems when the right questions are asked. Of course, the severity of the problems varies substantially. The more serious moisture problems require action, whereas some - such as minor window condensation - do not. Nonetheless, many of the older studies or surveys of moisture problems in homes dramatically underestimate the percentage of homes that supposedly have problems because the proper questions were not asked and those doing the asking did not understand the importance of asking the right question.

Furthermore, responses by occupants may be biased by the available literature that emphasizes that most houses are almost always good enough to resist moisture problems and that the occupants are the cause of most of the problems. This may strongly influence the response rate of people to any survey directed at the incidence of moisture problems. Thus, the Iowa survey findings are probably typical of most housing stock. Moreover, there are no published surveys of the incidence of moisture problems in multi-family housing; the situation there should be even worse for reasons that will be explained later in this chapter.

Finally, most agencies have focused on the durability issues associated with housing moisture problems. Only recently has it become clear that the very high incidence of moisture problems in homes is adversely affecting the health, welfare, and safety of the occupants. Thus, the need for action to resolve the moisture problems is probably more critical than has heretofore been believed. It is a problem that should receive considerably more attention.

*The Portland Study*

During the 1979-80 winter, the interiors of 103 older homes in Portland, Oregon [4792 degree days (DD)] were inspected and found to have an average indoor daytime relative humidity and temperature of 56% and 20.3$^{o}$C (68.5 $^{o}$F) [61. The average indoor relative humidity should be considerably higher in the milder fall and spring weather. Mold and mildew were noted in one third of the homes. While 73% of the homes had storm windows, window condensation was common. Only 46% of the homes used a bathroom exhaust fan and 91% lowered the thermostat at night, which can lead to increased nighttime relative humidities. While the homes were not particularly tight (blower test results averaged 16.2 ACH at 50 Pa, which corresponds to a natural infiltration rate of about three quarters), nonetheless there was a clear lack of satisfactory indoor moisture control that leads to high indoor humidities and resultant moisture problems in these older homes. Had these homes been airtightened, say as part or a weatherization program, the indoor humidities and problems would have been even worse.

*The Spokane Study*

The interior spaces of 96 older homes in arid Spokane, Washington (6835 DD) were similarly inspected during the 1962-83 winter and found to have an average indoor daytime relative humidity and temperature of 47% and 20$^{o}$C (67$^{o}$F) [7]. Mold and mildew were noted in 38% of the homes. While 96% of the homes had storm windows, 59% had condensation on windows and 36% had mold/mildew on window sills. In this sample of older homes, only 44% used a bathroom exhaust fan, while 61% lowered the thermostat at night, 27% had the clothes dryer vented indoors, 79% had no gutters or downspouts, and 43% (10 of 23) of the homes with partial crawl spaces did not have a ground cover. Even in this colder, drier climate, indoor moisture problems were very prevalent, indicating lack; of indoor moisture control.

*The Lane County Housing Authority Study*

In November 1984, six small existing rental residences operated by the Lane County Housing Authority, in Eugene, Oregon were inspected [8]. There were numerous complaints of moisture problems in the roughly 400 units in the complex; the six units visited were supposedly typical homes. The average relative humidity (RH) for all six units was 67%. Mold/mildew was observed in three of the six units. There was a minor amount of staining on window sills due to liquid accumulation from condensation; there was considerable window condensation in most of the units.

The bathroom and kitchen exhaust fans in many units were not working properly, some did not have fans, some fans were so noisy they were not used, and some occupants simply did not bother to use them. Clearly the occupants could not be relied upon to operate their fans to keep humidity levels at acceptable levels, especially since they did not understand the need to use exhaust fans to reduce the incidence of indoor moisture problems. Finally, the units had crawl spaces, but they had no ground covers. The Housing Authority decided to install 36 pint-per-day portable dehumidifiers with automatic defrost control in each of the 400 units to provide automatic moisture removal and control. As a result, the incidence of problems and complaints dropped dramatically. Since their installation, the units have reliably controlled indoor moisture.

*Canada Mortgage and Housing Corporation (CMHC) Study*

In 1982, CMHC engaged a firm to determine the types of residential moisture problems encountered in different parts of Canada. The resulting survey [9] included only moisture problems already reported by CMHC (NHA) inspectors, municipal inspectors, and local housing authorities. Indoor problems included mold and mildew, windows condensation and sill damage, and basement damage due to leakage and dampness. It was reported that there were at least 10,000 housing units in Canada which have both indoor and outdoor problems serious enough to cause financial loss. The number of homes then subject to moisture damage represented slightly more than 1% of the NHA housing stock. However, the incidence of such problems was expected to grow. Furthermore, the survey only accounted for those homes where damage was serious and reported because of the need for repair.

Thus, it is reasonable to assume that an even greater proportion of homes have unreported indoor moisture problems like mold and mildew and condensation damage that are primarily aesthetic rather than structural. It even 1% or the roughly one hundred million U.S. dwelling units have indoor moisture damage, then one million U.S. homes have indoor moisture damage. If the studies noted earlier are any indication, the existence of indoor moisture problems is much more widespread than 1% of the housing stock. Clearly there is a lack of adequate indoor moisture control in a large number of the existing U.S. and Canadian housing stock.

*Tri State Homes*

One of the most unique and severe cases or moisture damage in residential walls occurred in the large group of manufactured homes known as the Tri State Homes [10]. Between 1970 and 1987, more than 5000 such homes were manufactured, 3400 of which were built and installed in Wisconsin. After 1986, extensive wall wood decay was reported. The manufacturing company declared bankruptcy and was liquidated just before reports of moisture damage surfaced. As a result of the extensive wall wood decay and the associated publicity, considerable attention was focused on the attendant indoor moisture problems.

Site visits and home inspections, including a survey of homeowners and airtightness measurements, revealed that the homes were very airtight and poorly ventilated (no exhaust fans), leading to high indoor relative humidities. Mold and mildew inside the homes were common, but no more so than the older less airtight homes inspected in the Portland and Spokane studies [6,7]. 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. Once again, this was another example of the widespread existence of indoor moisture problems in existing homes. More importantly, it is a major case where indoor moisture problems were conclusively shown to cause an unhealthy environment for the occupants [11].

*Nova Scotia Interior Moisture Projects*

Between January and March 1988, 94 homes across Nova Scotia, Canada, of different sizes, ages, and styles with reported moisture problems were inspected [121: Moisture problems were caused by a combination of poor ventilation and high moisture penetration, although other factors were involved. Condensation and moisture damage were most common on window sills, trim, and frames (85 of 94 homes), at outside wall corners (44 homes), on ceilings (33 homes), in closets (25 homes), in bedrooms (24 homes), and in attics (23 homes). While the number of indoor problems was high, the weather is rather severe from a moisture point of view (cold, humid, and windy), especially since there is little or no dying period during the year.

In 67 of the 94 homes. the inspection identified one or more sources of moisture as a potential contributor to the moisture problem in the home. Sources of moisture generation in order of frequency were: stove top boiling, wood stored indoors, showers, leaky or wet basements or crawl spaces, unrented clothes dryers. kerosene heaters. and furnace humidifiers. It is well known that the last two can be important sources of health problems.

While many homes had ventilation systems such as bathroom fans (59 fans) or vented range hoods (30) or a central ventilation system (19), many were undersized (too low a rated capacity) or poorly installed and were not moving sufficient quantities of air. Ventilation improvements were the most often recommended method of resolving moisture problems.

Unexpected findings of the project included: (1) the number of homes with serious deterioration in attic areas (sheathing damage often due to a combination of high interior humidity combined with a flawed ceiling air barrier allowing moist indoor air to enter the attic because of the stack effect), (2) the lack of mechanical ventilation in homes less than two years old, and (3) the number of 20- to 30-year-old homes with high rates of air leakage suffering from mold and condensation problems.

The study concluded that interior moisture problems are relatively widespread, and that they occur most often in homes with electric heat and in newer homes. It also was noted that understanding of moisture problems appeared to be poor among homeowners and contractors, inappropriate remedies often were used, and it was difficult for homeowners to find information and advice about their moisture problems.

In Phase II of this project [3], homeowners were surveyed to determine actions taken to resolve moisture problems and the effectiveness of the actions. In addition, five houses had ventilation equipment installed to determine its effectiveness.

A number of conclusions were reached. First, homeowners who acted in a substantial manner upon staff recommendations succeeded in either solving or reducing the moisture problem in their home. More than 75% of the moisture problems encountered during the home inspections were resolved or reduced at a total cost of less than $750 per home with a combination of measures in the following areas: (1) improved mechanical ventilation, (2) reduced moisture generation, (3) draftproofing, and (4) better air circulation. Almost 50% of the homeowners were able to carry out the recommendations without assistance from a contractor. Homeowners did, however, find it difficult to locate proper ventilation equipment, such as 110 ft./min fans, wind-up timers, vent hoods, and other fittings in retail stores. In addition, the!: reported difficulty arranging contractors willing to install low-cost ventilation systems in accordance with good practice. Finally, it was determined that there was no significant increase in heating or electrical costs as a result of operation of the exhaust-only ventilation equipment in the five demonstration houses.

*Small Homes Council-Building Research Council (SHC / BRC)*

Home inspections were conducted on 670 single-family residences in Champaign County, Illinois, and the SHC/BRC compiled the results in order to determine how widespread and severe moisture damage was within the county 1141. All visible surfaces were inspected.

Moisture problems were distinguished from water problems such as roof leaks. The results showed that 5.4%, of the homes suffered major moisture damage - that is, damage which necessitated the repair or replacement of structural members (usually floor framing or attic sheathing). Another 3.5% suffered some sort of moisture damage to the visible surfaces, such as mildew, peeling paint, or deterioration of window finish, although that damage often was quite minor (for example, water spotting on ceilings or sign of condensation on windows). While the damage may be considered minor, the associated health effects may be serious. There was a clear correlation between the presence of evaporative sources of moisture, such as exposed soil in a crawl space. and damage to the structure. The evaporative sources are the concern of construction practice rather than lifestyle.

*Miscellaneous Legal Cases*

The cases described above have clearly demonstrated that indoor moisture problems are rather common in the United States and Canada. They are classic cases typically caused by an expected combination of weather effects, excess moisture sources, and lack of systems to control excess moisture. Most of the cases that will be described in this and the following sections are rather different in that there was some unexpected hut nonetheless commonplace cause, such as leaks.

Severe mold and mildew was found to exist on walls and carpets in a large number of the 72 units in a four-year-old condominium apartment complex in Seattle, Washington. The problem was initially blamed on lack of a wall vapor barrier. The actual cause was traced to a variety of external wall leaks that allowed rainwater to enter the walls from the outside, soak the cellulose wall insulation, and wet the walls and nearby floors. The water leaks occurred where the inexpensive caulk sealing external wood siding and stucco joints deteriorated with age and where exterior sealing was unsatisfactory.

In another Oakland, California case, a strong musty/moldy smell in a kitchen and its cabinets as well as warped hardboard siding were traced to an automatic lawn watering sprinkler that was misaimed and wetted the siding every day. While it is often difficult to recognize and diagnose, sometimes indoor moisture problems are caused by leaks and other external water sources. Incidentally, in the Portland Study [6] about 12% of the 103 homes had wall leaks that affected the moisture content of the wall cavity wood members or the cavity insulation.

A common example of external water sources often observed in the field by the author is where gutter downspouts are missing or not connected to a sewer or other suitable outfall. The water drains into the ground right next to the foundation, wicks through and under the concrete foundation, enters the crawl space ground, evaporates from the ground (typically when no ground cover exists), and enters the house as a result of normal air infiltration.

Based on unpublished test results from the Building Research Association of New Zealand, the author has estimated the rate of evaporation of moisture from 1000 $ft^2$ of normal soil to be about 100 lb per day, whereas the rate increases to about 400 lb per day if there is standing water covering the crawl space ground. These results are in agreement with other estimates [151. Obviously the estimated values are highly dependent on soil conditions. but the main point is that large amounts of moisture can evaporate from crawl space soil. Likely a substantial portion of that moisture gets into the house above since infiltration pulls air from the crawl space into the house because of the stack effect. Thus moisture from a crawl space often results in mold and mildew in closets or other interior spaces with poor air circulation and can result in increased indoor relative humidities which then lead to problems. If left uncorrected, it also can result in decay of floor wood members. The evaporation moisture source can be substantially reduced by the addition of a ground cover.

Another legal case involved a very small 1915 Portland home that had an acrid musty smell throughout the house. very bad mold and mildew on the inside of the exterior walls, moldy clothes in bedroom closets, and mold in kitchen closets on exterior walls. The walls were not insulated. There was a gas heater in the living room but no heaters in the other rooms. The house was supported by wooden posts directly in contact with the ground and had no foundation walls. The shingle siding was directly in contact with the ground. Water from the downspouts at the corners of the house soaked the crawl space and wetted the support posts. They, as well as the siding, were rotted out. Rather than fix the source of the problem, the owner drilled holes in the wall shingles to ventilate the walls and even left the 1-in, holes open! That ventilation, of course, cooled the wall cavity and the plaster walls and increased rather than decreased the mold and mildew. This example points out that many people do not understand the effects of moisture in buildings.

In a recent case in San Francisco, a five-year-old home that was one of seven similar units had unusually high moisture contents in the wood members of one of its wall cavities. All the other units had much lower moisture levels in their walls. Inspection revealed that the master bedroom had considerable window condensation during very mild spring weather. Furthermore, there was severe mold on the sheetrock in the master bedroom closet. The relative humidity in the bedroom was found to be about 65%. Inspection in a remote corner of the crawl space revealed a substantial tub leak that had wetted the wall near it, tore up the fiberglass batt insulation in the area as a result of the water in the insulation, and left water pooling on the crawl space ground that was uncovered because a geologist told the owners that the ground needed to breath to release its moisture! Careful inspection of the tub showed relatively small cracks in the tub grouting that were leaking substantially during daily showers. These leaks were the cause of the mold in the bedroom and the elevated wall moisture levels. Various building personnel and the owner had tried without success to determine the cause of the closet mold over a five-year time span.

Another legal moisture problem case involved a municipal pool building in western Oregon. the building houses two large pools. a small whirlpool. locker rooms, exercise rooms. and mechanical equipment rooms. Shortly after the building was built about five years earlier, the sloped metal roof began what was believed to be leaking, regularly into most of the interior spaces. 11 was thought to be caused by a roof leak because the leaking got worse every time it rained. In addition, there was water leaking into light fixtures and collecting in noticeable amounts both inside and outside of the building, and some of the metal hardware inside the building was corroding badly.

The metal roof was repaired to prevent leakage by caulking all seams and installing taller metal seam caps, but the leakage persisted. The mechanical HVAC equipment also was checked to see if any part was malfunctioning and somehow causing the problem, hut no problems were noted. The problem later was diagnosed as a simple dewpoint phenomenon combined with an improper design of the mechanical system that was to provide comfort control of the indoor air.

Given the indoor air conditions for the pool building of about 60 to 65% relative humidity and 27 to 29$^{o}$C (80 to 85$^{o}$F). the dew point temperature of the indoor air was just a little less than about 21$^{o}$C (70$^{o}$F). Furthermore, the HVAC system did dehumidify the indoor air. but it supplied 10% outdoor air for ventilation, and there was no dedicated part of the system to exhaust indoor air. By virtue of this design flaw, the building was pressurized, and the humid, corrosive indoor air that needed to be exhausted simply leaked out through the building shell wherever it could, including through the cathedral-type enclosed roof cavity with its wooden structural members and its metal roof.

Thus, any time the outdoor air temperature and the adjacent metal roof surface was below the 21$^{o}$C (70$^{o}$F) dew point temperature of the indoor air, moisture in the air in the roof cavity condensed on the underside of the metal roof. In western Oregon, the outdoor temperature gets below 21$^{o}$C (70$^{o}$F) almost every day of the year, and so condensation occurred most every day-When it rained, the metal roof surface was further cooled, and so the opportunities for condensation increased even further.

The condensed water then flowed down the inside of the roof cavity, collected at wooden battens that supported the metal roof, and eventually leaked out of numerous small openings in the interior and even exterior of the plywood ceiling deck, especially where lighting fixture connectors and conduit penetrated the deck.

After the problem was correctly diagnosed, the roof was opened from the outside in a few locations, inspected, and the moisture content of wooden members measured. Generally speaking, the wood was very wet in many locations, measuring above 50% moisture content in more than one spot. Furthermore, the wooden battens and the plywood decking were decayed in a number of places. The whole roof needed to be replaced.

What is unfortunate is that installation of a few hundred dollar simple exhaust fan to slightly depressurize the building so humid indoor air could not get into the roof cavity probably would have prevented this moisture problem that ultimately cost close to a million dollars. As a first line of attack in designing to prevent moisture problems in pool rooms, the indoor air space almost always should be depressurized.

It also is frustrating to realize that mechanical engineering and architecture design professionals could make such basic design errors in a building where understanding moisture was of such crucial importance. It is further frustrating to realize that numerous building professionals-including maintenance personnel, contractors. and mechanical engineers-were unable to properly and quickly diagnose what is a relatively straightforward moisture problem. It is clear to this author that the fundamentals of moisture in buildings is poorly understood by most building professionals. It is also clear that the concept of the building as a system where each subsystem can and usually does have an effect on all others is even more poorly understood. The lesson to be learned here is that training: is badly needed at all levels that focuses on developing a basic understanding of the role of moisture in buildings, especially in the context of the building as a complete system.

*Weatherization Cases*

Recently in Portland, Oregon, an older apartment complex experienced complaints of increased mold and mildew and window condensation after the complex had ceiling insulation blown in. The mold occurred primarily on the ceilings near the exterior walls. The units had concrete block walls, were very airtight, had no kitchen or bathroom exhaust fans, and were small in size. The units probably had high indoor relative humidities prior to the weatherization.

Sealing leaks and blowing the ceiling insulation tightened the house, resulting in even higher indoor relative humidities. However, the ceiling mold resulted because the ceiling insulation was blown in without eve baffles (that are supposed to keep insulation out of the soffit vents) and did not extend to the outer edge of the ceilings. Thus, the outer ceiling surfaces near the soffit vents were cold, which coupled with the higher indoor relative humidities, led to mold in that area. Once baffles were added and the ceiling was properly fully insulated, the mold problems were no longer present.

The point of the above case is that poorly executed weatherization can cause indoor moisture problems. Moreover, untold numbers of cases of indoor moisture problems have been created by weatherization of homes by weatherization contractors, utilities, and low-income housing weatherization crews. The low-income homes are much more prone to such problems because the agencies weatherizing them focus on airtightening measures (often using blower doors to find leaks) and because those homes typically have conditions and construction characteristics that make them more susceptible to moisture problems. Furthermore. it is not uncommon for low-income housing weatherization crews to reduce the airtightness of those homes by 25 to 50% especially with the introduction of high-density blowing of cellulose of wall insulation and the sealing of attic bypasses and duct leaks. Furthermore, the low-income homes are typically small in size, kept cooler than most, more likely to have poor or unused spot ventilation systems or none at all, and have higher than average occupant loads-all of which lead to higher indoor relative humidity levels [16].

Typically, about 10% of the homes visited already are too tight and below tightness guidelines [17] established by the agencies to avoid indoor air pollution problems. including moisture problems. Building tightness limits for existing homes have been developed, usually based on the ventilation requirements of 15 $ft^3$/min per person Or 0.35 ACH, whichever is greater, set out in ASHRAE Standard 62-1989. These guidelines assume that mechanical ventilation is too expensive and so limit the tightness of buildings as a means of trying to assure adequate fresh air for the occupants.

The situation with weatherization of existing homes may become critical in the near future. While low--income housing weatherization agencies are just now recognizing that airtightening to save energy definitely can lead to moisture problems and consequent health effects, most utilities that are just now expanding their weatherization programs are not aware of the huge potential for such problems. We have seen just the tip of the iceberg. Moisture-related problems in existing homes are already widely present, and the more such homes are tightened the more moisture and health problems we will see.

Moreover, almost all our experience is with single-family detached housing. Yet it would appear that the situation with multi-family housing maybe much worse. It simply has not been studied. The units are smaller, there is less exterior wall area through which infiltration occurs that flushes away moisture generated indoors, and the ventilation systems appear to be poorer. The situation maybe just as bad in manufactured homes because of their small sizes. high occupant loads, and relatively poor ventilation systems.

Simply stated, indoor moisture control in all types of existing homes is a myth. If it happens, it usually occurs by happenstance rather than by proper design. Thus, indoor moisture control in existing housing is a major problem that needs considerable further study.

One other significant cause of indoor moisture problems was noted by Bruce Davis, at the time housing director of the Economic Opportunity Agency in Fayetteville, Arkansas. In that part of the country as well as elsewhere, unvented gas propane, and kerosene space heaters are commonly in use in low-income housing. It is also common for low income households to use their ovens to heat the dwelling. One study found that between about 40 and 50% of all urban low income dwellings are heated with their stoves [18].

With such heaters, all the products of combustion, including water vapor, are exhausted directly into the indoor living space. Continuous operation of a typical 30,000 BTU/hr unvented gas heater produces about 8 gal of water per day, which is more than twice that generated by a typical family of three or four (about 3 to 4 gal per day). Some ovens and unvented space heaters can produce up to about 50% more water than that example. Thus, homes with unvented gas space heaters often have very major indoor moisture problems. Bruce Davis can attest to numerous such cases. Such homes should never be tightened as part of a weatherization program, as the indoor moisture situation can only get worse.

Finally, in working with a Cape Cod, Massachusetts utility doing weatherization of existing homes, it was noted that a majority of homes there had dehumidifiers operating in basements during the summertime to control humidity. This moisture problem appears to be caused at least in part by evaporation of moisture from concrete basement walls and floors; it may also be related to infiltration of humid, warm outdoor air that condenses on the cold concrete surfaces that are below the dew point of the air that enters the basement. This summertime moisture problem is under study by the utility. It appears to be rather common in many parts of the United States and Canada If nothing else, it results in considerable energy use to operate the dehumidifiers.

Incidentally, the author has developed a detailed residential moisture problem assessment form/checklist for the utility to help its weatherization personnel assess and resolve moisture problems; it is presented in the Appendix.

## Older Existing Homes in Southern Climates

*Gulf Coast Masonry Wall Homes Field Study*

Moisture problems in hot and humid southern climates are fairly common, but there is little field study documentation in the open literature (in part perhaps because such “problems” are assumed to be fairly normal). Trechsel et al. [19] conducted a survey of 86 houses with masonry walls in Pensacola Naval Station. Florida. Of those houses: 30% had current, past, or potential moisture problems and 48%, had mildew problems. A total of 66% had mildew or moisture problems. or both, and only 34% had neither moisture nor mildew problems. Moisture was commonly observed in the gypsum board, the source of which was rainwater penetration through cracks in the masonry walls and at windows.

Of 28 rooms with identified moisture problems, 26 (93%) were bedrooms. Problems also were found in bathrooms and mechanical rooms, but were not counted. No problems were found in living moms. Of the 28 moisture problems, 61% were under or next to windows, and 39% were either on walls without windows or at some distance from the window. Inadequate wintertime ventilation along with insufficient winter heat, particularly in bedrooms, contributed to the moisture problems.

*Florida Air Conditioning System Studies*

Over the past few years, the ductwork of hundreds of air conditioned homes in Florida have been examined and sealed. It has been found that the ducts are leaky, which affects energy use and moisture problems within the homes. Leaky supply ducts in attics simply waste energy, but leaky returns in attics often suck in hot, humid air from the attic that causes poor air conditioning performance and sometimes makes the houses more humid than without the air conditioning. This leads to moisture problems like the growth of mold and mildew. Sealing the ductwork has been found to solve the problems.

Operation of forced air distribution systems also has been found to create substantial pressure imbalances within the homes, often sucking hot and humid outdoor air into wall and other cavities where the moist air then condenses on relatively cool surfaces exposed to air-conditioned air. That, too, has led to indoor moisture problems and could very well be the source of health problems.

## Newly Constructed Homes in Northern Climates

*The Northwest Wall Moisture Study*

In 1986-1987, the interior living spaces and the ventilation systems of 86 newly constructed houses in the Pacific Northwest were inspected in detail to determine if building them to energy-efficient standards with more insulation [at least R-3.3 $m^2K/W$ (R-19$^o$F $ft^2$•h/Btu) in walls] and relatively airtight with an air-vapor retarder causes indoor moisture problems or damage [20,2 1]. The test houses were located in three climate regions: 50 in the metropolitan Seattle-Olympia area, 16 on the rainy Washington coast, and 20 in the cold Montana region. The 86 test homes selected were chosen from 255 randomly selected candidate single-family homes, almost half of which had moisture problems.

The homes ranged in age between a few months old and about three years old. Of the 86 test homes, 73 had an air-to- air heat exchanger (AAHX): the others had a dehumidifier. At the time of the study, whole house exhaust-only ventilation was not in use in the region. The mean air change rate of the homes, as determined from blower door tests of some but not all of the homes using the Lawrence Berkeley Laboratory methodology [22], was 0.28 ACH.

Numerous moisture-related problems were observed within the homes, primarily because of inadequate moisture control and consequent high indoor relative humidities. One third of these new homes had mold and mildew on indoor surfaces such as walls, one third had mold and mildew on window frames and/or sills, almost three quarters had condensation on window glass and frames, and one quarter had window sill damage as a result of window condensation.

A majority of the ventilation systems, including spot exhaust fans and air-to-air heat exchangers, were not working as well as expected or were not being used by the occupants. Overall, for a variety of reasons there was no AAHX ventilation in about one third of the homes, no kitchen ventilation in almost two thirds of the homes, and no bathroom ventilation in about half of the homes. Of the bathroom exhaust fans that did work, the actual exhaust flow of the systems, including ducts, that were measured was only about half of the rated capacity of the fans. All of these ventilation system problems resulted in inadequate removal of excess moisture.

The findings of the study dramatically point out the need for better indoor moisture control in these and other new homes. For future tightly built homes, moisture control must have a much higher priority in their design, construction, inspection, and ongoing operation. Specific recommendations to improve indoor moisture control through better ventilation, dehumidification, and automatic control of such systems were made to researchers. builders, and contractors; building code officials; and energy-efficient home occupants.

*The Effect of Ventilation on Indoor Moisture Levels*

Most indoor moisture problems are related to too much moisture (i.e., too high relative humidity) within the heated living space. A typical family generates about 20 to 24 pints of water vapor per day (about 3 gal), the majority of which is due to respiration and perspiration (see Chapter 8). That moisture, which is continuously added to the interior space, must be removed in order to maintain satisfactory indoor conditions. Typically, the water vapor generated indoors is removed or flushed out by the infiltration of cold, dry outdoor air, often with the help of mechanical ventilation and/or dehumidification. In very cold climates where the outdoor air is very dry (cold air holds little water vapor), natural infiltration and ventilation usually works well during the winter. However, in mild and humid climates, or during fall and spring even in areas with cold winters, the outdoor air may be almost as moist as the indoor air, making infiltration and ventilation less effective in removing the indoor moisture. In such cases, possibly continuous ventilation or more likely dehumidification maybe necessary to maintain satisfactorily low indoor moisture levels.

*Indoor Moisture Control Using Ventilation*

The traditional approach to indoor moisture control is to utilize ventilation. In older homes, spot ventilation in the form of bathroom and kitchen exhaust fans has been the only mechanical ventilation. Because such systems often are subpar or not used, ventilation has not proven to be particularly effective in older homes. Often older homes have been relatively leaky, which has resulted in sufficient natural ventilation(infiltration) to control indoor moisture levels, albeit somewhat poorly in many climates and situations.

In newly constructed homes, spot ventilation is now being augmented with additional central ventilation using air-to-air heat exchangers (AAHX) and whole house exhaust-only ventilation systems. Yet as noted above [20,21], these systems have not provided satisfactory indoor moisture control. Part of the reason is that they have not been used as much as needed, if at all, and another part is that the systems often have not been designed or installed properly so that they work as they should.

However: another important reason that is usually not recognized is that all ventilation systems do not provide anywhere near the actual ventilation flow that one expects based on the nominal or rated capacity or flow rate. For example, in the Northwest Wall Moisture Study and other studies measurements of flow through bathroom exhaust fan systems, including the ductwork and terminations, have found the measured ft/min flow rate typically to be about half of the rated value [20,22]. Thus, a 50 $ft^3$/min fan system has a measured flow rate of about 25 $ft^3$/min.

There is one other factor which is not well understood that leads to a further reduction in the actual ventilation when an exhaust fan is turned on. This phenomenon can be explained as follows. Since in cold climates during the heating season, air is naturally leaving the building near its top (exfiltration) and entering near its base (infiltration), there is a region in between where there is no flow. That region is known as the “neutral pressure level or plane.” Above that plane the pressure of the indoor air is greater than that of the outdoor air, whereas below the plane the pressure of the indoor air is less than that of the outdoor air. If there is no wind and the locations of any openings in the building shell are evenly distributed, then the neutral pressure plane will be at the mid-height of the building.

If a ventilation fan exhausts air at the ceiling level during cold weather when there is no wind, then the total airflow out of the building is the sum of the mechanical ventilation exhaust airflow plus the natural exfiltration. This must be equal to the amount of air entering the house due to infiltration. In order for the infiltration to increase when the fan is turned on, the surface pressures must be redistributed such that the neutral pressure plane moves upward.

When the plane rises, the exfiltration that occurred before the fan was turned on decreases. In a sense, some of the air that was exfiltrating when the fan was off is mechanically exhausted when the fan is on. Thus, the real additional ventilation of the house when an exhaust fan is turned on is less than the measured airflow through the fan system. The net actual ventilation is only about half of the measured flow rate through the exhaust fan system. For example, if a 25 $ft^3$/min airflow is measured through a nominal 50ft3/min bathroom exhaust fan, the real additional ventilation of the house is only about 12 $ft^3$/min. Thus, the actual increase in ventilation when an exhaust fan is turned on is only about one quarter of the nominal or rated flow rate! This effect has been measured by Palmiter [23].

What this means is that exhaust ventilation systems do not do what they have been supposed to do for all these years. The conventional sizing rules simply provide inadequate amounts of ventilation.

This problem is further compounded by the fact that occupants seldom run their spot ventilation systems such as bathroom fans for more than 5 or 10 min (if at all). Given the above results about actual ventilation versus rated capacity, the fans should be operated four times longer to provide sufficient ventilation. It is no wonder that ventilation has been ineffective in controlling indoor moisture problems.

In order for it to work, fan capacities have to be markedly increased or operating times have to be increased. Operating times can easily be increased by using automatic controls such as automatic dehumidistats or timers. These controls turn the fans on when indoor humidity levels rise above preset values, and the fans run long enough to reduce the relative humidity to the set value and then automatically turn off. No occupant action is required. In the authors own home, the bathroom exhaust fan is controlled with a dehumidistat. After a shower, the fan typically runs about 1 h before automatically turning off (the measured flow rate is 40 ft/min).

*Indoor Moisture Control Using Dehumidifiers*

Another approach to controlling indoor moisture control that has proven successful in a wide range of conditions is to install a portable dehumidifier. Dehumidification is probably the most effective strategy for houses with indoor moisture problems, especially in mild and humid conditions since during such times ventilation may not be particularly effective. One US, field study by the author [24] in which the performance of a dehumidifier was monitored in an actual home found that an indoor relative humidity of 50% or somewhat less could easily be maintained in a home that would otherwise have indoor relative humidities in the mid-60s. Two Great Britain field studies also found that dehumidifiers work well, even at fairly low indoor temperatures [25,26]. The author is presently field testing a new high-capacity dehumidifier, and preliminary results indicate that it can maintain an indoor relative humidity of about 40 to 45% while costing less to operate than a conventional residential dehumidifier.

Field experience that is seldom published has resulted in a useful set of selection-and-use recommendations, A model with automatic defrost control needs to be selected so the unit will operate most effectively at typical winter indoor temperatures. Otherwise the coils will frost or freeze up, and little or no water will be removed, even though the unit appears to be running. Since even units with automatic defrost control still frost up a little bit at low indoor temperatures, it helps to locate the unit in a small room such as a closet so that the heat from the unit warms the air, reduces frosting, and thus results in the unit operating more efficiently.

It also is important to select a model with large enough capacity (say greater than 36 to 40 pints per day water removal capacity) so that sufficient water vapor can be condensed our of the indoor air to maintain satisfactory indoor relative humidity levels during non-summer conditions when the indoor conditions are cooler. See the July 1990 Consumer Reports magazine for assistance in selecting an appropriate model (about $300). If possible, locate the unit on a shelf in a laundry closet so the washer drain can be used for disposal of the collected condensate. Any closet will do if the door is louvered or undercut, but then a drain line needs to be plumbed. Avoid installing dehumidifiers in bedrooms because their noise can be bothersome. If that is the only available location, then install a timer so the unit will not operate during sleeping hours. Note that dehumidifiers generally are not added to forced air heating systems because of the relatively very high cost to do so.

In most cases, annual operating costs should be less than $50. The operating cost is for electricity but it should be noted that the units act as space heaters that displace the need for the main home heating system. Moreover, the units condense water out of the air and that releases free heat, so they are rather efficient. In the U.S. field study noted above [24], the free heat amounted to 60% of the purchased energy. For electrically heated homes with elevated moisture levels that need to be controlled, installing a dehumidifier may. be economically justifiable as an energy conservation measure; thus, a moisture problem may turn into a energy resource.

## FIELD STUDIES OF CRAWL SPACE MOISTURE PROBLEMS

Most state building codes require the use of crawl space ventilation and many require installation of a ground cover. Ventilation is intended to help dry out any moisture that might get into the crawl space, while the purpose of a ground cover is to reduce the input of moisture from the ground caused by evaporation from the surface of the soil. Conventional wisdom, especially within building codes agencies, has it that crawl space ventilation is absolutely necessary in all climates and that the addition of a ground cover reduces the amount of ventilation area needed, typically from about 1 $ft^2$ per 150 $ft^2$ of floor area without a ground cover to about 1 $ft^2$ per 1500 $ft^2$ of floor area with a ground cover, depending on the vent screen type [27]. However, it is generally believed that some ventilation is still necessary even if a ground cover is in place.

While the importance of a ground cover is irrefutable, the effect of the degree of coverage has been of some concern. More importantly, there is now growing research evidence that crawl space ventilation may not be necessary. In fact, many building scientists now recognize that in some warm, humid climates where homes are air conditioned, venting in the summer may actually increase the incidence of condensation and subsequent wood decay and structural damage. The humid, outdoor air acts as a source of moisture, and the floor temperatures in air conditioned homes are often below the dew point temperature of the ventilated crawl space air. Sealing the vents in the summer in such situations typically will reduce the incidence of condensation. The field studies described below deal with these and other questions.

### University of California Ventilation and Ground Cover Study

Recent efforts to save energy have resulted in the use of insulated crawl space foundation walls in combination with a ground cover and reduced area crawl space vents that close automatically when outdoor temperatures are low [typically below about 4$^{o}$C (40$^{o}$F)]. That approach raised concern over the possible effect on wood moisture levels, especially in slow-draining soils. A field study to answer such concerns was undertaken by Quarles [28] to examine the effects of the presence of a ground cover and of ventilation on the moisture content of wood framing members in a crawl space in slow-draining soil.

The test home was located in Richmond, California (in the San Francisco Bay area). Wood moisture contents were monitored over a 16-month period with resistance-type moisture probes while amounts of ventilation and ground coverage were varied.

Venting strategies tested included: standard venting (1 $ft^2$ per 150 $ft^2$ of floor area), reduced venting (1 $ft^2$ per 1500 $ft^2$ of floor area). and no venting. Ground cover levels included 0, 75, 90, and 100% coverage. Testing was not conducted with no ground cover and no venting because with no cover and reduced ventilation mold began to grow on the joists in one corner of the crawl space. Soil moisture and crawl space relative humidity and temperature also were monitored.

Results showed that, with venting reduced to 1 $ft^2$ per 1500 $ft^2$ of floor area, adequate protection against high moisture contents could be obtained with as little as 90% ground cover. The results of this study indicated that adequate protection against excessively high wood moisture contents in crawl spaces can be obtained with any of the following treatment combinations: (1) standard venting, no ground cover, (2) reduced venting, 90% ground cover, (3) reduced venting, 100% ground cover, and (4) no venting, 100% ground cover (and probably 90% ground cover). The critical factor in maintaining low wood moisture contents with reduced and no ventilation was maintaining adequate ground cover. At the reduced ventilation level, ground coverage somewhat greater than 75% could assure moisture content levels below 20%. With no ventilation, coverage of about 90% or better provided adequate protection against elevated moisture levels.

These results generally confirm those from many different regions of the United States reported in previous publications cited in Quarles paper [28]. In particular, Duff conducted two separate investigations in the Southeast in a test home built over a well-drained soil [29.30]. He reported that excessive moisture content conditions (traditionally defined as those in which the wood moisture content exceeded 20%) were avoided as long as at least 90% of the ground was covered, even when the perimeter stem wall vents were completely closed. Moody et al. [31] also reported that closing crawl space vents in a Tennessee home did not result in excessive wood moisture content. All these results reinforce the need and importance of using a ground cover vapor retarder, even if imperfect, especially when reduced or no ventilation is used. They further suggest that crawl space ventilation is nor necessary for moisture control and may even be detrimental in humid regions. Unvented crawl spaces are, of course, better from an energy efficiency standpoint than vented ones.

Quarles results also showed that wood moisture contents could vary significantly within a relatively small crawl space, suggesting that if moisture problems do occur, they often are localized, as also was noted by Choong and Cassens [321.

### Measurements of Moisture in New Jersey Crawl Spaces

Wood and crawl space air humidity measurements were made in 15 crawl spaces in a New Jersey development [33]. Six of the crawl spaces had their masonry block walls insulated with 1-in.-thick extruded polystyrene panels. At the same time, the ground was covered with polyethylene sheets to reduce moisture transport from the wet ground below these houses. In three of the retrofitted houses, the vents in the crawl space were sealed, while in the others vents were left open. The remaining houses did not receive any crawl space retrofits and had open vents. Periodic visits were made to measure air humidity and wood moisture in these crawl spaces over the period of a year. Seasonal variations of wood moisture content were noted with higher values occurring in the summer months. The relationship between air humidity and wood moisture content in crawl spaces was determined.

For the insulated crawl spaces, there was little difference in moisture content between crawl spaces with vents open and those with vents closed; in both cases, moisture contents stayed within safe limits. In three of the six untreated crawl spaces, however, the average wood moisture content exceeded 20% for at least part of the year, with very high levels at some locations. The results suggested that if the ground has been covered with a vapor retarder (i.e., ground cover), leaving crawl space vents open is not necessary to contain moisture within safe levels. While most code jurisdictions require crawl space ventilation, this study suggests that it may not be necessary.

### Tennessee Valley Authority Survey of Weatherized Homes

Thirty-six existing homes that had been weatherized and had complaints of subsequent moisture problems were visited and examined in the early 1980s [34]. The problems were found to be more common and varied than anticipated. Three types of excessive moisture problems were found, mainly inside or under homes, with the most serious being related to improper crawl space ventilation, improper control of either surface or free water, or a combination thereof. Discussion included the deleterious effects of dimensional changes caused by excessively rapid drying when a crawl space ground cover was installed. Moisture contents of the substructure of each house were measured and generally fell close to or below the fiber saturation range of wood. However, visible signs of condensation or surface water were noted in 78% of the houses, often located in floor insulation. One sixth of the homes bad visible decay in floor joists or other floor members. There was no indication of whether or not the floor condensation was related to air conditioning of the indoor space.

Field evidence from various unpublished sources suggests that such crawl space wood decay problems occur relatively frequently in southern climates, but relatively infrequently in northern climates. In published studies directed by the author of hundreds of both new and older existing crawl space homes in the Pacific Northwest [6,7,20], wood members in crawl spaces were inspected for high moisture contents or wood decay. Yet in all those cases, there was never a single case of elevated moisture contents (near or above the fiber saturation point of about 30% [4]) or wood decay, except in a few isolated cases where wood members were in direct contact with the ground.

In the Northwest, the winter air is cold and do, and normal infiltration of that air into the crawl space and floor probably keeps the wood members dry. In the summer, the air is warm but dry, which again keeps the wood fairly dry. However, in southern climates the summer air is quite humid and a source of moisture in ventilated crawl spaces. The moisture can easily condense on the floor in air conditioned homes since the floor surface is then often below the dew point temperature of the air. It is probably best not to ventilate crawl spaces in such climates.

If so, the codes that require crawl space ventilation should be changed.

### National Research Council Saskatoon Study

Moisture contents were monitored in the wood members of three floor insulation configurations in an outdoor test facility in Saskatoon, Saskatchewan, Canada from mid- December 1989 to mid-May 1990 [35]. The three configurations included: floor joists with a polyethylene vapor barrier about 30% through the batt insulation and caulked extruded polystyrene on the inside face, floor joists with caulked extruded polystyrene on the inside face, and floor joists with caulked extruded polystyrene on the inside face and a polyethylene vapor barrier on the cold side of the rim joist. The rooms indoor relative humidity was maintained at 50%, and the room was pressurized 20 Pa above ambient to maintain an airflow through the building envelope from inside to outside to provide high moisture stress conditions. Further details of the study are presented in the later section on wall moisture field tests.

In all three configurations, the moisture contents were low, with maximum values in all three cases of about 10%. However, in the third case the moisture pin was located on the warm side of the rim joist, not on the cold side against the vapor barrier. Thus, there is the possibility that the moisture content is considerably higher on the cold side of the rim joist.

### Canada Mortgage and Housing Corporation Study

A study of crawl space moisture problems in western Canada provided answers regarding a variety of both successful and unsuccessful techniques for curing moisture problems and maintaining satisfactorily dry crawl space conditions [36]. One house had a spring in the crawl space, so the builder installed extra vents to the outdoors and a ducted supply of warm air. Both approaches were ineffective in attempting to dry the crawl space.

Another house had high humidity levels throughout the house and a persistent musty odor in the living room. The crawl space had a concrete slab but no ground cover beneath it. There was so much water pooling on the crawl space floor that the builder suspected a leak. It was then noted that the brick chimney terminated at the subfloor level above the crawl space. It appeared that moisture-laden air from the crawl space was rising up the chimney and forming condensation which then dripped down onto the crawl space floor.

The builder first installed a high-capacity exhaust fan with dehumidistat control, but that was not able to reduce the relative humidity in the crawl space. Apparently the rate of evaporation just increased. Next the insulation was removed from the crawl space walls to make them warmer and hopefully reduce the amount of condensation. But that did not solve the problem either.

Sheltair Scientific (the research group performing the study) installed a 6-mil polyethylene ground cover over the concrete slab and then poured a second slab over the ground cover. The relative humidity in the crawl space dropped to an acceptable level, and the moisture content of the sub-floor, joists, and header were substantially reduced to safe levels.

## FIELD STUDIES OF BASEMENT MOISTURE CONDITIONS

### Underground Space Center Basement Foam Insulation Study

The thermal performance of both exterior and interior full wall R-1.8 $m^2$•K/W (R-10 $ft^2$•h•F/Btu) extruded polystyrene insulation was examined in a new foundation test facility in Minnesota while also investigating the effect of adding wall insulation on moisture transport into the basement [37,38]. Both poured masonry and concrete block walls were examined with the basement temperature maintained at 20$^o$C (68$^o$F). No waterproofing or dampproofing measures were applied. Great care was taken to seal the basement ceiling and maintain a zero temperature gradient across it. A constant rate of dehumidification was provided in each 20 by 20-ft (6 by 6-m) basement test module to measure the moisture transport into the basement.

The interior and exterior foundation insulation applications of the same thermal resistance and covering equivalent surface areas yielded almost identical energy savings on an annual basis. In contrast, the water vapor transport-retarding properties of the exterior and interior insulation placements showed a significant difference.

The uninsulated poured concrete mode allowed almost 50% more moisture into the test cavity than its uninsulated concrete block counterpart due to its higher effective permeability. The uninsulated concrete block module had a dehumidifier condensate weekly volume that ranged between 3.6 and 6.6 gal. In comparison, the block module insulated on the exterior yielded only between 2.5 and 5.7 gal. per week, which was 23% less on average than its uninsulated counterpart. However, the module with exterior insulation allowed 2.3 times as much water to pass through the below grade envelope as did the module with interior insulation at a constant rate of internal dehumidification. This also resulted in a lower average relative humidity of 49% in the internally insulated module compared with 55% for the externally insulated module. Thus, interior extruded polystyrene insulation placement is preferable because of its superior vapor transport retardation capability. The results do not apply to fiberglass foundation insulation nor do they consider the effect of frost penetration into the basement wall.

It should be noted that these research results may have relevance to a common basement moisture problem wherein a dehumidifier is needed in the summertime to control musty odor or mold and mildew associated with elevated relative humidities. The application of interior foam insulation to an existing basement wall may help reduce summer moisture transport into the basement so that a dehumidifier is needed less or even not at all. Since summer dehumidifier operation consumes energy, applying interior insulation may reduce the associated energy cost and make the retrofit insulation more cost effective as a winter heat energy savings measure. This possibility should be investigated.

## LABORATORY AND FIELD STUDIES OF ATTIC CONDENSATION

The studies discussed in this section deal only with condensation in attics in northern climates. The author does not know of any published attic moisture problem studies undertaken in southern climates. The studies presented are aimed at developing a better understanding of the dynamics of moisture in attics to help develop improved guidelines to prevent attic moisture problems.

Moisture problems in attic wood members have been a source of concern for the structural integrity of homes. One of the major problems is the migration of water vapor from the living space into the attic. Moisture can potentially condense in cold parts of the attic, thus possibly leading to mold growth, wood decay, and structural damage. Dutt [39] has shown that moisture transport in and out of attics via air movement greatly outweighs moisture transport by diffusion, showing that the best way to keep moisture out of attics is to seal possible air infiltration routes between the living space and the attic. Recent research has focused on the role of moisture storage in the attic wood members.

### National Bureau of Standards Laboratory Study

A series of attic ventilation tests were carried out by Burch et al. [40] in a small test house with a pitched roof/ventilated attic, all of which was located inside an environmental chamber. The attic was exposed to a series of steady and diurnal outdoor temperature conditions. For some of the tests, the attic was closed off without ventilation and house air was induced to exfiltrate through the ceiling into the attic.

An unexpected finding was that attic condensation at the roof sheathing did not occur under any of the test conditions. The attic wood surfaces adsorbed water vapor and maintained the wood surface dew point temperature below the roof surface temperature. thereby preventing condensation. It was noted that it would take long periods of adsorption (more than three months) before condensation would occur. Because the roof also was found to actually give up moisture, this experimental study confirmed the dynamic nature of roof adsorption and desorption.

These results should not be construed to imply that condensation will not occur. It is often noted in the field, especially when large attic leaks exist in houses with high indoor humidity levels. The importance of ceiling leaks was recognized in this study. It is conjectured that a higher indoor relative humidity than the 44% used in the study coupled possibly with localized attic leaks might have resulted in localized condensation, as is often seen in the field.

### Princeton Attic Field Studies

Harrje et al. [41] measured the seasonal variations in wood moisture content in two New Jersey attics. Wood moisture levels were measured using two types of electrical resistance probes. In one houses attic, measurements in wood sheathing revealed large seasonal variations. The moisture content was highest in winter, fell in the spring, reached its lowest value in the summer, and increased again in the fall. The north sheathing moisture content was high-approaching 19% - in the cold part of the year, compared to 10 to 11% for the ceiling joists, roof rafters, and the south-facing sheathing. However, it dried out at a rapid rate in early spring and became identical in moisture content to other attic wood. One important factor in the drying seems to be the increased solar radiation on the north-facing roof. Measurements in a second attic showed extensive condensation and very high moisture content in the winter with rapid drying in the spring and no sign of wood decay.

In addition, the attic wood moisture absorption/desorption rate averaged over a season was shown to make a small but noticeable contribution to the total attic moisture balance, which was dominated by airflow to and from the attic. In order to relate long-term trends with short-term variations, measurements of attic air humidity were also attempted, but proved to be unreliable.

### Lawrence Berkeley Laboratory Attic Humidity Field Studies

Cleary and colleagues at LBL monitored the attic of a single-family unoccupied house in the mild climate of Oroville. California over the four-month period of January through April 1984 [42-44]. The purpose was to provide measured data that would help develop a model of the dynamic moisture characteristics of attics so as to help develop better guidelines for attic moisture control, including ventilation needs.

While in the past it has been assumed that an attic was an inert structure on which moisture would either condense or pass through unaffected, these studies conclusively shows that the wood members in an attic are in constant flux absorbing and releasing moisture. This moisture cycles on a daily basis and also seasonally. Furthermore, there is considerable flow of water into and out of the roof sheathing. Part of the flow of water into the sheathing is from ventilation air. A simple model to predict the seasonal variation of the wood moisture content was developed using hour-by-hour measurements of wood resistance, attic, and outside dew point and meteorological variables to validate the model.

### Northwest Wall Moisture Study

The attics of 86 newly constructed homes in Washington (66 homes) and Montana (20 homes) were inspected during the 1987 winter for signs of moisture damage, and measurements were made of the moisture content of roof sheathing and rafters [20]. Generally speaking, the wood moisture contents were less than 20% except in a few cases where exhaust fans were exhausting into the attic air space rather than outside the attic. In one such case, the roof was severely rotted. There were a few cases of mold and minor frost coatings on the underside of the sheathing, but it was not considered deleterious.

### Alberta Building Envelope Moisture Accumulation Field Study

Tests were carried out during the 1988-1989 and the 1989-1990 heating seasons on a single-story instrumented house with a full basement and gable end attic in Edmonton, Alberta, Canada [45]. A dual tracer gas technique was developed to monitor indoor infiltration and attic ventilation rates and to infer indoor-attic exchange rates. The house was monitored in two attic ventilation configurations: one with gable vents and the other with soffitt eaves and a roof-mounted turbine ventilator. Moisture contents of the wood members were measured with moisture pins.

Attic ventilation rates varied linearly with wind speed, with considerably larger rates for the soffitt-turbine configuration. Any stack effect was small by comparison. Indoor-attic exchange rates, which convected large amounts of moisture into the attic, varied up to a maximum of 40% of the indoor infiltration rate. The exchange rate did not depend on the wind speed, but it did show a weak dependence of the indoor-outdoor temperature difference (the stack effect).

The roof sheathing moisture content remained below 10% moisture content by weight without any seasonal accumulation of moisture. Instead, short-term (on the order of a week) moisture accumulation occurred during cold weather followed by drying when milder temperatures prevailed. The attic ventilation during periods of warmer temperatures removed all of the moisture deposited during the cold weather and so was effective in controlling attic moisture deposition.

### Weatherization Studies

The author has been involved with state low-income housing and utility weatherization programs throughout the northern United States. It has become clear that attic condensation occurs nearly always only when there is a leak in the ceiling that allows humid indoor air to enter the attic due to the stack effect or room pressurization caused by operation of a forced air distribution system. As the indoor air enters the attic, the water vapor in that air condenses on some cold surface. Unfortunately, there are numerous ways and places where indoor air leaks into the attic, including attic bypasses, ventilation fans that exhaust directly into the attic rather than the outside air, leaks in attic forced air system ductwork, and leaks around vent pipes, electrical fixtures, and attic hatches. Wet insulation, elevated wood moisture contents, and even wood decay are often noted during weatherization inspections. The lesson is that careful air sealing to decrease air leakage from houses to their attics in order to reduce space heating costs will usually greatly reduce and even eliminate most such moisture problems. In addition, while most weatherization programs emphasize adding attic ventilation whenever attic insulation is installed, proper ceiling air sealing is probably much more important. If done properly, there would be little or no need for additional attic ventilation, and more energy would be saved.

## FIELD STUDIES OF ROOFING MOISTURE PROBLEMS

### Flat Roof Condensation/Leak Study

An investigation was undertaken in June 1985 to determine the cause and resolution of existing roof moisture damage in three large flat-roofed buildings near Medford, Oregon 46]. The roofs were wood-framed with plywood inner and outer deck surfaces, R-1.9 $m^2$•K/W (R-11 $ft^2$h•F/Btu) batt insulation, and a thin rubber membrane covering the outer plywood surface. The buildings were constructed in the early 1970s. Roof moisture damage problems included numerous cases of water dripping from ceilings into the interior of the buildings, a hole in the outside surface of the roof of one of the buildings, and ice damage inside a building with a freezer room.

The two major candidate causes were a leak of water from the outside into the roof cavity that was causing leakage into the buildings and possible structural damage due to wood decay, or an accumulation of moisture in the roof cavity from condensation of water vapor migrating in the wintertime from the inside of the building toward the outside. As a result of inspection, including making openings into the roof cavity, and moisture measurements, numerous leaks of water from the roof cavities into the interiors of the buildings were observed as were high wood moisture contents in some locations and even some wood decay and structural damage. The roof ventilation system also was found to be impaired because ventilation air was inadvertently blocked during construction.

All the evidence strongly suggested that the roof moisture damage was caused by the fact that, while not easily observable, the exterior rubber roof surface deteriorated to such an extent that water was slowly leaking into the roof cavity. It was decided that the flat roof natural ventilation system, even if not impaired, would not have been able to provide enough airflow to dry out the moisture from a leak. Finally, while condensation is often blamed for roof moisture damage, the evidence in this case indicated that it was not a factor. Sometimes it is, and sometimes it isn’t. This is obviously not a unique case, but rather is one of many that happens to be documented in the literature.

## LABORATORY STUDIES OF ROOFING MOISTURE PROBLEMS

### Building Research Association of New Zealand Study

A laboratory investigation of solar-driven moisture transfer through absorbent roofing materials was undertaken because moisture problems were noted in the field in cases where cellulose-fiber-reinforced cement shingles were used in cathedral-type roof applications in New Zealand [47]. It was speculated that the moisture transfer through the roofing was caused by solar heating rather than leaks or other causes. Thus, the purpose of the research project was to try to determine the cause of the moisture transfer that was occurring as well as any possible remedial actions.

A laboratory test rig was developed to simulate rain that would wet different types of absorbent roofing materials and then simulate solar heating such that any moisture transferred through the roofing into the closed roof cavity below could be isolated and measured. Testing verified that the shingles absorbed considerable moisture from the rain and that solar heating indeed did result in substantial moisture transfer through the roofing material. While the presence of conventional breather-type building paper underneath the shingles did not greatly impede the transfer of moisture into the closed roof cavity below, it was found that interleaving nonbreachable building paper with poly attached between the layers of shingles dramatically reduced and nearly eliminated the moisture transfer into the roof cavity. This remedial approach has been adopted by the roofing material manufacturer and is recommended for future applications involving cathedral roofs.

Tests of other less successful remedial measures as well as other common absorbent roofing materials also were undertaken. There appears to be considerable need to do a followup study of solar heating moisture transfer through wooden shingles since they were found to exhibit the largest moisture transfer of all the absorbent materials tested in this study. Solar heating moisture transfer may very well be responsible for the premature degradation of roofing shingles applied over plywood sheathing rather than spaced battens.

## FIELD STUDIES OF MOISTURE PROBLEMS INSIDE EXTERIOR WALLS

### Older Existing Homes in Northern Climates

*Potential Wall Moisture Problems When Retrofitting Wall Insulation*

During the mid- to late 1970s and the early 1980s when retrofitting of wall insulation became very popular, there existed a prevalent theory that by adding wall insulation, the outer wall layers would get colder, and hence water vapor migrating through the wall from the inside to the outside would be more likely to condense and accumulate. If so, minor effects might occur, such as mold/mildew/staining, siding warping, paint blistering, and wet insulation and greater heat loss. Moreover, the worst effects postulated were condensation and resultant liquid water accumulation, subsequent wood decay (dry rot), and structural damage.

In 1979 Weidt 1481 opened the walls of 33 existing homes in Minnesota to examine insulation characteristics and somewhat surprisingly noted the absence of any liquid accumulation or decay in that cold climate. An additional similar study of 159 homes [49] found the same surprising result in homes throughout the northeastern United States. In order to determine if the prevailing theory or the limited field findings were correct, two major field studies were completed (under the technical direction of the author).

*The Portland and Spokane Studies*

In Portland, Oregon (4732 DD) and Spokane, Washington (6835 DD), 93 and 103 older homes, respectively, with and without retrofitted wall insulation, were carefully inspected for moisture problems and their walls opened in three or four places to measure wall cavity moisture levels and look for moisture damage [6,7]. The homes were typical of the existing housing stock.

As noted earlier, interior moisture problems were very prevalent, in large part due to lack of satisfactory indoor moisture control. The average indoor relative humidities were 56% for the Portland homes and 47% for the Spokane homes, with many homes having relative humidities in the seventies.

From the wall-opening measurements, no high wood moisture contents were noted out of 5234 wall cavity wood member readings, except where leaks or “splashback” was found. In the 103 Portland homes, no moisture contents above 20% were measured. Splashback in this case was excessive wetting of walls with shingles from water splashing on the ground and back onto the shingles-due to lack of gutters. Even with splashback, only 0.2% of the moisture content readings were above the fiber saturation point of wood, and no wood decay was observed, except where leaks were found. Even then, only a few cases of wood decay were seen.

In 681 wall openings, condensed liquid or frost was never observed inside a wall cavity. In addition, those walls that had insulation added actually had a lower incidence of most moisture-related problems within or outside the walls.

The major conclusion of the two field studies was that retrofitting wall insulation in older, leaky homes in climates like those of Portland and Spokane does not create or accelerate moisture damage. Any moisture damage within the wall cavities was always caused by leaks. Furthermore, because there are no associated wall moisture problems, there is no need to add a vapor barrier when retrofitting wall insulation in older existing homes.

It is important to note that these results may or may not be applicable in other climates. Many other climates are less forgiving in that there is far less drying potential. In other words, there is less opportunity for wetted walls to dry out during warm weather (e.g., summer), which is the only time wood decay can occur. Yet, surprisingly to some, the author knows of no cases anywhere in the continental United States where the installation of blown-in insulation has created wood decay. The installation of blown-in cellulose has in one instance been documented to cause siding problems; this case will be discussed shortly.

The walls of older homes stay dry because even though moisture enters the wall cavities from inside the house, the moisture drys out due to the relatively leaky exterior portion of the walls. Recall that most of the wall sheathing in the Portland and Spokane studies was board-type wood with substantial air leakage rather than more airtight plywood panels. The results might have been different if the homes had plywood sheathing. In fact, we of the Spokane homes had plywood sheathing, and their walls had among the highest moisture contents. However, there was no moisture-related damage.

Based on these field study findings, it is recommended that any wall airtightening primarily involve sealing the interior portion of the wall, such as by caulking the inside wall-floor joints behind the baseboard molding. and installing electrical switch plate/ outlet gaskets. However, neither of these measures are likely to be cost effective, except if done by the occupants. It is not a good idea to caulk the wall exterior portion except to reduce or prevent rain or snow intrusion or leaks. If the wall insulation addition clearly leads to substantial paint blistering, then insert siding wedges available from paint stores between the horizontal siding laps to make an air space that provides a capillary break as well as air circulation and drainage. That should prevent further blistering.

*Does Weatherizing Homes Create Moisture Problems?*

Weatherizing existing, older homes generally does not create moisture problems around the building envelope exterior (attics, crawl spaces, and wall exterior surfaces). If anything, it reduces their incidence. Moreover, based on the results of the Portland and Spokane field studies and others, retrofitting wall insulation does not create moisture problems inside the exterior wall cavities.

As far as moisture problems inside the homes, many types of weatherizing such as adding storm windows or adding wall insulation can actually reduce the incidence of such moisture-related problems. However, some types of weatherizing such as airtightening or incorrectly insulating can change conditions enough to lead to moisture problems inside homes. Many low-income homes, for example, are prone to such weatherization-induced moisture problems since they typically are homes with a high occupancy and small living space with poor heating and ventilation that are more prone to moisture problems. In fact, about 10% of the low-income housing stock that recently has been considered for weatherization falls below the latest building tightness limits set to prevent indoor air quality problems, including moisture problems. A large portion of the recently weatherized homes are tightened right to the limit, so that moisture related problems are more prevalent and often actually caused by weatherization efforts.

### Tri State Homes

As noted in an earlier section, one of the most unique and severe cases of moisture damage in residential walls occurred in the large group of manufactured homes known as the Tn State homes [/0]. Between 1970 and 1982, more than 5000 such homes were manufactured, 3400 of which were made in Wisconsin. After 1986, extensive wall wood decay was reported. The manufacturing company declared bankruptcy and was liquidated just before reports of moisture damage surfaced.

Site visits and a home inspection program revealed decay in fewer than half the homes. Nonetheless, the number of homes with decay was substantial. Typically, wall decay is very rare and usually caused by leaks. Most decay in the Tn State homes was in the plywood sheathing, with far less damage to the wall framing.

According to Merrill and TenWolde [0], a survey of homeowners and airtightness measurements indicated that the damage was primarily due to excessively high indoor relative 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 be a significant influence.

It should be noted that part of the sheathing decay was caused by shower water leaking into the wall cavities. The bathroom windows were located in the shower space and were known to leak shower water that collected in the window tracks into the wall cavity. This introduced water into the wall cavities, where it was then able to migrate into other stud spaces through large holes drilled for wiring. This cause, however, did not account for all the damage in other walls of the homes.

It is believed that while the houses are tight (about 0.3 ACH from blower door tests using the LBL methodology [22]), they were not extremely so, and many others in that region are every bit as tight without any wood decay. Moreover, other houses in the area and elsewhere had similar occupant densities. In fact small, airtight homes with high occupant densities are not uncommon in most areas of the northern United States, and yet decay in walls is seldom seen. Something had to be different in the Tn State homes.

It was concluded in a court case that the installation of a very good exterior vapor retarder (low perm building paper) between the plywood sheathing and the siding in the absence of an effective interior vapor retarder was the significant contributing factor in the creation of conditions conducive to wood decay. Actually, the problem was most likely caused by the combination of fairly high indoor moisture levels (no one has argued that the homes were dry indoors) and the exterior vapor retarder that trapped moisture within the wall cavities. While the wetting potential of the walls was relatively high, the drying potential was rather poor.

The one major factor that is different about these homes is the unusual wall construction. Had no cold exterior vapor retarder been present, the problem probably never would have happened. At any rate, this case of extensive wall decay is unique. There are numerous examples of similar heavily occupied, poorly ventilated, and airtight homes (often in multi-family housing), and yet decay in such walls is seldom observed in any other U.S. northern cold winter climate location. It is indeed fortunate that such wood decay in walls is in fact very rare.

#### *Cleveland Siding and Paint Failures*

This project involved investigating numerous moisture related siding and paint failures in Cleveland, Ohio that appeared a year or two after blown-in insulation was retrofitted in existing homes [50]. In addition, complaints of paint peeling and actual wood siding failures in new homes where wood siding was installed over insulating sheathing were examined. A survey of 150 homes with problems was undertaken, including some detailed wall investigations where sidings, sheathings, and insulations were removed. Peeling paint ranged from extensive to minor on both the exterior of the siding and the interior of the wall.

The key factor in all cases was that the failures were moisture related, and after cavity insulation was added the “drying potential” of the exterior portion of the walls was sufficiently reduced to ultimately cause paint peeling and blistering problems. Problems often were worse on south or west-facing walls where solar heating created a strong vapor pressure gradient that drove moisture into the walls. That result is contrary to popular thinking wherein it is believed that such walls should be drier because of the solar heating and therefore have fewer moisture problems. Installation of plastic siding wedges available from paint stores between horizontal siding laps proved to be a very effective means of providing a capillary break and increasing drainage and drying.

No definitive answer was found as to why there appear to be more such problems occurring with blown-in insulation and not with batt insulations. This author theorizes that the difference may be due more to the air leakiness of the wall cavities of the older retrofitted homes. Many of them have rough-sawn wooden 1 by 4-ft (0.30 by 1.2-in) or 1 by 6-ft (0.30 by 1.8-m) or 1 by 8-ft (0.30 by 2.4-m) sheathing boards nailed horizontally or diagonally to 2 by 4-ft (0.60 by 1.2-m) studs. The walls are much leakier than those with panel type sheathing (e.g., plywood or fiberboard), and the board-type sheathing has a considerable moisture absorption capacity. In the Cleveland study, those homes with such sheathing did not experience paint or siding problems. In fact, most of the test homes in the Portland and Spokane studies [6,7] had such sheathing. Statistical analysis of the data in those studies found in one case that houses with insulation blown in had slightly more blistering paint, whereas in the other the opposite was true. In neither case were the siding problems considered severe. There was no decay noted in either of those studies, and the statistical analysis did indicate that other indicators of wall moisture problems actually were lower with the insulated walls compared to those without insulation.

It also was recognized in the Cleveland investigation that an interior moisture source could not be conveniently cited in all cases as is popularly done. Moisture entering the wall from the outside was deemed to be very important in many cases, and especially in the cases with exterior insulating sheathing. In a more recent study of new Northwest homes directed by the author and described shortly, moisture entering wall cavities from the outside was found to be the most important factory in causing wood members of walls to have elevated moisture levels. As a consequence, in the Cleveland study it was realized that employing strategies and techniques that were aimed at effectively eliminating moisture entering the wall from the interior could not always be relied upon to eliminate the paint and siding problems.

Finally, it was recognized that the addition of exterior insulating, sheathing to a wall cavity does increase the drying potential of all the wall components to its interior, but it is ironic that its installation may lead to an increase in siding or exterior wall moisture problems. In the Northwest Wall Moisture Study [20] wood members in wall cavities with exterior insulating sheathing were in fact found to be significantly drier than those without. However, there was no evidence of any type of paint or siding problems in those new homes, possibly in part because most of them had exterior stain applied rather than paint. Nonetheless, there was almost no siding damage such as cupping or warping or splitting.

## Newly Constructed Homes in Northern Climates

*National Bureau of Standards Insulating Sheathing Tests*

Burch et al. [51] ran laboratory tests of a wall with and without low--permeability exterior insulating sheathing to determine if it resulted in accumulation of moisture within an insulated wall cavity during winter conditions. At the time it was not clear whether its addition would increase or decrease wall moisture levels. The test results showed that the addition of a low-permeability exterior insulating sheathing retrofit reduced moisture accumulation within the existing wood siding and sheathing. It was further determined that increasing the water vapor resistance of the exterior portion of the wall by adding the insulating sheathing had only a small effect on the rate of moisture accumulation from the inside of the wall cavity.

*U.S. Forest Products Laboratory Field Test*

Small, unoccupied test structures were constructed near Madison, Wisconsin to test exposure of eight types of insulated wall panels at controlled indoor conditions and typical outdoor weather conditions [52,53]. One test panel was framed with 2 by 6-ft (0.60 by 1.8-m) studs and full fiberglass batt insulation. All the remaining panels were framed with 2 by 4 ft (0.60 by 1.2-m) studs. There were no very high R-value walls tested as is now becoming common in many cold climates.

The primary variables were the sheathing material and the vapor retarder. Sheathing materials included fiberboard, plywood, extruded polystyrene foam, and foil-backed polyisocyanurate foam. The vapor retarders were either continuous polyethylene film or asphalt-impregnated kraft paper backing on blanket insulation stapled between studs. The panels were instrumented with moisture sensors and tested without (Phase 1) and with (Phase 2) penetrations (electrical outlets) in the indoor surface to examine the relative effects of diffusion and air movement as mechanisms of moisture migration.

Continuous inside vapor retarders effectively prevented cold weather condensation in all the panels. Installation of an electrical outlet with subsequent air leakage resulted in somewhat elevated moisture levels. Although condensation occurred for limited time periods in some panels at both test sites, the moisture content of framing did not rise to critical levels. It was concluded that there is no high potential for decay in any of the materials of any of the walls tested.

It should be noted that the test panels were never actually opened and inspected during the winter when “condensation” supposedly occurred. “Condensation’ was simply presumed to occur when the wood moisture content measurement probe readings were over their maximum limit of 20%,. “Condensation” also was presumed to occur because a dark substance was noticed running down on the outside of the painted lap siding, seemingly from between the laps. It is possible that condensation did occur. What that presumably means is that there were liquid water droplets on wood members or foam sheathing within the wall cavity.

Yet the author has inspected about 1200 wall cavities that were opened up in about 300 homes in winter climates ranging from mild and moist to that of Montana, which is more severe than Madison, Wisconsin. He has never observed liquid water or frost in any normal insulated wall cavity nor any evidence of an accumulation of liquid water that is often referred to. In fact, the author is not aware of any scientific study where liquid or frost has been observed in an insulated wall in the continental United Stares. He has observed mold and dark staining of plywood sheathing inside wall cavities, but no actual liquid or frost.

The dark coffee-colored stains observed in the Madison, Wisconsin tests have also been observed on more than one occasion by the author. However, after removing the siding to check for moisture behind the siding, none was found. They were all very dry on the back side. It is presumed that the staining is a phenomenon related to a combination of moisture transfer and the natural tannins in the wood itself. It does not appear to be caused by 'condensation" and an accumulation of liquid water between the siding laps, at least in the cases observed by the author in the Northwest.

In conclusion, there is a very common belief that water vapor condenses in wall cavities and is present in liquid or frost form. That belief does not appear to be supported by field observations. "Condensation" perhaps does occur, but if so, the liquid appears to be immediately absorbed into wood. Interestingly, as noted later in this chapter, Forest [54] has observed that moisture in wood members of insulated walls appears to be absorbed in cold weather but desorbed (dried out) in somewhat milder winter weather, with a time constant of the order of a week. Thus, condensation is apparently followed by regular drying that prevents an accumulation of liquid or frost. Surprisingly, to the authors knowledge, condensation has never been observed on the warm side of exterior insulating foam sheathing, in spite of the fact that in very cold weather temperatures at that interface in the wall are probably below the dew point temperature. Kane and Titley [55] noted that increasing the sheathing/insulation temperature by using insulating sheathing can significantly increase the capacity of air to contain moisture, which clearly helps reduce condensation.

*Canada Mortgage Housing Corporation Wall Drying Study*

Three highly instrumented test huts, including 48 test panels, were constructed in three locations representative of climatic conditions found in Atlantic Canada. The purpose was to investigate the cause of moisture damage in walls of wood-frame housing in Atlantic Canada and to suggest practical solutions. Monitoring the moisture conditions in the test huts was especially aimed at examining the drying of walls with different constructions that were initially wet, including investigating the use of furring strips between siding and the exterior sheathing as a means of enhancing drying or keeping walls dry [56.57]. The wall panels were constructed of locally supplied lumber, all of which had moisture contents above 26%. Data collection occurred between March 1986 and August 1987.

A joint task force comprising representatives of Canada Mortgage and Housing Corporation, the Canadian Home Builders Association, and the National Research Council of Canada (Atlantic Region) was formed to oversee the field research project and the production of a good-practice, advisory document (Construction Principals to Inhibit Moisture Accumulation in Walls of New, Wood-Frame Housing in Atlantic Canada'), and to visit housing with moisture problems. In conjunction with these activities, a survey was conducted to measure the moisture content of framing lumber typically used in new housing.

The task force presented a number of results, conclusions, and recommendations, as follows. All of the 48 test panels exhibited some degree of drying during the monitoring phase-south walls more than north walls. Test panels with sheathing systems that were more permeable to water vapor dried more quickly than those with less permeable sheathing systems. Statistical analysis results indicated that the permeability of the sheathing systems to water vapor was the most significant factor in the rate of drying and the final moisture content of the test panels. The use of exterior sheathing materials with a very low permeability in combination with 'wet' framing lumber or insulation materials having a high moisture content puts walls to a high degree of risk of moisture problems.

Most test panels which stayed wet for an extended period of time exhibited some fungal growth on the framing lumber and wood-based sheathing materials. The frequent occurrence of conditions that theoretically can lead to condensation on the back of the siding suggests that the use of furring strips may be beneficial in preventing moisture accumulation in wood and wood-based siding and sheathing materials. Furring strips installed behind vinyl siding had no significant effect. The entry of water from the exterior, due to poor detailing, poor installation of siding systems and flashing, inadequate exterior air barriers, plus lack of regular maintenance were frequent factors in walls damaged by moisture, as was noted in the Northwest Wall Moisture Study [20].

Many of the houses visited exhibited mold, mildew, and condensation on the interior surfaces of exterior walls and relatively low indoor temperatures in the troubled areas. It was noted that householders do not have suitable information on the operation and maintenance of houses to avoid moisture problems. Further, design professional, building scientist, subcontractors, material manufacturers, builders, and inspectors do not have a sufficient understanding of the causes and prevention of moisture damage in walls. Finally, framing lumber surveyed in Atlantic Canada typically exceeded a moisture content of 19% and in most cases exceeded the fiber saturation moisture content. The lack of availability of dry framing lumber is a significant contributor to the moisture load in wall systems. Using the field test data, a wall drying model has been developed.

*Dow Chemical Canada Study of Walls With Exterior Foam Sheathing*

Moisture contents were measured by Kane and Titley [55] in the wood studs of seven occupied homes that had a low permeance foam sheathing, with or without a noninsulating sheathing such as plywood, in four Canadian cities. Moisture contents were measured over a period of one to six years. depending on the home, with Delmhorst moisture elements and then read with Delmhorst moisture meters. While both insulating and noninsulating sheathings were not installed in the same house for the best side-by-side comparison, nonetheless the results indicate that moisture levels were not excessive regardless of the exterior sheathing installed. Stud moisture contents were generally less than 15%,. and always less than 25%. The water vapor permeance of the walls studied was shown to be an insignificant factor in controlling the moisture content in studs. The use of extruded polystyrene as external sheathing did not cause moisture accumulation in the wood studs. In fact, the author of this chapter does not know of any documented case of moisture accumulation or damage occurring as a result of the installation of exterior low permeance foam sheathing. In the next study described, its use was actually shown to result in drier walls.

*The Northwest Wall Moisture Study*

The exterior walls of 86 newly constructed houses in the Pacific Northwest were cut open and examined to determine if building them to energy-efficient standards with more insulation [at least R-3.3 $m^2$•K/W (R-19 $ft^2$h•$^o$F/Btu)] and an air vapor retarder causes unacceptably high levels of moisture or moisture damage within walls [20]. The test houses were located in three climate regions: 50 in the metropolitan Seattle-Olympia area, 16 on the rainy Washington coast, and 20 in the cold Montana region.

Measurements of the moisture content of wood members within the wall cavities were first made between January and March 1987. Over half of the test homes had at least one wall wood member with over 20% moisture content. On average the highest readings occurred in sheathing and sill (mud) plates. More than one third of all the sheathing measured had moisture contents over 20%, while more than one half of all the sill plates were over 20%. The highest moisture content measured was approximately 55%.

There were significant differences between regions, with the homes in the mild and humid Washington coastal area being the wettest and those in the cold Montana region being the driest. However, the cold region homes were often still very wet. Since the coastal climate is mild with relative humidities that average about 90% throughout the fall, winter, and spring, and since the equilibrium wood moisture content at a relative humidity of 90% is about 21%. the high wood moisture contents in the coastal homes are not too surprising.

The 28 homes with the wettest walls were reopened during the 1988 summer to see if the walls had dried out enough to avoid wood decay. The wall cavity wood members of the cold region homes had thoroughly dried out such that there is no reasonable likelihood of wood decay occurring there, except in the case of leaks. On the other hand, many of the walls in the coastal and metro (Seattle-Olympia) homes had not dried sufficiently to rule out the possibility of wood decay and subsequent structural damage occurring in the future. How long it takes for wood decay to develop is unknown, although many of the walls are wet enough to decay during warm weather.

While there were no cases of wood decay observed in any of the wall cavities during any part of this study, sometimes it takes many years for decay to develop and be noticed, as for example in the Tn-States Homes case [10]. In those homes, severe wall structural damage occurred due to wood decay, but the homes were about a decade old before the damage was discovered. Incidentally, in the Northwest study there were no cases of condensed moisture or liquid water accumulation observed within any of the 28 insulated wall cavities.

The walls of the 16 coastal and metro test homes that were still wet during the summer were again reopened during the 1989 winter. While the walls were generally drier, they were still wet enough to be of concern. The drying that occurred between the 1987 and 1989 winters appears to be the result of a period of abnormally cold, dry, and extremely windy weather just before the 1989 wall openings. Record low temperatures and strong winds were recorded all across the region for almost three weeks.

Thus the question of whether the high moisture contents will lead to wood decay and subsequent structural damage is still unresolved. The walls of one or two of the worst test homes should be regularly opened and checked for a few years to see if they are, in fact, slowly drying or if any decay occurs.

What also is unclear is whether similar results would occur in the walls of newly constructed current practice homes in the region and perhaps even in the new energy-efficient Super Good Cents manufactured homes. There is reason to believe that those homes could be worse because they have similar insulation levels and are nearly as airtight, but they lack an AAHX or dehumidifier. Moreover, there is a good possibility that wall moisture levels will be as high, if not higher, in the many multi-family homes recently built in the region. That is because the individual units are smaller, have less exposed exterior wall area, and generally have less expensive/effective ventilation systems. Thus, the finding of moisture-related problems in this study of single-family homes may only be the tip of the iceberg.

*Statistical Data Analysis* - Statistical analysis of the field data was undertaken to try to find out what caused the high wall moisture contents, and a number of factors were found to be significant. Wet walls were strongly associated with high indoor relative humidities. The wettest walls and highest indoor relative humidities were in the humid coastal region. Many homes had indoor relative humidities that were clearly too high. Thus, one of the major factors contributing to high wall moisture levels was the lack of indoor moisture control. Reducing indoor relative humidities with improved moisture control systems that are presently available but seldom used should reduce wall moisture levels. One of the main conclusions of this study is that better indoor moisture control is a major programmatic need in new Northwest housing and probably in most other similar new housing [20].

Most of the wettest walls were in homes with T1-11 plywood panel siding and shingle siding. These siding types are especially prone to what is called “splashback” because their lower edges and back sides are often not satisfactorily painted or sealed. They readily absorb rainwater or melted snow that splashes up from the ground, and that moisture is transmitted into the wall cavity wood members. Walls with insufficient clearance between the bottom of the siding and the ground were especially, prone to splashback; many of the homes had siding whose bottom edge was within a few inches of the ground. Walls also were significantly wetter if they did not have an exterior air barrier such as Tyvek or a moisture barrier such as building paper behind the siding that provided resistance to capillary action. These findings point out that while moisture is generally believed to enter wall cavities from the inside, significant amounts of moisture leading to elevated wall moisture levels also can enter from the outside. Thus, control of exterior moisture may be at least as important as interior moisture.

To avoid high wall cavity moisture levels when T1-11 and shingle siding materials are used, the lower edges need to be much better protected, the ground-to-siding clearances need to be maintained above some minimum level, such as about 2 ft (0.60 m), and an exterior moisture barrier or possibly an air space behind the siding needs to be installed. Adding exterior insulating sheathing also may be wise.

In addition, high sheathing moisture contents often were found at sites where moist indoor air leaked through the wall cavity, such as through electrical outlets and a variety of penetrations in the polyethylene air-vapor retarder, indicating the need for better sealing on the inside of the wall. A further discussion of this topic will be presented in the next section.

The high sill plate moisture levels were likely caused in part by moisture from the wet ground wicking up by capillary action through the crawl space or basement concrete foundation walls into the adjacent sill plates and in part by the effects of splashback wetting.

Another programmatic problem was noted by comparing moisture levels in walls with different amounts of cavity insulation. It was found that building walls with more cavity insulation definitely lead to increased moisture levels in them. Fortunately, that adverse finding is balanced by the positive finding that walls with exterior insulating sheathing are significantly drier than walls without it 581. Burch et al. [51] conducted laboratory tests and found a similar result. In the field study, almost none of the wettest walls had such sheathing and half of the driest had it.

These walls are drier because the insulating sheathing keeps the wall cavity wood members warmer and also because the sheathing is an excellent exterior moisture barrier or break that keeps wet siding from transmitting or wicking moisture into the wall cavity better than other moisture barriers. The results of this study indicate that the use of exterior insulating sheathing is one way of providing additional wall insulation while at the same time reducing the potential for wall moisture problems.

While the walls of homes with a polyethylene air-vapor retarder were slightly drier than those without, or with polyethylene only on the walls and not on the ceiling, the differences were not statistically significant. However, there were almost no homes with wet or very wet walls that had both a polyethylene air-vapor retarder and external insulating sheathing. Furthermore, the airtightness of the home was not significant.

Statistical analysis of the effect of the age of the homes on wall moisture levels was undertaken to see if the high wall moisture values were caused by the use of wet construction materials in the relatively airtight walls that are slow to dry out. There were no indications that this was a factor (i.e., the newest homes in each region were not wetter). However, the initial material wetness may still be an important factor. Continuous field monitoring of wall moisture levels is needed to find out.

In order to make these research results useful to the building community at large, specific recommendations were made to builders and contractors, building code officials, and energy-efficient home occupants [20]; they are too extensive to be repeated here.

*Northwest Study of Correlation of Air Leakage and High Moisture Content Sites*

In the Northwest Wall Moisture Studs [20] of 86 new energy-efficient Pacific Northwest homes with relatively airtight construction, walls were opened up and unacceptably high wood sheathing moisture contents were measured in numerous wall cavities. A separate field investigation was undertaken at one Helena, Montana home in an effort to determine the cause [59]. The moisture content of the wall sheathing was measured from the outside of the wall, both high and low, in every stud cavity of two walls (120 locations). Three locations were found with more than 40% moisture content, four locations with between 30 and 40%, and eleven locations with between 20 and 30%. Because evidence suggested that the source of the winter moisture buildup in the wood sheathing was moist indoor air migrating out through penetrations in the polyethylene air/vapor barrier, infrared thermography was used during house pressurization and depressurization to locate air-leak sites and paths. Numerous air leaks were observed both on the inside and outside of the exterior walls even though the house was found to be very airtight (1.2 ACH at 50 Pa). Many of the leaks resulted from improper sealing or poor workmanship and could have been avoided. What is most important is that a definite correlation was found between the locations of many of the major air leaks and the locations of sheathing with high moisture content. In almost every one of the 18 places where the sheathing moisture content was more than 20%, there was a noticeable air leak in the wall cavity. Thus, the air leaks on the interior portion of the walls introduced moisture into the tightly built wall cavities that could not dry out during the winter. In the study, suggestions were made to help minimize the effects of air leakage and keep tightly built wall cavities dry. A number of recommendations for further study also were presented.

*Alberta Building Envelope Moisture Accumulation Field Study*

Tests were carried out during the 1989-1990 heating season on a single-story house with a full basement and gable end attic in Edmonton, Alberta, Canada [45]. Four south and four north wall panels were monitored, half of which had glass fiber insulation while the other half had sprayed cellulose insulation. Each insulation type had two types of exterior sheathing one was conventional plywood and the other had a vented air gap between the insulation and the exterior plywood sheathing. Each panel had a small leakage site through the interior drywall which allowed air to exfiltrate or infiltrate depending on ambient conditions. Moisture contents of the wood-based wall components were measured hourly with moisture pins, while airflow through the wall panels was measured directly with a small orifice plate flow meter.

Infiltration flows were generally higher than exfiltration flows, and the direction of flow was determined mainly by the wind direction. After the cellulose dried, it had a 20 to 30% higher flow resistance than glass fiber. That is in agreement with the earlier results from a field study involving blower door tests on older homes before and after having wall insulation of different kinds blown [6].

Sheathing moisture contents in the glass fiber panels showed a cyclic moisture absorption-desorption pattern with peak moisture contents reaching 16% moisture content in the north panels. Absorption was correlated directly with periods of large exfiltration through the leakage site during cold weather while desorption occurred during subsequent mild periods. There was no evidence of a steady increase in sheathing moisture content associated with diffusion of water vapor from indoors to the sheathing.

The cellulose panels exhibited a rapid initial increase in sheathing moisture to a peak of 36% moisture content, associated with redistribution of moisture within the wall cavity (the cellulose initially had 50 to 60% moisture content). However, there was gradual drying throughout the heating season. Direct solar gain on the south panels resulted in much lower sheathing moisture contents.

*Edmonton, Canada Field Monitoring of Wet-Sprayed Cellulose in Walls*

Seven different wall sections or orientations of a typical home insulated with wet-sprayed cellose were instrumented to evaluate the rate of drying and the effect of moisture on wall building components and to evaluate the effect of wet- sprayed cellulose on air leakage [60]. Point-in-time monitoring of wood moisture contents took place for one year. Installation of the cellulose increased the initially dry wood component moisture contents to approximately fiber saturation within 30 days of installation. The framing dried to near preinstallation levels within six months. Factors affecting the rate of drying were determined. It was concluded that the cellulose cannot be considered an air barrier. The exterior sheathing provided the majority of the air resistance across the wall sections tested. Examination of sections of the exterior walls one year after construction gave limited evidence of deterioration.

*National Research Council Saskatchewan Field Study*

Tests were conducted that involved monitoring moisture levels in the wood members of six different wood-frame construction north-facing wall panel sections in an outdoor test facility at the Prairie Regional Station of the Institute for Research in Construction in Saskatchewan, Saskatoon, Canada [35]. The insulation levels in the walls were relatively large, ranging from a nominal value of R-3.9 to R-7.1 $m^2$•K/W (R-21.9 to R-39.9 $ft^2$•h•F/Btu); that is essentially the same range as the 86 test homes examined in the Northwest Wall Moisture Study [20] in which it was found that increased cavity insulation levels led to increased moisture contents in the cavity wood members (as high as 55% in one case).

The indoor relative humidity was kept at 50%, which was felt to be not atypical of that in future tightly built houses in the region. The pressure inside the room was set to approximately 20 Pa above ambient to maintain a relatively constant airflow through the panels from inside to outside. That is about as much room pressurization as one would expect from the operation of a typical forced air heating system. Moisture contents of wall wood members were measured manually from moisture pins using a moisture meter at two week intervals during the period from mid-December 1989 to mid-May 1990. The walls were constructed of kiln-dried wood that was initially between 8 and 1% moisture content. Two of the wall panels had special calibrated orifices inserted to measure the flow rate through the walls.

It was found that five of the six wall panels exhibited wood moisture contents above 20% during the winter. In fact, all five had readings above 40%, with one having a reading as high as 70%. However, just as in the Montana homes tested in the Northwest Wall Moisture Study, the walls all dried out over the summer months. Thus, in such climates that have relatively warm and dry summers, there would not appear to be any likely structural degradation in new homes with heavily insulated walls. Furthermore, the results suggest that room pressurization may lead to rather high moisture levels during the winter, but nonetheless the walls will probably dry out in such climates. That may not be as true in less forgiving climates with less drying potential, such as northern marine climates.

## Older Existing Homes in Southern Climates

*Gulf Coast Masonry Wall Field Study*

Trechsel, Achenbach, and Conklin [19] conducted a field study of moisture problems in the exterior walls of a masonry housing development in Pensacola Naval Air Station, Florida from September of 1982 to May 1983. As noted earlier, indoor moisture problems included moist and waterlogged wallboard and mildew on walls and in furnishings. Most of the Problems occurred below or adjacent to windows. Measurements of temperatures, relative humidities, air infiltration, and water leakage were made on several houses, and an occupant survey of 86 houses was undertaken to assess and resolve the existing indoor moisture problems. Standing water was observed in concrete block cavities.

It was concluded that rainwater penetrating through cracks in the masonry walls and at windows was the major source of moisture observed in the gypsum hoard and the wall insulation. Inadequate ventilation, particularly in bedrooms, and possibly capillary rise of moisture from the foundations may also have contributed to the moisture problems.

## Newly Constructed Homes in Southern Climates

*U.S. Forest Products Laboratory Wall Panel Tests*

TenWolde and Mei [61] conducted tests on an air conditioned test building with nine instrumented south wall panels of different constructions in the warm, humid climate of Beaumont, Texas. All panels had 89-mm ($3^1/_2$-in.) fiberglass batt insulation and hardboard siding over either wood fiberboard sheathing or aluminum-faced molded expanded polystyrene sheathing. A polyethylene sheet was installed between the fiberboard sheathing and siding in one panel, whereas another contained a ventilated airspace between the fiberboard sheathing and siding. Two of the panels contained a polyethylene vapor retarder on the room side of the batt insulation. Temperatures and humidity conditions in the panels were recorded from early spring until late fall in 1984.

Generally speaking, all the wail panels showed little or no evidence of condensation. and walls with an outside vapor retarder as well as walls without any vapor retarders remained dry throughout the study period. The results did not clearly show a need for a vapor retarder on the outside of the wall. The siding in walls without the aluminum or polyethylene between the siding and the sheathing generally was drier and experienced less fluctuation in moisture conditions than the siding installed over the aluminum facing or the polyethylene sheet. An interior vapor retarder was found to be somewhat undesirable unless an exterior vapor retarder is installed as well. The ventilated airspace had little effect on moisture conditions in the siding or the rest of the wall, but the results might have been different with foil-faced sheathing. Taping of the joints between sheathing panels had no effect on moisture conditions in the walls.

A somewhat similar study was conducted by monitoring eight test panels in an unoccupied building in Gulfport, Mississippi [52]. The building and test panels were the same as those previously reported in the section on 'Newly Constructed Homes in Northern Climates.' In fact, the results were essentially the same. Although condensation occurred for limited time periods in some panels, the moisture content of framing did not rise to critical levels and so the potential for deterioration of materials was deemed to be minor.

## CONCLUSIONS

### Indoor Excess Moisture Problems

It should be stressed that indoor moisture problems have not been particularly well documented, in part because they are often considered more of an aesthetic nuisance than exterior or wall cavity moisture problems that may involve structural damage, which is clearly more severe. Based on the Iowa survey experience, it is also likely that some type of indoor moisture problem exists in almost all houses, and in most instances in the past the right questions of occupants simply have not been asked to accurately determine the degree to which moisture-related problems exist.

The situation maybe very similar with health effects related to indoor moisture problems. We probably haven't done a good enough job of asking the right questions and so likely have underestimated, perhaps significantly, the degree to which such problems exist. In years past, things like mold and mildew were mainly considered a nuisance, whereas now it is increasingly being recognized that mold and mildew can have serious health repercussions. Thus, indoor moisture "problems' need to be taken much more seriously than they have in the past.

Certainly, in the authors experience, as well as judging from the studies discussed in this chapter, indoor moisture problems are vastly more pervasive than exterior or wall problems in the United States. Generally speaking, indoor moisture control has not been a serious concern of the building community or the building science research community. As a result, indoor moisture problems are fairly commonplace, both in older existing and newly constructed homes. At the other extreme, wall moisture problems are relatively rare.

Most of the indoor moisture problems are related to excessively high indoor relative humidities caused by the lack of satisfactory indoor moisture control. Moisture control has occurred mostly by chance rather than by proper design. Ventilation systems have not provided reliable moisture control and probably should not be relied upon to do so, especially in mild weather when ventilation is relatively ineffective. Dehumidification for general moisture control. in combination with spot ventilation and automatic control of exhaust fans for source control, along with continuous whole house ventilation for control of all other indoor air pollutants appears to be a very workable solution.

There appears to be a dramatic need for better indoor moisture control in both new and existing residences. Moisture control should have a much higher priority in programs involving weatherization of existing homes and in the design, construction, inspection, and ongoing operation of new homes. Without increased emphasis on substantially improving indoor moisture control in all homes, moisture problems will only get worse, leading to reduced durability of the homes and increased health problems for the occupants.

### Exterior Excess Moisture Problems

One of the major findings of the research noted in this chapter is that crawl space ventilation is not necessary in most climates and in fact may even cause severe moisture problems in warm, humid climates, especially in air conditioned homes. Yet in spite of the overwhelming scientific evidence to that effect, building code agencies do not seem to be aware of this situation and almost uniformly require crawl space ventilation. This needs to be changed, especially when it is realized that eliminating ventilation will save energy and reduce construction costs. Of course, in some situations, ventilation may he desirable, such as to help mitigate radon.

Attic moisture problems have been found to be strongly related to the exfiltration of moist indoor air through a variety of ceiling bypasses or penetrations, especially when the installation of attic insulation results in relatively cold roof sheathing that acts as a condensing surface. Sealing the bypasses and penetrations should greatly help reduce attic moisture problems. As with crawl spaces, there is a growing feeling within the building science community that the present code levels of attic ventilation have little relevance today and need to be reconsidered.

It also is important to again stress that exterior moisture problems do not occur anywhere as often as indoor moisture problems. Yet, the vast majority of research is related to either exterior or wall moisture problems rather than indoor moisture problems. What few research results that are available regarding the health effects of indoor moisture problems, in combination with the fact that indoor moisture problems appear fairly commonplace, strongly suggest that the health effects of moisture-related biological contaminants could be vastly more serious than has generally been recognized. Our priorities appear to be incorrect and in need of major change.

### Excess Moisture Problems and Damage Inside Exterior Walls

These problems have received considerable attention, and yet wood decay and resultant structural damage inside exterior walls is relatively rare, albeit expensive when problems do occur. However, again this author believes our priorities are wrong. Our first priority in dealing with housing should be the health and safety of the occupants. Houses should not make the occupants sick! Only after we have learned to make healthy buildings should we turn our attention to the second highest priority, which is maintaining the durability of buildings.

Designing buildings that we live in should not result in the failure of the buildings themselves. It seems we have placed most of our emphasis on durability or even affordability (saving energy used in buildings). However, the major emphasis for building scientists should be to develop methods to provide satisfactory health and safety of the occupants of the homes that are constructed. We need to recognize the need to reorder our priorities and focus more of our efforts on providing healthy indoor environments. One major step in that direction would be to start paying considerably more attention to assessing and solving indoor moisture problems.

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## APPENDIX

### RESIDENTIAL MOISTURE PROBLEM ASSESSMENT CHECKLIST

Name: ____________________________________________________________ Date: _____/_____/_____

Address: ________________________________________________________________________________

Hone phone #: _______________________________ Work phone #: _________________________________

Service #: __________________________________ Tech #: ___________________ House ID#: __________

### Excess Moisture Symptoms/Problems

Interior: Occupant/Auditor Comments

☐ Mold/mildew/stains on surfaces (e.g. walls, ceiling)

Note room type and location: ________________________________________________________

- ☐ In bedroom closets: ☐ Mold/mildew on clothing
- ☐ Behind furniture (poor air circulation)
- ☐ Mold/mildew/staining on ceiling below attic insulation voids
- ☐ Mold/mildew/dampness in carpet

☐ Mold/mildew/staining on window frames

☐ Mold in furnace humidifier water tray (a potential major health problem)

☐ Musty or damp odor

☐ Condensation on window glass/frames

- ☐ Almost none
- ☐ Only on very cold winter days
- ☐ Often throughout the winter
- ☐ Often during the fall and spring
- ☐ Only on a few windows
- ☐ On most windows
- ☐ Water sometimes runs down onto sill
- ☐ Water often runs down onto sill

☐ Sill condensation damage (staining, rot): minor [ ], major [ ]

☐ Sweaty pipes (note location and season)

☐ Basement dampness and leakage

☐ Efflorescence (white powdery substance), mold and/or dampness on foundation walls

☐ Other (describe)

Exterior:

☐ Evidence of splashback (explain)

☐ Attic condensation and/or frost

☐ Waler stains on roof sheathing

☐ Attic nail halos (dark rust stains around nails) indicating long term chronic moisture

☐ Attic bypasses/air leaks (including dark stains of insulation or moist insulation)

☐ Roof leaks; ☐ ice dams

☐ Blistering/peeling paint (note side of hause)

☐ Buckled siding (note type and location)

☐ Crawl space mold/mildew

☐ Wood decay (describe and note location)

☐ Wood member moisture content greater than 30%

☐ Other (describe)

## Monitoring and Occupant Interview Results - Continued

Dehumidifier: none[ ]; # in basement[ ], used summer[ ], used spring/fall[ ], used wirter[ ]; # in other locations[ ] used summer[ ], used spring/fall[ ], used winter[ ]; locations: ______________________________

Brands, model #s, and capacities (pints/day): ______________________________

Method of control: on continuously[ ], operates as needed[ ]

Water (condensate) removal method: drain line[ ], manually as container fills[ ]

If manual removal. gallons per day of water removed (occupants best guess): __________

Other (describe): ______________________________

## A Potential Moisture Sources

☐ Unvented space heater (e.g. kerosene, propane, or gas heater)
*This can be one of the largest moisture sources in a home.*

☐ Humidifier: portable[ ], furnace[ ]; used during heating season: almost always[ ], sometimes[ ], seldom[ ]

☐ Clothes dryer vented indoors; loads of wash per week: _____

☐ Plugged dryer vent (look from outside)

☐ Clothes dried indoors

☐ Firewood stored indoors, including basement

☐ Crawl space without ground cover

☐ Water pooling on crawl space ground cover

☐ Poor grading-water ponds/puddles near house or water drains toward house

☐ Basement flooding

☐ Open concrete block cores in basement walls

☐ Liquid water seepage through foundation walls

☐ Open sump pump hole

☐ Exposed dirt/hole through basement concrete floor (e.g. for well or water pipe entrance)

☐ Gutter downspout not connected to sewer or suitable drain or otherwise ineffective

☐ No gutters

☐ Plumbing leaks

☐ Poorly caulked tub or shower enclosure grout

☐ Cooking without lids

☐ Cooking without using kitchen exhaust fan

☐ Gas stove: for cooking[ 3, for space heating[

☐ Forced air heating system return duct leakage

☐ Kitchen or bathroom fan(s) exhausting into attic (not to outside)

☐ Aquariums

☐ Recent remodeling or construction

## Occupant/Auditor Comments and Additional Remarks

## Basic House Characteristics

House age. (yrs): __________; # of occupants: day __________, nite __________; # of smokers: __________
Heated area (sq ft):__________; 1st floor ceiling height (__________ft, ______ inches); # stories: __________
Window glazing: single[ ], double (or single wlstorm)[ ], triple[ ], dbl low-e[ ]
Window frames: wood[ ], metal[ ], TIM (thermally-improved metal)[ ], vinyl[ ]
Wall insulation: Y____, N____; ceiling insulation: Y____, N____
Floor type: basement[ ](heated:__________%, unheated: __________%), crawl[ ], slab[ ], mixed[ ]
Foundation wall type: concrete[ ], conc. block[ ], stone/brick[ ]
Spaceheating system: electric resistance[ ], heat pump[ ], forced air furnace[ ],
vented space heater[ ], unvented space heater (e.g., kerosene heater)[ ]
Wood stove, fireplace insert, or fireplace regularly used for space heating: Y____, N____
Gas or propane range (oven) regularly used for space heating: Y____, N____

## Monitoring and Occupant Interview Results

CFM5O: pre-air sealing __________________, post-air sealing __________________
Thermostat settings: heating ______$^{o}$F; cooling ______$^{o}$F (NA if not applicable)
Measured temperatures (dry bulb)[1]: living room ______$^{o}$F, master bedroom ______$^{o}$F
heated basement ______$^{o}$F, unheated basement ______$^{o}$F; outside air ______$^{o}$F
Measured RH: living room ______% master bedroom ______%, heated basement ______%
unheated basement ______%, other (location:__________________) ______%
outside air ______%
Primary bathing/showering bathroom exhaust fan: Y____, N____; rated cfm ______;
# showers per day: ______
Other bathroom exhaust fan Y____, N____; rated cfm
If bathroom fan(s) exist(s):
Exhaust fan hlades clogged with dust/dirt/grease: primary bathroom Y____, N____;
other bath Y____, N____
Exhaust fans work (toilet paper test): primary bathroom Y____, N____;
other bath Y____, N____
Measured exhaust fan cfm: master bathroom ______, other bath ______
Bathroom fans used when bathing/showering: seldom[ ], sometimes[ ], whenever needed to clear windows or mirror[ ], almost always[ ]; occupants limit use because fan is too noisy: Y____, N____
Bathroom fan typically operated more than 15 minutes: Y____, N____
Bathroom mirror stays fogged after showering: never[ ], seldom[ ], often for a few minutes or less[ ], often for more than five to ten minutes[ ]
Bathroom and kitchen exhaust fans ducted/vented: to attic[ ], to outdoors[ ]
Kitchen exhaust fan: none[ ], recirculating, nonvented type[ ], vented type[ ]
Vented kitchen fan works: Y____, N____; filter screen clogged with grease: Y____, N____
Kitchen exhaust fan used: seldom [ ], whenever needed to clear windows or odors[ ], almost always when cooking[ ]; occupants limit use because fan is noisy: Y____, N____ Forced air system return duct leak test w/smoke generator: leaking[ ], well sealed[ ]

1. Basement and outside air temperatures and relative humidities should be measured year round; in the other room locations they should be measured only during the heating season (fall, winter, spring).

## Recommended Moisture Control Strategies

- ☐ Indoor moisture source control
  - ☐ Discontinue use of unvented space heater, including oven for space heating (major source of indoor air pollutants)
  - ☐ Vent clothes dryer outside
  - ☐ Clear plugged dryer vent
  - ☐ Dry clothes outside
  - ☐ Store firewood outside
  - ☐ Cover aquariums
  - ☐ Discontinue use of humidifier or vaporizer, especially in spring, summer, and fall when not needed
- ☐ Install crawl space ground cover
- ☐ Improve grading so that water drains away from house
- ☐ Install gutters
- ☐ Improve existing gutter drainage (low cost option is to add 8-10 foot downspout extensions to move the gutter water flow away from the foundation)
- ☐ Dampproof basement
- ☐ Seal/caulk basement cracks
- ☐ Cover/seal sump pump opening
- ☐ Cover/seal exposed dirt in basement concrete floor hole
- ☐ Seal forced air return duct leaks with mastic (NOT duct tape)
- ☐ Seal attic bypasses and other air leaks into attic
- ☐ Eliminate attic insulation voids
- ☐ Educate occupants regarding need to increase use of ventilation systems
- ☐ Install bathroom fan automatic control: timer! 3 or dehumidistat! I
- ☐ Clean/vacuum dirty/clogged exhaust fan blades/filters that constrict air flow
- ☐ Install bathroom exhaust fan: quiet (2 sone minimum), 80 cfm minimum rated capacity
- ☐ Dehumidifier (40 pint per day minimum)(use existing model only if it has automatic defrost control)
- ☐ Improve closet air circulation (leave doors open or install louvered doors) or heat closet (leave light on)
- ☐ Clean mold from furnace humidifier water tray
- ☐ Other (describe)
- ☐
- ☐
- ☐

## Moisture Control Actions Already Undertaken by Occupants

*Action Description With Approximate Date and Results of Action:*

- ☐
- ☐
- ☐

*Checklist designed by George Tsongas; version 4 (revised 11-3-92)*