Case Studies of Moisture Problems in Buildings

G. Proskiw, PEng
Member ASHRAE

ABSTRACT

Seven buildings, displaying various types of moisture distress, were examined to diagnose the causes of these problems. By employing a variety of diagnostic tools, the moisture transport/deposition mechanism for each building was identified, a diagnosis developed, and remedial action determined. Using the lessons learned with these seven structures, guidelines were developed to aid in the identification of moisture problems in other buildings.

INTRODUCTION

Perhaps the greatest truism ever uttered about building science is a little quote which appears in the introduction of Moisture Migration In Buildings, a Special Technical Publication (#779) published by the American Society for Testing and Materials:

> Except for structural errors, about 90 percent of all building construction problems are associated with water in some way. (ASTM, 1982)

A functional understanding of moisture sources, transport mechanisms and failure modes is a fundamental requirement of good building science and a key skill set for practitioners who find themselves attempting to understand why a building does not function as it was intended. This paper will examine various case studies involving buildings which suffered from moisture distress and then use these to develop general principles which can be used to guide investigations of other problem structures. Also included is a short discussion of various diagnostic tests, examination procedures and other tools which can be used in these assessments. All of the buildings described in this paper are located in southern Manitoba, Canada—a region with long, cold winters (5500 to 6000 Celsius heating degree-days or 9900 to 10,800 Fahrenheit degree-days), hot summers and low to moderate levels of precipitation.

MOISTURE AND BUILDINGS

There are very few construction materials, components or systems which are not vulnerable to some form of moisture attack. Furthermore, most buildings are exposed to numerous sources of moisture, whether in vapor, liquid or solid form. Moisture can cause material or component damage through a number of failure mechanisms including:

- Wood rot
- Freeze/thaw damage
- Dimensional changes
- Delamination
- Corrosion
- Mold development
- Staining
- Degradation of non-moisture resistant materials
- Efflorescence
- Loss of insulating capabilities

MOISTURE TRANSPORT/ DEPOSITION MECHANISMS

Understanding moisture transport, moisture deposition and the mechanisms by which they occur are key requirements for diagnosing and correcting many types of building problems. Over the years, a variety of schemes have been proposed

***Gary Proskiw** is President of Proskiw Engineering, Ltd., Winnipeg, Manitoba, Canada.*

for classifying moisture transport and deposition mechanisms. In this paper, they will be organized into six categories: air leakage, vapor diffusion, gravity flow, capillarity action, wind-driven rain and surface condensation.

Air Leakage

All buildings experience uncontrolled air leakage due to the combined effects of stack action, wind and operation of mechanical systems. Since a building cannot store air, it will normally experience both air infiltration and exfiltration, although at different locations on the envelope. However, since air also contains appreciable amounts of water vapor, air leakage is also a very effective moisture transport mechanism. If exfiltrating air is cooled to its dew point during its transit through the envelope (which can easily occur under winter conditions), interstitial condensation will result. Given the byzantine nature of most air leakage pathways, this can result in moisture deposition in very unexpected locations.

Vapor Diffusion

With the exception of metal, glass and some plastics, most building materials are fairly porous on a microscopic level. As a result, water vapor molecules are able to diffuse through the material if there is a difference in the water vapor pressure across the material or component. Fortunately, this process is relatively weak compared to the other transport mechanisms, and vapor diffusion is seldom a major cause of building distress.

Capillarity

Capillarity is the process by which liquid water moves (or wicks) through an ostensibly solid material by virtue of the surface tension of the water molecule. It can transport large quantities of water both vertically and horizontally and is normally controlled through use of materials which have either very small or very large pore dimensions.

Gravity

Perhaps the most basic of all transport mechanisms, gravity flow occurs whenever liquid water is able to transit through or around a material by virtue of a hydrostatic head. It is potentially the most powerful of all the transport mechanisms and is normally controlled through use of waterproof materials or by draining the source of water.

Wind-Driven Rain

Under the right circumstances, large amounts of water can be forced into the building envelope due to wind-driven rain. If adequate drainage or other protection is not provided, major damage can result.

Surface Condensation

Although not usually considered by some as a separate transport mechanism, surface condensation occurs when moist air comes into contact with a cold interior surface on the building envelope, resulting in condensation on the exposed surface. It is normally controlled by raising the surface temperature of the envelope (for example, by increasing the thermal resistance) or by lowering the relative humidity of the air.

DIAGNOSTIC TOOLS

One method of diagnosing moisture problems is to identify the source(s) of the moisture and then determine how it is being transported to the affected parts of the building. Potential moisture sources are usually easy to identify or at least to short list. The transport mechanism is generally more difficult to assess, but its proper determination often leads to an understanding of the problem. Once that has been achieved, a remedial action plan can be developed. Fortunately, there are a number of tests, tools and examination protocols which can provide useful guidance when one is attempting to understand the mechanism(s) at work when investigating moisture-related building problems.

Airtightness Tests And Examinations

An airtightness test is performed by installing a high capacity blower in a suitable doorway to the building, depressurizing the structure to a pre-defined level and then measuring the amount of air leakage which occurs. It not only permits the air leakage to be characterized (quantitatively), but it can also be used to identify locations where air leakage is occurring and provide a general indication of how powerful the leakage is under standardized test conditions (qualitatively). The latter is particularly useful when a single zone in a multi-zone building is being tested since a qualitative evaluation can identify the leakage locations and provide guidance on any remedial work which may be required. Protocols such as CGSB 149.10 or ASTM E 779 can be used.

Pressure Diagnostics

Pressure diagnostics refers to the measurement of various pressure differentials across building components or between individual zones in a building, either under natural conditions or courtesy of some type of mechanical pressurization. For example, by measuring the pressure differential between two zones in a building under natural conditions and then with one of the zones depressurized, the degree of pressure communication between the two zones can be established. This could be used to establish the degree to which air leakage is responsible for moisture transport between zones. No standardized protocol exists.

Polyethylene Test

The so-called polyethylene test is used to determine whether moisture is moving through an assembly by capillary action (CMHC, 1992). Pieces of clear sheet polyethylene, approximately 0.6 m x 0.6 m (2' x 2') are attached to the suspect surface with duct tape and left for two or three days. If, at the end of the exposure period, no damp spots are visible on the backside of the polyethylene, then it can be concluded that moisture is not moving across the surface by capillary action. If condensation forms on the top of the polyethylene, then it is originating from internal (building) sources. This test is useful for applications such as determining whether water is moving through a concrete floor slab by capillary action or gravity flow.

Standing Water Test

This "test" (actually, an observation) complements the polyethylene test described above and is used to separate moisture movement due to capillary action from that which occurs due to gravity flow (CMHC, 1992). Basically, it makes use of the fact that water on a horizontal surface likely appeared due to one of these two mechanisms. Unlike gravity flow however, capillary action is not capable of transporting water to a surface in sufficient quantities for standing water to develop. Thus, the presence of pools of water (as opposed to simply a damp surface) indicates that gravity flow is likely the source of the observed moisture.

Spray Test

This test is used to assess whether wind-driven rain is moving water into the building envelope. Using a specially constructed spray rack (which contains a number of regularly spaced nozzles) or a hose, water is sprayed over the suspect area for a period of time (about five to fifteen minutes). The building interior (and exterior, if necessary) are then examined for evidence of water penetration.

Infra-Red Thermography

Thermography can be a very useful tool for diagnosing air leakage and surface condensation problems. When an airtightness test is performed with a non-trivial temperature difference between the indoors and outdoors, the infiltrating air will cool any surfaces close to the air leaks which can then be readily identified using thermography. Surface condensation problems can also be diagnosed using thermography since they require the existence of cold spots on the building envelope (or other surface) to occur.

Dew-Point Calculations

This procedure is useful for diagnosing surface condensation problems and is particularly helpful since surface condensation can form in a very thin layer which may not be visible to the naked eye. The air temperature and relative humidity are measured under representative conditions and used to calculate the air's dew point using a psychrometric chart. By measuring the surface temperature of the suspect area, or performing calculations to estimate the surface temperature using knowledge of the thermal resistance of the assembly, the maximum allowable relative humidity level which can be sustained without surface condensation occurring can be calculated. If this humidity level is exceeded by the observed conditions, then surface condensation can be assumed to be likely.

CASE STUDIES

Building #1—Condominium with Leaky Windows

Building Description. This four story, wood frame condominium was approximately four years old at the time of the investigation. Constructed with high levels of insulation (e.g. the walls used RSI 4.93, R-28 batts) and relatively airtight details, the building employed high performance PVC windows with double or triple glazing, insulated spacer bars and argon gas fills. One unusual feature of the building was that each suite had its own natural gas direct vent furnace and distribution system which used perimeter ductwork physically situated in the corner between the exterior wall and the ceiling. Mechanical humidification was seldom used and interior humidity levels were moderate.

Reported/Observed Symptoms. The building had a history of moisture problems dating back to its initial occupancy. At various times during the winter, significant quantities of moisture were observed to be leaking out of the wall system to the outdoors, always above the windows. The problem was reported to be more prevalent in corner suites. The wetting events occurred predominately during short periods of unusually warm weather which occur during the winter. The contractor had already replaced a number of the windows with no improvement in the problem.

Analysis Protocol. Two observations suggested that the windows were not the source of the problem. First, the reported location of the water leaks was at the top of the windows (above the window heads), not through or below the windows. This indicated that the water was entering the wall system above the windows, draining down through the walls until it reached the window head where it was directed to the outdoors. Second, the appearance of the problem during winter warm spells implied that air leakage was the culprit since these two phenomena have been linked together. Continuous air leakage through an insulated pathway in the building envelope results in interstitial condensation which, during periods of extreme sub-freezing temperatures, results in the build-up of ice within the envelope – often in surprisingly large quantities. When a period of warm weather occurs, all or most of this ice melts, resulting in the apparent creation of leaks in the envelope which are often painfully visible to all concerned. In fact, this event can produce a flood-like appearance since several months' worth of condensation may melt within a few hours. Given these observations and this possible explanation, the question to be resolved was where the air leaks were occurring and what was causing them. To investigate, a qualitative air leakage examination was performed using a standard, residential blower door on one of the suites which had displayed the symptoms. Not unexpectedly, this revealed that while leakage pathways could be identified, they were not unusual in terms of their prevalence or magnitude. Furthermore, the pathways could not readily be correlated with the areas where the water problems were observed (above the windows).

At this point, the investigation took a new course with the realization that if air leakage was the transport mechanism by which water was entering the wall system, then the driving force might be mechanically-induced air leakage, not naturally-induced exfiltration. This hypothesis was supported by the absence of correlation between those suites displaying the problem and their vertical location in the building (since air exfiltration problems tend to be most severe on the upper portions of the building envelope). In particular, the position of the heating system ductwork in the exterior wall/ceiling corner was a cause of concern. The construction drawings indicated that the drywall extended behind the duct bulkhead, but experience had shown that hidden joints are often extremely leaky. The fact that the problem was more pronounced in corner suites was consistent with this hypothesis since corner suites would have increased heat loss (relative to non-corner suites), meaning that their heating systems would have had to run more frequently. Consequently, this would have caused the bulkheads to be pressurized more often than was the case for non-corner suites. To avoid removing the drywall around the bulkheads, a series of pressure diagnostic measurements were performed to evaluate the pressure differential between the inside of the bulkhead and the outdoors.

Diagnosis. The pressure diagnostics revealed that when the furnace fan was operating, the pressure differential between the inside of the bulkheads and the outdoors increased from approximately zero to a maximum of +10 Pascals (Pa) as the result of duct leakage. Any leakage paths in the exterior wall air barrier behind the bulkheads would have been subject to a moderately strong driving force which would cause air exfiltration and moisture deposition, as shown in Figure 1.

Remedial Action. The ultimate solution would have been to repair the cracks behind the bulkheads; however, this would have involved considerable cost and disruption to the occupants. Instead, a series of pressure-relief grilles were installed in the bulkheads of each suite, giving a total relief area of approximately 400 cm^2 (62 in^2) per suite. Selected to have the same appearance as the heating registers, these grilles reduced the bulkhead-to-outdoor pressure differential to near zero, thereby significantly reducing the driving force for air leakage and moisture deposition. At a cost of less than $100 per suite, this technically sub-optimal solution was selected as the most practical solution to the problem.

Building #2—Apartment with Mold Above the Ceiling

Building Description. This three story, walk-up apartment building was about 30 years old at the time of the investigation. The exterior wall system used masonry construction with interior strapping and insulation. The flat roof was built with wood framing and modest amounts of insulation. The foundation consisted of a crawl space which covered the entire footprint of the building; furthermore, the crawl space was sub-divided into a number of discrete spaces which roughly corresponded to the floor plan above – one space for the corridor and a series of enclosed spaces below each main floor suite. Heating in the building was provided by gas-fired boilers in conjunction with perimeter baseboard heaters. Mechanical ventilation consisted of occupant-controlled bathroom fans exhausting through the roof. Neither mechanical humidification nor corridor pressurization was provided.

Reported/Observed Symptoms. The building exhibited a very curious moisture problem. One of the suites on the top floor experienced unusually high relative humidity levels which had led to mold development on various surfaces and water leakage out of openings in some drywall surfaces (such as ceiling-mounted light fixtures). The problem had persisted for several years, during which time a number of different tenants had occupied the suite. The damage had been repaired several times at considerable expense but re-occurred the next heating season. At the time of the investigation, most of the ceiling and exterior wall drywall had been removed, revealing the rotting wood ceiling joists and roof sheathing, mold growth and corrosion of metal components. The roof above the suite had recently been replaced and appeared to be leak-free. No other suites in the building exhibited the problem.

Analysis Protocol. The fact that only one suite, located on the top floor, was exhibiting the problem strongly suggested that a roof leak was the problem. However, the recently-applied new roof above the suite appeared to be in excellent condition. Furthermore, no roof leakage was observed during the heavy rains that occurred while the underside of the roof was exposed to the suite below. Also, the mold and staining patterns evident on the roof sheathing were widespread and uniform over the suite ceiling area - not concen-

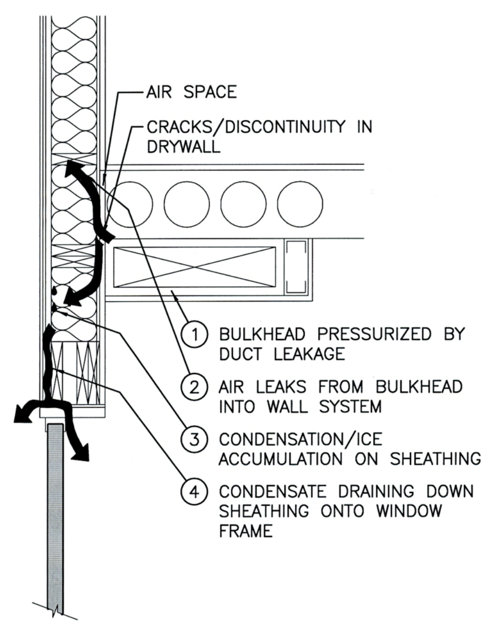

Figure 1 *Mechanically induced air exfiltration into exterior wall system.*

trated in one or two locations which would be expected with a roof leak. Therefore, other potential sources of moisture had to be considered. Examining the building, the only significant source of water was in the crawl space, which occasionally had standing water present despite the use of exhaust fans. But how was moisture getting from the crawl space to the roof – and in only one suite?

To determine if moisture movement could be occurring from the crawl space to the suite, pressure diagnostics were employed between these two spaces. A blower door was installed in the doorway of the problem suite on the third floor and used to exhaust air into the corridor so as to establish a pressure differential of 20 to 35 Pa across the exterior envelope. Then, pressure differentials were measured between a) the crawl space and the suite on the main floor which was located (two floors) below the problem suite and b) the crawl space and the main floor corridor.

Diagnosis. As expected, activation of the blower door had no appreciable effect on the pressure differential between the main floor suite and that portion of the crawl space directly below it. However, the pressure differential between the crawl space and the main floor corridor immediately dropped by approximately 11 Pa when the blower door was activated. This indicated that the problem suite was able to communicate with the crawl space through some (as yet) unknown pathway.

Examination of the crawl space revealed two large holes in the wall of the concrete crawl space wall which separated the crawl space corridor from the crawl space suite space directly below the main floor suite described above. These had been added after the building was completed and were used to route new electrical and gas lines. No other such access holes could be found. This permitted water vapor from the main part of the crawl space to enter the enclosed space (two floors) below the problem suite. But how was it getting to the third floor while bypassing the two intermediate floors? Further examination revealed that a small plumbing chase started in the crawl space and ran vertically to the underside of the roof on the third floor with no openings on the main or second floors, as shown in Figure 2. The underside of the chase was open to the crawl space. Thus, air leakage was able to take place from the wet crawl space (two floors) below the problem suite courtesy of the two utility holes, into the bottom of the plumbing chase where it rose via stack effect into the enclosed roof cavity. Since the roof had little insulation, the roof space was comparatively cool, which permitted condensation to occur. Since the utility holes occurred in only one location, only the problem suite was affected.

Remedial Action. The solution to this problem was almost too easy: seal the top and bottom of the plumbing chase along with the two access holes made in the concrete walls in the crawl space. This stopped any air movement and prevented the transport of water vapor from the crawl space into the roof space on the third floor. Using a can of one-component polyurethane foam, the building's maintenance man was able to repair the problem for a total expenditure of about $10, although improvements were also recommended to the crawl space to reduce the moisture loading.

Building #3—Apartment Building with Peculiar Wet Spots on the Ceiling

Description. This eight-year old, three story, masonry structure served as a temporary residence for personnel on a military base. The foundation consisted of a crawl space with grade beams and piles while the structural floors of the building were constructed from concrete hollow core panels. The roof used a conventional truss assembly with asphalt shingles. The mechanical ventilation system consisted of a corridor pressurization system plus individual room exhausts from each suite which were ducted horizontally from the bathroom, across the bedroom through the exterior wall of the building. Space heating was provided from a remote, central heating plant while domestic hot water was provided from a series of natural gas tanks located on the main floor.

Reported/Observed Symptoms. In February, 2004, the building's staff noticed a series of wet spots on the undersides of the hollow core ceilings in various rooms in the building. Curiously, all of these wet areas were located in main floor rooms on the west side of the building, typically towards the north end of the structure. Similar wetting was not observed on the second or third floors.

Analysis Protocol. Initially, it had been assumed that the problem was simply a plumbing leak on the second or third floor which permitted water to leak into the hollow core floor system. However, closer inspection revealed there were no plumbing lines or other potential sources of moisture above the wetted areas. Further, all of the spots appeared to be located at approximately the same distance from the exterior walls. In any event, a single plumbing leak would not have

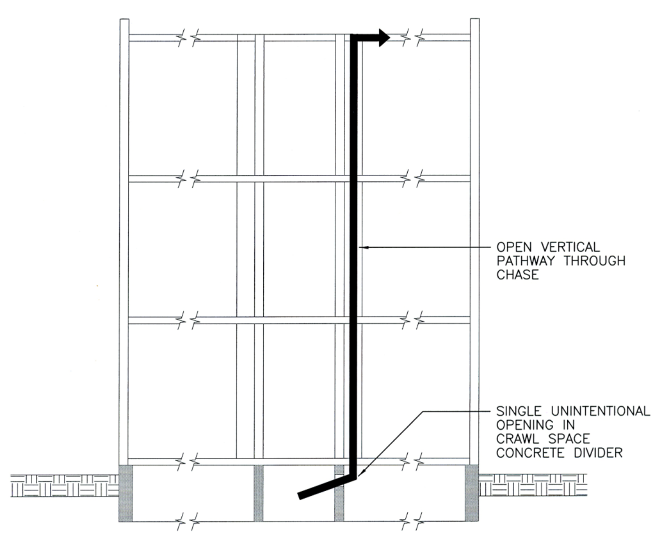

Figure 2 *Moisture transport from crawlspace to roof system.*

explained the emergence of the wet spots in several suites located some distance from each other. Since no apparent explanation could be offered to explain the wetting patterns, a careful visual examination was conducted of both the exterior and interior of the building. This revealed some interesting observations. First, several backdraft dampers on the suite exhaust ducts were damaged or missing. Second, the building was located in a relatively open area with nominal vegetation in the immediate vicinity. However, a number of downspouts on the west side of the building were either missing or seriously damaged. This permitted roof water to be dumped directly adjacent to the building, thereby raising water levels in the immediate vicinity of the foundation. This problem was compounded by the fact that the downspouts terminated on concrete splash blocks (at grade) which were only about 1 m (3') in length. Depending on the size of the excavation used for the foundation, roof water draining off the splash blocks could still enter the soil within the backfilled, water permeable soil around the foundation.

An examination conducted of the building's crawl space revealed that significant quantities of water were present on top of the polyethylene moisture barrier covering the undisturbed soil in the crawl space. Subsequent information provided by the building's staff revealed that in the spring of 2003, the crawl space suffered a major flooding event, with water levels reaching a depth of about 0.3 m (1').

Using pressure diagnostics, it was determined that under winter conditions, the crawl space was positively pressurized to about 8 Pa relative to the first floor. In addition, air was found to be leaking from the crawl space into the open ends of a series of telecommunications conduits which penetrated vertically into the hollow core ceiling of the crawl space. It was also observed that the distance from the conduit penetrations to the exterior wall was equal to the distance between the wet spots (on the floor above) and the exterior wall, suggesting a correspondence between the two.

Diagnosis. The wet spots were caused by a bizarre example of interzonal air movement within the building. As shown in Figure 3, humid crawl space air was able to leak into the open ends of the conduits due to stack effect. The conduits then entered various junction boxes on the main floor. Since the boxes were not airtight, the air leaked into the hollow steel stud partition wall housing the conduits. Next, the air moved up the partition wall into the oversized holes cut for the conduits in the floor slabs. Some of this air then entered the open end of the hollow core slab. The air then migrated laterally through the hollow cores parallel to the exterior wall, across the room, to the concrete block partition wall (which functioned as a fire wall). This lateral movement occurred because the steel stud walls were capped at the top of the third floor whereas the concrete block wall penetrated through the ceiling line of the third floor since it formed a fire separation.

However, as the air passed through the hollow core slab, just before it reached the concrete block partition wall, it was (with the correct ambient conditions) cooled from the underside by air infiltrating from the outdoors through the metal exhaust duct running between the bathroom and the outdoors. Under the appropriate conditions, some of this air in the hollow core was cooled sufficiently that moisture condensed out of the air stream. This was aggravated by the fact that birds had built nests in some of these exhaust ducts, thus jamming the backdraft dampers open (although the dampers were very loose in any event) and consequently eliminating any significant resistance to air flow. This also explained why the ceiling wetting was only observed on the ceiling of the first floor. Since the bathroom exhaust ducts on the first floor were located below the building's neutral pressure plane (which was estimated to be situated at about the ceiling level of the second floor), the first floor exhaust hoods on the exterior wall would normally have been exposed to negative pressure differentials during the winter. Since the dampers were loose fitting, the exhaust ducts functioned as air inlets whenever the fans were off (which, based on data from other buildings, was about 95% of the time). In contrast, the exhaust hoods on the second and third floors would have normally been exposed to positive pressure differentials, which meant that air would have moved in the opposite direction (indoors to outdoors), thus precluding any cooling of the ducts and preventing any condensation of moisture from the air in the hollow cores immediately above the ducts. The water condensed in the floor system then flowed horizontally to the low spot in the hollow core slab. If it encountered a micro-crack or other discontinuity, it was able to leak through the crack and stain the underside of the ceiling on the first floor.

Remedial Action. The ceiling staining problem was solved by carefully sealing the ends of the conduits in the crawl space using urethane foam, thereby preventing air from entering the conduits and creating the scenario described above. In addition, the backdraft dampers were repaired and

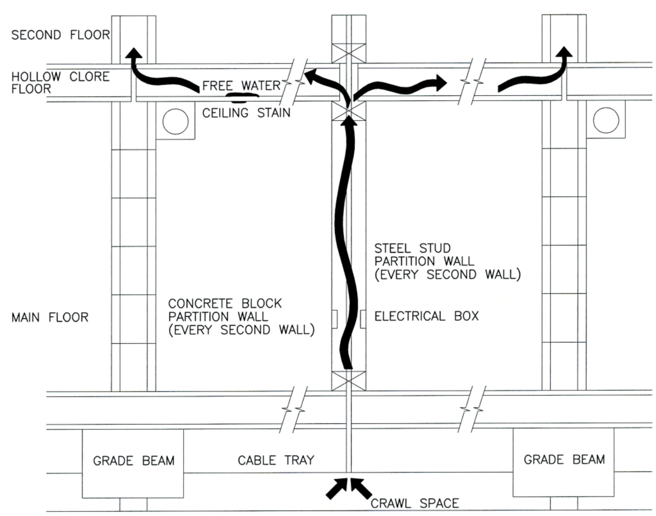

Figure 3 *Moisture transport from crawlspace to floor system.*

the exterior drainage was improved to route surface water away from the building.

Building #4—Condominium with Wet Walls

Description. This six-story, 40+ year old condominium had a history of moisture problems in its exterior wall system which dated back 10 to 15 years. The wall system used a brick veneer, 20 cm (8") concrete blocks, 38 cm x 38 cm (2x2) wood strapping and insulation on the interior covered by a polyethylene vapor barrier and drywall. The original windows were double-glazed, horizontal aluminum sliders with wood frames, although several had been replaced by the unit holders at various times over the last decade. The problem had become increasingly frustrating to the owners who had commissioned a number of investigations over the last five years to identify the cause of the problem. Recommendations from these investigations were varied and ranged up to a total re-skinning of the wall system and a cost exceeding a million dollars.

Reported/Observed Symptoms. For the last 10 to 15 years, the building had experienced various types of moisture-related problems including blemished and buckling drywall surfaces on the exterior walls and mould development, in various suites. The blemishes were present at various locations on the interior drywall surfaces of the exterior walls. Furthermore, they were located about 30 cm (12") above the floor, running in a horizontal direction and were most pronounced under the windows, around the hydronic heating cabinets and near electrical outlets. According to the Property Manager, the problems were most pronounced on the 4th, 5th, and 6th floors of the building. No unusual sources of moisture were present in the building, and humidity levels were typical for structures of this type.

Analysis Protocol. A number of qualitative air leakage examinations had been conducted over the preceding five years on various suites in the building to identify the location and relative severity of leakage pathways. While these identified numerous sources of air leakage, they were not considered unusual for buildings of this type or vintage. To provide more insight, a series of week-long measurements were made to assess the pressure differentials across the exterior wall and the ceiling on the top floor. In addition, a questionnaire was prepared and sent to approximately two dozen tenants.

Diagnosis. The pressure differential measurements revealed modestly positive differentials across the upper wall surfaces and ceiling; however, these were well within the range of expected values. Since the problems tended to be more prevalent on upper portions of the building, air exfiltration seemed to be playing a role. However, the exact mechanism could not be identified. At this point, the results of the tenant questionnaire were reviewed to see what insight they could provide. This revealed several interesting pieces of information. First, of the 13 suites in which the windows had been replaced (and whose owners had responded to the questionnaire), the original problems had failed to re-appear in all cases. Also, the windows which had been replaced were predominately on the upper floors of the building which corresponded to those wall sections which had reported the most severe wall problems. This suggested that both (stack effect-induced) air leakage and the windows themselves were links in the overall failure chain.

To understand how these observations fit together, it was only necessary to follow the logical chain of events which began with interstitial window condensation. As air leaked out through the windows during the winter, moisture condensed out of the exfiltrating air and froze into ice between the two panes of glass. In the spring, the accumulated ice melted, resulting in a short-duration flooding of the windows. Most of this moisture collected on the window sill where it was supposed to drain to the outdoors. However, drainage from the existing windows was problematic at best. In many cases, the condensation accumulated on the sills where it was able to leak through the wooden sill into the wood-frame wall below the window. Further, interior wood strapping on the exterior walls facilitated horizontal moisture movement. Examination of a number of the existing window sills showed that shrinkage and cracking had occurred, which would have provided ample pathways for water leakage.

Remedial Action. To control the problem in those suites which still had their original windows, a two-stage approach was developed. The first stage consisted of sealing the existing wood window sills and sides using an appropriate caulking (to seal any visible cracks and other leakage pathways) along with application of a suitable coating to the exposed wooden sills and frames to waterproof them against future leakage. The cost of these repairs was estimated at a few hundred dollars per suite. It was felt that if this strategy adequately addressed the problem, then no further action was required other than periodic maintenance. However, if this measure proved inadequate in some suites, then it was recommended that the existing windows in those suites should be replaced with new units of the type used in other suites in the building. The cost of this work was estimated to be one to two thousand dollars per suite.

Building #5—House with Wet Basement

Description. This single-story, detached, wood-frame house constructed in 2001 used a raised bungalow (one story) design in which the foundation was slightly higher out of the ground than a standard bungalow. The foundation consisted of a cast concrete basement with interior 38x64 (2x3) framing, RSI 3.52 (R-20) batt insulation, 6-mil polyethylene air/vapor barrier with drywall on the inner surface. Dampproofing had been applied to the exterior of the below-grade portion of the foundation and the weeping tiles were placed beside the foundation footings (not at the cove between the footings and the foundation wall) and then drained to a sump pit in the basement. The floor slab was conventional cast concrete placed on top of a polyethylene moisture barrier which in turn rested on approximately 4 inches of granular fill.

Reported/Observed Symptoms. The problem first became evident in February, 2002 when wet spots were observed at various locations on the stucco covering the exterior walls at elevations corresponding to the basement floor header level. Handfuls of frost were also discovered in the header space. Following the builder's advice, the polyethylene air/vapor barrier and insulation in the header area were removed and allowed to dry. This proved unsuccessful, and a number of other solutions were attempted, including spraying the headers with polyurethane foam and addition of a Heat Recovery Ventilator to control humidity levels. Not only did this not solve the problem, but also closer examination revealed wet spots on the concrete behind the insulation in areas where it had not been previously observed. The exterior of the foundation walls were ostensibly protected against water ingress by the use of asphalt dampproofing, while the basement floor slab was protected by the granular fill and polyethylene below the slab. Unfortunately, as is almost always the case, a discontinuity existed in the foundation dampproofing where the concrete footings rested on the soil since their undersides were unprotected. However, this was an almost universal design feature for other houses in this area, including those immediately adjacent to the subject house – none of which experienced any problem.

Analysis Protocol. A series of test holes were augured around the house perimeter in the area immediately adjacent to the house to determine the soil stratigraphy at each location and to measure ground water levels. Standpipe piezometers were installed in two of these holes to measure water levels. In addition, a series of elevations were surveyed to determine the depth of the footings in relation to the soil immediately around the house.

Diagnosis. The soil tests revealed that the house was sitting on a thin layer of silt, which in turn rested on a thicker layer of clay. This created a condition known as a perched water table. While both silt and clay are fine-grained materials, their properties are very different. Silt is quite permeable to liquid water while clay is comparatively impermeable. When a layer of silt sits on top of a layer of clay, a condition is created in which soil water can percolate readily down through the silt until it reaches the clay layer at which point its downward progress is halted. In essence, the clay creates a bowl-like effect in which the water is prevented from draining further into the ground and creates a layer of water in the silt.

Unfortunately, the soil stratigraphy and the survey levels revealed that the bottom of the footings were located within this silt layer. Thus, as water percolated down through the silt, it eventually reached the clay layer which impeded movement further into the soil. Since the bottom of the footings was in the silt, they were kept wet as long as there was sufficient water in the soil. This condition permitted water to be drawn up through the bottom of the footings due to capillary action where it could travel vertically up through the porous concrete of the wall and wet the wall surface. The presence of the weeping tiles beside the footings did not provide protection against this phenomenon since they could only remove water which was at or above their level. Had they been installed at a lower elevation, they would have been able to keep the bottom of the footings dry.

Although little was known about how much water had been added on-site to the concrete, the situation would have been aggravated if the concrete was cast with a high water-to-cement ratio since concrete's permeability increases dramatically with an increasing water-to-cement ratio.

Remedial Action. Obviously, it was not feasible to install a capillary break under the footings. Instead, a system was put in place to lower the water level around the foundation by increasing drainage. A new sump pit with additional holes in the vertical walls of the plastic liner was installed in place of the original pit. This allowed drainage to occur to a lower vertical level than was originally possible since, after the new pit was installed, ground water could drain laterally through the silt into the sump pit. In addition, a polyethylene moisture barrier was installed on the interior of the basement walls to provide a capillary break between the wall and the interior insulation and framing.

Building(s) #6—Houses with Upper-Level Moisture Problems

Description. This example consists of a small collection of houses which had all experienced similar types of moisture problems. In all cases, moisture problems in the upper levels of the house appeared, typically in the attic. For example, in one case, an older 2 1/2-story house experienced a severe failure of the lathe and plaster ceiling when a large section of it collapsed into the room below. Suspecting a roof leak, the owner examined the underside of the roof sheathing only to discover no obvious signs of water leakage.

Reported/Observed Symptoms. In all cases, the problems occurred over upper portions of the envelope, suggesting an air exfiltration-induced problem. Furthermore, in all cases the houses' original, naturally aspirated, natural gas furnace had been replaced with a direct vent, sealed combustion unit which had its own outdoor combustion air inlet. In some cases, the existing naturally aspirated hot water tanks had also been replaced with electric units, thus permitting the furnace/water heater vent to be sealed. The furnace replacements had occurred within the preceding few years.

Analysis Protocol. No on-site testing was conducted.

Diagnosis. The problems experienced by these buildings were classic examples of the house-as-a-system philosophy. As shown in Figure 4, the moisture problems were caused by increased air exfiltration into the attic and other portions of the upper building envelope as the result of the recent replacement of the original, naturally aspirated furnace. These types of devices require large amounts of combustion and dilution air which is drawn from the zone in which the furnace is situated. Effectively, this means that the furnace depressurizes the building with the result that the neutral pressure plane is located just below the ceiling. As a result, air exfiltration from

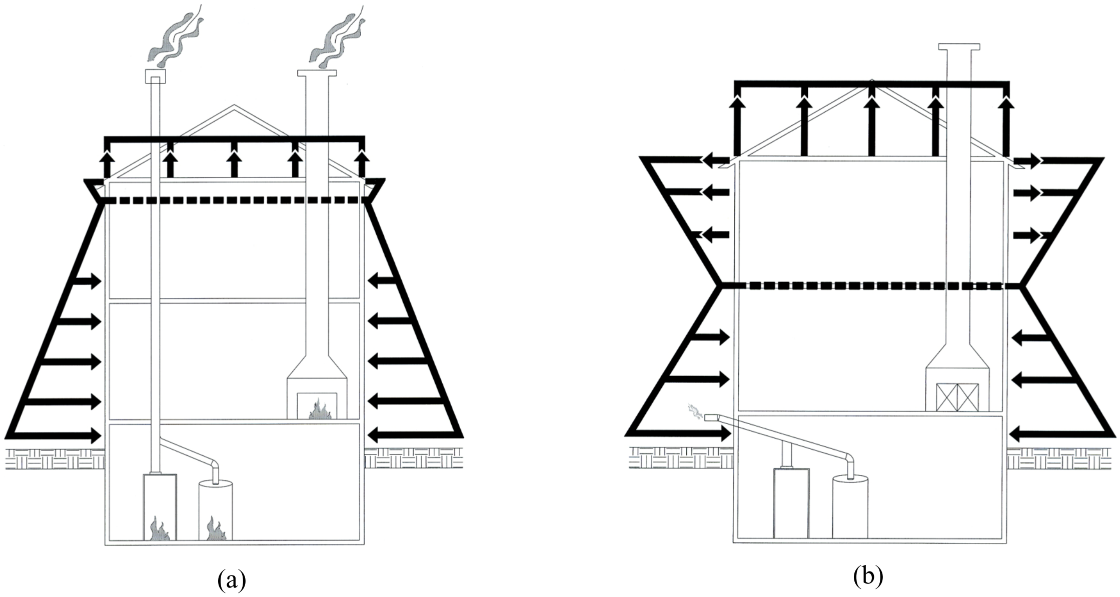

Figure 4 *Stack-induced envelope pressure differentials with (a) combustion appliances and (b) no combustion appliances.*

the house into the attic and upper parts of the envelope is minimal. In addition, this arrangement also lowers the houses' humidity levels since the air change rate of outdoor air induced by the furnace tends to provide a constant supply of dry, outdoor air.

However, when the naturally aspirated furnace was replaced with a direct vent unit (which draws its air directly from the outdoors), two effects occurred. First, the neutral pressure plane was lowered significantly – typically to about mid-building height, which significantly increased the positive pressure differential across the ceiling and upper portions of the envelope and dramatically increased air exfiltration into the attic. Second, since the houses' overall air change rate was reduced, interior humidity levels rose, often by significant amounts. As a result, the average moisture content of the air exfiltrating into the envelope was much higher than had previously been the case. The net effect was a large increase in the amount of moisture being transported into the upper parts of the envelope.

Remedial Action. A couple of strategies were recommended to deal with this problem. First, it was proposed that winter humidity levels be maintained at the lowest levels consistent with good indoor air quality. Second, it was recommended that all air leakage pathways on the upper portions of the envelope should be sealed. This included all attic penetrations such as plumbing and electrical lines, access hatches, the tops of partition walls, chimney and vent penetrations, etc. It could also include major pathways such as the floor joists on the top floors of 1 1/2- and 2 1/2-story houses since these can provide an unimpeded pathway for air leakage from the house interior to the spaces behind the kneewalls.

Building #7—Motel Indoor Swimming Pool

Description. The final example was an indoor swimming pool forming part of a relatively new motel complex. Site observations showed that moisture damage was occurring in one room (the tower room) forming part of the pool area. Although water splashing from a nearby water slide was fairly common, and may have contributed to the observed problems, it was believed that additional factors were at work.

Reported/Observed Symptoms. Drywall staining, delamination of taped joints, physical degradation of the drywall, and some mold development were all observed.

Analysis Protocol. Dew point calculations.

Diagnosis. Based on the observed moisture patterns, coupled with dew point calculations (to estimate the potential for surface condensation), it was concluded that the damage had been caused by moisture condensing on the cooler drywall surfaces in the tower portion of the pool room. While the wall assembly was relatively well insulated, the condensation was occurring in the immediate vicinity of thermal bridges created by structural framing members and (in one location) where an insulation anomaly may have existed. The dew point calculations indicated that under extreme winter conditions, the surface temperature of the drywall in the vicinity of the thermal bridges (such as the wood studs or other wood framing members, as well as embedded steel columns), would be at or below the dew point of the interior air. This permitted surface condensation to occur and ultimately resulted in the observed moisture damage. It is also worth noting that the observed moisture problems did not show any correlation to air leakage pathways which existed into the building envelope, strongly suggesting that air exfiltration/moisture deposition was not responsible for the problems. This conclusion was reinforced by the fact that the moisture accumulation was reported as being most evident during the coldest part of the winter rather than in the early spring when exfiltration-transported moisture, stored within the envelope in the form of ice, normally melted and became apparent.

Remedial Action. After the damaged areas had been repaired, the potential for future surface condensation was reduced by adding extruded polystyrene insulation and a second layer of drywall over the repaired drywall surfaces in those locations on or near the thermal bridges. Based on the dew point calculations, it was recommended that 3.8 cm (1.5") of extruded polystyrene be added, which increased the thermal resistance by RSI 1.32 (R-7.5). In addition, the tower area was re-painted with high quality epoxy paint. According to the manufacturer's literature, the paint had a water vapor transmission of 17.3 ng/(s·m^2·Pa) (0.30 perms in imperial units). Extruded polystyrene with a thickness of 3.8 cm (1.5") has a permeance of 15-61 ng/(s·m^2·Pa) (0.27 to 1.07 perms). By combining the two materials as proposed, the net calculated permeance of the paint and insulation would be 8 to 14 ng/(s·m^2·Pa) (0.14 to 0.24 perms). For comparison purposes, Type I vapor diffusion retarders are required to have a permeance of 14.375 ng/(s·m^2·Pa) or less.

TYING IT ALL TOGETHER

Understanding and diagnosing building moisture problems requires sound observational skills and a working knowledge of building science and local construction practices, coupled with a little intuition (luck also helps). Faced with a new problem in an affected building, it is tempting to leap to possible solutions, especially solutions which are within the investigator's experience. However, this should be avoided. It is important to keep an open mind and identify all relevant information, including that which does not fit the initial paradigm. Reviewing the previous case studies, it is also apparent that more than one moisture transport/deposition mechanism may be responsible for the problem. For example, in Building #3, water entered the crawl space via gravity flow and then was transported to the upper levels of the building courtesy of air leakage. If either of these mechanisms had been prevented, the problem would not have occurred.

Using the lessons learned from the preceding case studies along with those from other problem buildings, some key characteristics of the six moisture transport/deposition mechanisms can be identified. These are summarized in Table 1 on the next page (for buildings located in heating climates) and are offered as a guide for diagnosing moisture problems.

REFERENCES

ASTM. 1982. Special Technical Publication 779, *Moisture Migration in Buildings*. American Society for Testing and Materials. Philadelphia.

ASTM. 1992. Standard E 779, *Determining Air Leakage Rate by Fan Pressurization*. American Society for Testing and Materials. Philadelphia.

CAN/CGSB. 1986. Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method. Canadian General Standards Board, Ottawa.

CMHC, prepared by the IBI Group. 1992. *Investigating, Diagnosing & Treating Your Damp Basement*. Canada Mortgage and Housing Corporation.

Table 1. Moisture Transport/Deposition Characteristics

Transport/ Deposition Mechanism	Location Of Symptoms	Symptoms Wide-spread Or Discrete?	When Are Symptoms Most Evident?	Material Characteristics	Time Period Over Which The Event Typically Occurs	Prevalence	Diagnostic Tools
Air leakage	Usually at, or near, top of building	Generally discrete	Mid winter and spring thaw	Requires air leakage pathways in envelope	Months	Very common	Airtightness tests, Pressure diagnostics, Infrared thermography
Vapor diffusion	Anywhere in building envelope	Widespread	Spring thaw	No obvious fault may be visible	Months	Very rare	
Capillarity	Concentrated at or near bottom of building	Widespread	Whenever water temperature is above freezing	Occurs through porous materials	Months	Common	Polyethylene test
Gravity	Water source is required above affected area	Discrete	Whenever water temperature is above freezing	Requires leakage paths below water source	Hours to months	Common	Standing water test
Wind-driven rain	Prevailing wind direction	Generally widespread	After heavy, driving rains	Requires water leakage pathways in envelope	Hours	Common	Spray test Standing water test
Surface condensation	On any cold surface	Generally discrete	During coldest part of year	Condensate may be absorbed into porous surfaces	Hours to days	Occasional	Infra-red thermography Dew-point calculations

Notes:
Location of symptoms: Where are the symptoms of moisture distress most prevalent on the building envelope?
Symptoms widespread or discrete? Do the symptoms appear over a broad area of the envelope or are they concentrated in discrete locations?
When are symptoms most evident? What time of year are the symptoms most evident?
Material characteristics: What are the characteristics of the building materials at, or near, where the symptoms appear?
Time period over which the event may occur: What time period is the event likely to take place over?
Prevalence: How common are envelope problems which are caused, or aggravated, by this transport/deposition mechanism?
Diagnostic tools: What field tests and methods can be used to diagnose this transport mechanism?