Detection of Moisture within Building Enclosures by Interior and Exterior Thermographic Inspections

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ABSTRACT
Infrared imagers have become vital diagnostic tools in building maintenance with mold related health issues becoming more prevalent. Although infrared imagers do not detect the presence of mold, they can be used to detect the presence of moisture by means of variances in conductive and phase change heat loss or gain. When commissioning new building envelopes, or carrying out building condition inspections of existing building envelopes, it is imperative to differentiate the source of the moisture accumulation between interior or exterior sources since remedial actions will vary considerably. Moisture detection methodologies for interior and exterior inspections vary and equipment specifications are different for both types of inspections. The physical mechanisms that produce moisture patterning in the infrared wavelengths are different for both interior and exterior inspections. Ensuring optimal inspection ambient conditions is paramount to obtain accurate inspection results. This paper will discuss the various types of thermal patterns created by surface penetration of water versus those patterns created by air leakage from the building interior in cold winter conditions. Moisture detection methodologies for interior inspections will be discussed and the importance of timing will be stressed regarding detection of moisture within assemblies by non-destructive means. Various types of exterior building envelopes will be discussed along with their performance characteristics and how these affect thermal patterns during various inspection procedures.

INTRODUCTION
Building enclosures are comprised of three main elements; roof assemblies, above grade assemblies and foundation wall assemblies. The mechanisms associated with entry of moisture within these three elements are the same but the intensity of the various mechanisms varies by as much as two orders of magnitude. In each assembly, the causal mechanisms leading to moisture intrusion need to be determined and the physical parameters need to be calculated to provide the appropriate built solution.

Understanding the causal mechanisms will also allow the inspector to determine the appropriate time of inspection for the greatest potential to detect moisture intrusion within the building fabric. Physical mechanisms leading to moisture accumulation in field situations are in constant state of change and flux thus understanding of transient state conditions and their effect on moisture patterning is a fundamental key to resolving causal mechanisms as well as determination of accurate solutions to the moisture intrusion. The equipment operator must understand the hygric buffer capacitance of the assemblies inspected along with the drying potential for each enclosure assembly. These performance features are generally consistent for generic types of assemblies and will determine if specific designs work well in specific climatic regions.

This paper will first look at roof assemblies, then above grade assemblies and finally below grade assemblies. Both interior and exterior inspection methodologies will be discussed for all three enclosure elements.

SLOPED ROOF ASSEMBLIES (INTERIOR OR EXTERIOR INSPECTIONS)
Roofs can be classified into **sloped** and **low-sloped** assemblies. Sloped assemblies are generally associated with residential buildings with vented attics. Air leakage is detectable in sloped roof assemblies at soffit joints or around roof projections provided that there is a temperature differential between interior and exterior of at least 18°F and a pressure differential of at least 5 Pa. With increased thermal sensitivity (30 – 50 mK) and spatial resolution (300 K pixels), direct air flow leaks at roof assemblies can be detected at temperature differentials of 6 – 8 °F under ideal environmental conditions.

Infrared imagers cannot be used to determine presence of moisture within these assemblies from exterior inspections. The resultant effects of roof leaks in sloped roofs are best detected by interior inspections on insulated ceiling assemblies saturated with rain or melt water. Since moisture is detected by means of conductive heat loss variances (the result of differences in the thermal conductance of dry roof material and moisture laden materials), these patterns are most obvious when temperature differentials between interior and exterior are greater than 10 ^oC (18 ^oF). Alternatively, if moisture finds its way into the interior gypsum board or plaster, evaporative cooling may be detected during the drying phase of the roof leak. This option only exists when there has been wetting and drying is occurring into the building interior within absorptive materials.

LOW-SLOPED ROOF ASSEMBLIES (INTERIOR OR EXTERIOR INSPECTIONS)

Low-sloped roofs can be classified into **conventional** and **inverted** roof membrane assemblies. Conventional assemblies have the roof membrane visibly located on the exterior of the assembly. Inverted roof assemblies place the roof membrane underneath the insulation. The roof insulation in inverted assemblies is generally non-water permeable and retains much of it insulation properties during wet conditions. Even though we could see moisture within surface ballast materials of inverted roof assemblies, there is no way to detect possible roof membrane defects since these are hidden from view and the presence of ponding water within the insulation or ballast materials does not generally relate to membrane failures. Infrared thermography can only be used to detect moisture within absorptive insulation underneath roof membranes in conventional type assemblies.

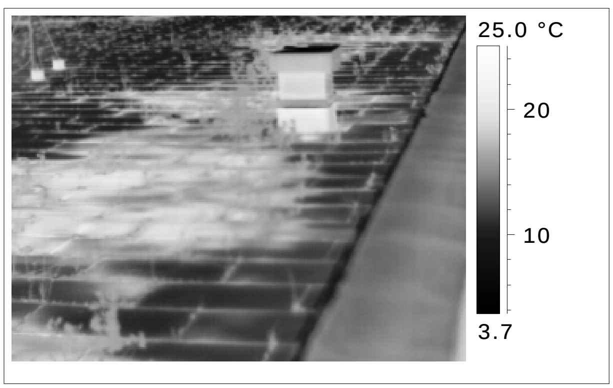


Figure 1. Infrared image of moisture within concrete clad Insulation over inverted roof membrane, $T_o = 20^oC$

Figure 2. Visual of concrete clad insulation over inverted roof membrane, no visible wetting on concrete.

The first sign of lack of drainage within the roof assembly could be growth of vegetation within joints. But this does not indicate any deficiency with the actual roof membrane.

Within conventional roof assemblies there are **built-up roofs (BUR)** and **single ply membrane** assemblies. BUR's consist of either 3 or 4-ply asphalt impregnated felts or two-ply modified bitumen roof membranes. Single-ply membrane assemblies are made up of three types of membranes (thermosets, thermoplastics and modified bitumens) that are either mechanically fastened to the roof substrate or ballasted. Infrared thermography can be used to detect the presence of moisture within the insulation layer found underneath the roof membrane in these roofs.

Two types of methodologies are used to detect moisture with insulation materials in roofing assemblies; a) **transient method** using solar heat gain during day time and inspecting transient conditions during and immediately after dawn or dusk, b) **static method** employed 4 to 8 hours after sunset when heat flow is near steady state conditions and surface temperatures variances between dry and wet insulation is a function of primarily conductive heat loss variances. The static method required a minimum of 10 ^oC (18 ^oF) temperature differential if the inspection is carried out from the exterior. The roof membrane is required to be dry and fee of snow cover so as to ensure full inspection coverage. Exterior inspections with outside ambient temperatures lower than a 5 ^oC (9 ^oF) delta-T produce variable results and are not recommended. If inspections are carried out from the interior, the temperature of the rainwater should be at least 5 ^oC (9 ^oF) cooler than interior ambient.

The transient methodology is primarily used in the industry due to its greater effectiveness. The degree of success is affected by such variables as the thickness of ballast, the reflectivity of the roof membrane or ballast, the temperature differential between interior and exterior, wind speed during exterior inspection, the absorptiveness of the insulation within the roof assembly, and the amount of solar heat gain during the day of inspection. All these factors play a role in the detection of moisture within roof insulation and determination of the specific locations of membrane failure is a tricky activity. Inspections with wind condition greater than 10 kph (6.2 mph) produce variable results and are not recommended. Under ideal conditions, the window of opportunity to detect moisture within the roof assembly is generally about 2 to 3 hours after sunset. Unfavorable site conditions reduce this time frame or eliminate it completely. If suitable environmental factors are not present and standard inspection methodologies are not adhered to, false negative results will be achieved.

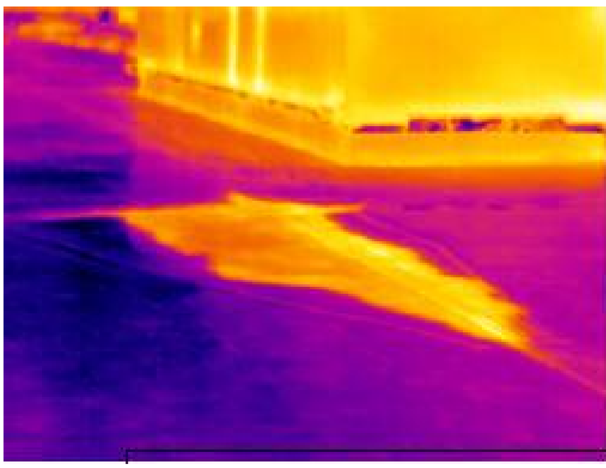


Figure 3. Moisture within insulation under one ply sheet membrane roof assembly as seen from exterior (Images courtesy of ITC)

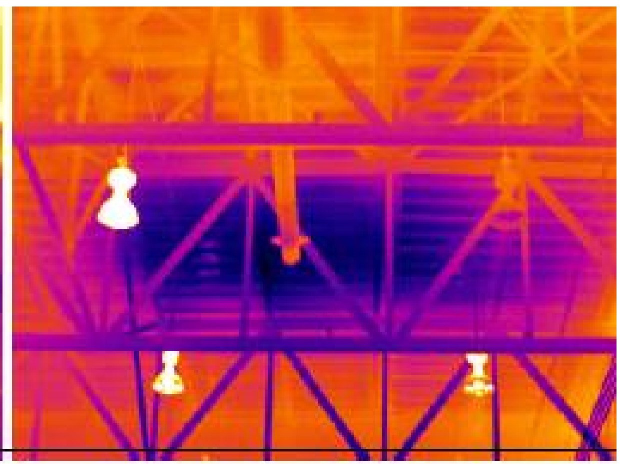


Figure 4. Moisture within insulation as seen from interior of building. Image courtesy of David Felleti, WJE)

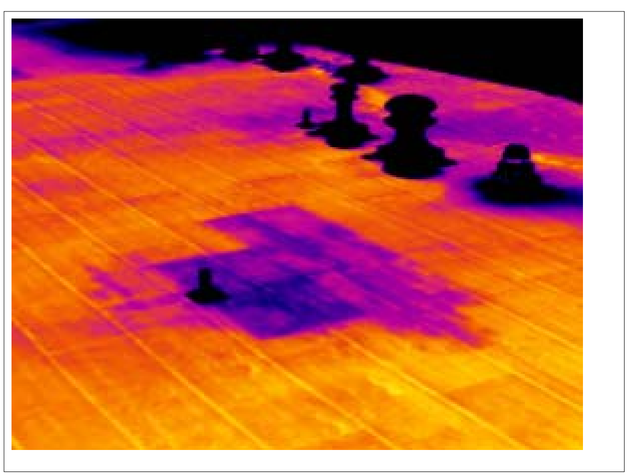


Figure 5. Moisture within insulation as seen from an adjoining roof taken at 11:22am in the morning. (Image courtesy of Lee Durstin, BCRA)

*Figure 6. **Same** area shown in Figure 5 (see arrow) taken at 8:54pm in the evening during a flyover. (Image courtesy of Lee Durstin, BCRA)*

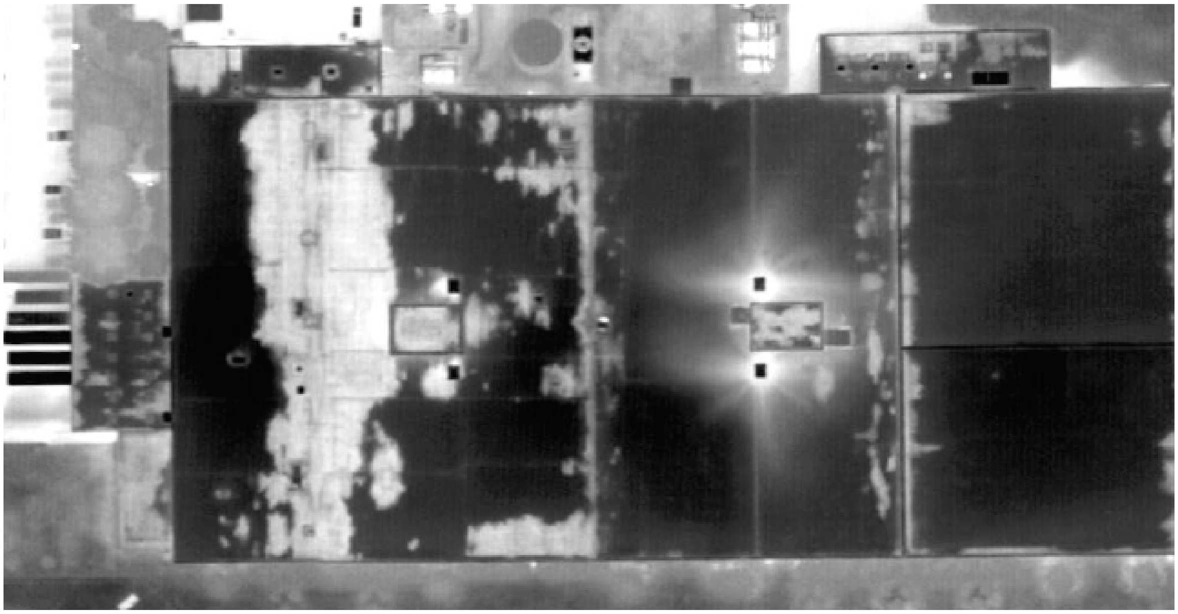


Figure 7. Aerial infrared image of moisture within insulation of conventional built-up roof. Note only one section of three requires replacement. The other two roof sections display minor roof leaks around curbs and flashings. (Courtesy of AITScan and Stockton Infrared, Greg Stockton)

Figure 8. Visual aerial photo. (Courtesy of AITScan, Greg Stockton)

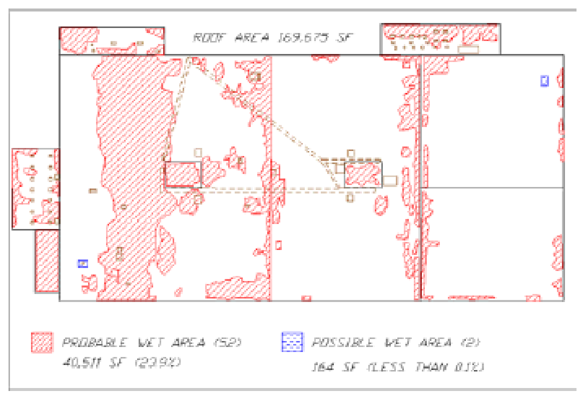


Figure 9. CAD drawing of suspected moisture. (Courtesy of AITScan, Greg Stockton)

Detection of moisture within built-up roofs can be carried out from three distinct distances associated with; 1) by walking under or over the roof assembly (Figures 3 and 4), 2) surveying from higher adjacent roofs (Figure 5), or 3) by fixed wing airplanes or helicopters (Figures 6 and 7). All are acceptable methodologies when suitable inspection conditions are present and appropriate infrared imagers are used. Small roofs may be more cost-effective to inspect by simple walk though using inexpensive 10K to 20K pixel imagers. Large roofs with vantage points from other adjacent roofs make hand-held inspections cost effective if employing 80K pixel imagers with better spatial resolution capabilities. For very large low-sloped roofs, or for many roofs in one geographical location or campus, aerial inspection is the quickest and most efficient means of collecting data on BUR and low sloped roof moisture intrusion. Dedicated high spatial resolution imagers (300K pixel or higher) are required for aerial inspections to ensure suitable spot size resolution to define moisture patterning and roof features. Focus and high-speed vibration issues need to be addressed in data collection methodologies from aerial fixed-wing or helicopter inspections for both fixed mounted and handheld imagers. These issues severely hamper image resolution if not dealt with.

TYPES OF ABOVE GRADE WALL ASSEMBLIES

Exterior wall assemblies used in medium and high rise buildings can be classified into four generic types of wall types: 1) masonry, 2) architectural pre-cast, 3) metal and glass curtain wall, 4) insulated steel assemblies. For low rise and residential buildings there is an additional type of generic wall assembly: 5) wood and steel frame.

Within these generic types of assemblies there is considerable variation in the type of cladding, insulation and assembly configuration of components required for control of moisture and air migration. Much of the variation is dependent on architectural aesthetics but these all need to address environmental factors imposed by local weather conditions throughout the year. In both extremely cold and hot humid climates, the control of water and water vapor through the building envelope is critical to the durability and long-term performance of the enclosure assemblies. Vapor retarders are used to control vapor diffusion not air leakage.

Air barriers, either as single components or as a group of components are used to control air movement from the exterior through to the interior. Air movement can transport 10 to 100 times more moisture through unintentional openings in the air barrier assemblies than vapor diffusion through the least effective vapor retarder. Detection of openings that facilitate moisture migration is critical to the control of vapor flow and moisture accumulation in exterior assemblies. Moisture intrusion into insulation material reduces their effectiveness by 50 – 80% resulting in increased operating energy costs. The added benefit to detection and remediation of unintentional air leaks within exterior enclosures is improved energy performance. Industry data indicates that 25-40% of energy costs for typical buildings are a result of air leakage. Reducing this figure by a modest 30% by detecting and sealing the largest and easiest openings can result in an 8 – 12% reduction in peak load demand for most buildings whether new or old. The use of infrared thermographic inspections to detect and remediate air leaks within building enclosures has been documented to generate paybacks in the range of 1-2 years making these one of the best energy conservation solutions in the building industry today.

FACE SEAL OR CAVITY WALL CONSTRUCTION

Exterior wall assemblies can be designed as either a) **face seal,** or b) **cavity wall**. Within face seal assemblies there are both low mass or high mass type walls. Low mass walls consist of generally insulated stud walls (either load or non load-bearing) with solar, wind, rain and vapor controlling exterior cladding. High mass walls consist of solid masonry walls (either insulated or uninsulated). These high mass walls can either be load-bearing or enclose an integral steel or concrete structural frame.

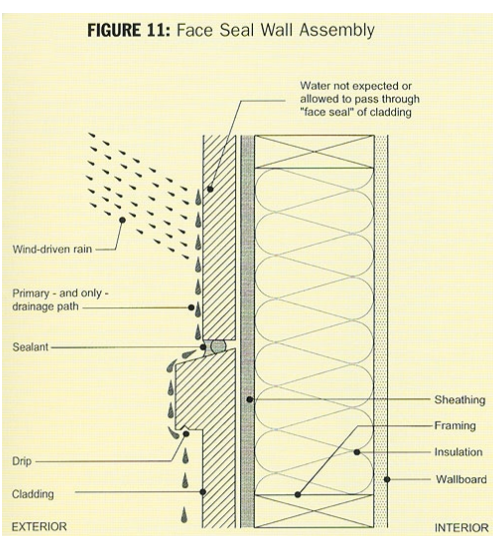


Figure 10. Typical Face Seal Low Mass Assembly.

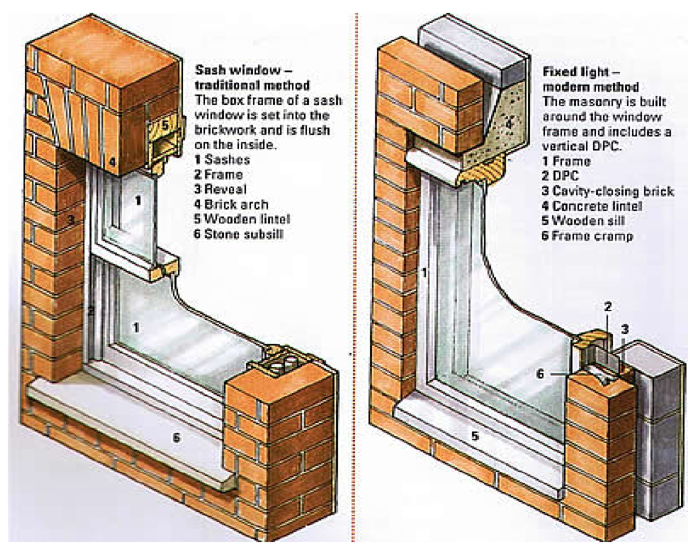


Figure 11. High Mass Face Seal and Cavity Wall Assemblies

Face seal assemblies rely on one plane (either interior or exterior surfaces) for the purpose of stopping water, vapor and air migration into and though the wall. If and when there are breaches in these air and water vapor impermeable surfaces, the degree to which water can be evacuated is dependent on the drainage planes and permeability of the materials within the wall assembly and the cladding.[1]

Cavity wall assemblies are more varied. They include traditional non-ventilated masonry wall assemblies as well as modern rain screen and pressure equalized rain screen type wall designs. These latter exterior enclosures come in numerous forms of generic wall types as mentioned earlier. Cavity walls rely on the exterior cladding to provide the water penetration protection along with through wall flashings to drain potential moisture to the exterior. These types of walls may or may not have a separate vapor barrier material for control of vapor diffusion. These types of walls rely on a series of materials to provide an air tightness or air barrier plane. In cold climates, air barrier materials are located either on the interior side of the wall or the interior side of the insulation within the wall. The air barrier assembly is hidden from view when located within the wall making inspection and repair difficult after construction. (In warm climates, the air vapor barrier assembly is generally placed on the exterior side of the insulation layer.)

The cladding materials in rain screen and pressure equalized rain screen assemblies are designed to vent and drain excess water that has penetrated the cladding materials. The air space between the cladding and the insulation or air barrier assembly is used as a capillary break between the cladding and the back up wall. When breaches in the air barrier assembly occur in cavity walls, ventilation/weep holes in the cladding provide an easy route for migration of air through to the exterior or from the exterior into the building interior. There is no certainty that cladding vent holes will be close to the breach in the air barrier assembly. Variability of location and size of air barrier openings result in variable air flow patterns within and through the wall assembly. In extremely cold or hot humid climates, airflow transports moisture from either the interior or exterior into the wall assembly. This is a primary cause for mold formation and premature wall deterioration.

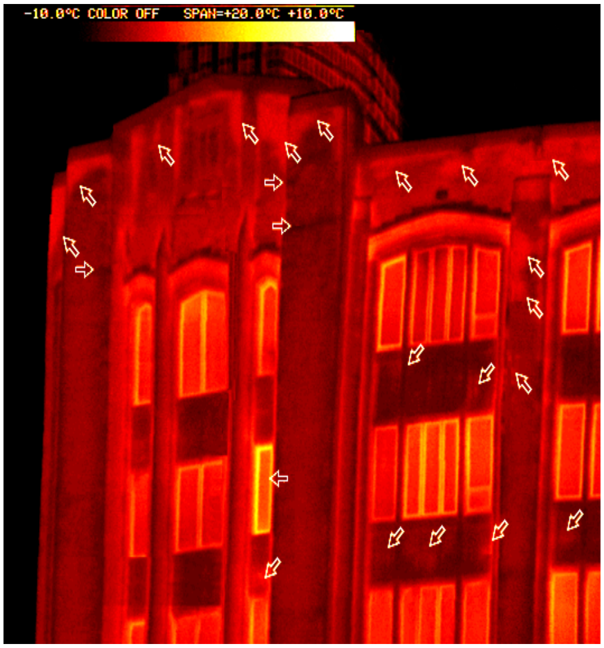
The use of infrared thermography for detection of openings in air barrier assemblies can be carried out by means of pressurization or depressurization of building interiors prior to and during infrared thermographic inspections. A resultant by-product of this type of inspection methodology is the accumulation of moisture within the wall assemblies as a result of increased pressurization. Thermal patterns generated by building pressurization produce information on the location and possible severity of the air barrier opening but in many situations, are accompanied by residual moisture accumulation in various building materials adjacent to air barrier breaches.

EXTERIOR INSPECTIONS; RAIN WATER MOISTURE PATTERNING

In cold climates, commissioning building envelope inspections are not always carried out in sub-zero temperatures. Exterior ambient temperatures between 1 ^{o}C and 15 ^{o}C (33.8 ^{o}F and 59 ^{o}F) are conditions often experienced by thermographers testing buildings for air leakage faults. During these conditions, rainfall may occur prior to actual inspections. The type of rainfall and intensity, along with wind conditions often result in variable wetting patterns on building claddings.

Both type of cladding, and assembly, influences the variability of wetting patterns on walls. Non-porous cladding materials shed water and do not retain rainwater thus do not show variable effects of rainwater on their surface temperatures after a rainfall. Porous materials show greater variable temperature effects as a result of moisture accumulation. Lightweight porous materials (wood and stucco) again show greater thermal variances due to rainwater penetration than high mass type porous material such as stone.

Rainwater thermal patterns are a result of the reduced thermal resistance of the cladding materials and are generally accompanied by small surface temperature changes. Only in instances where penetration goes beyond the cladding into the interstitial structure and insulation layers will it become a more pronounced thermal pattern. In cold climates the most significant durability issue is the potential for freeze/thaw damage to the cladding materials at areas where saturation occurs. In locations where rainwater penetration gets through the cladding, other materials such as weather barriers and sheathing often protect entry into the insulation layers and structure. In some conditions, where penetration does occur into these materials, infrared thermography is able to locate these problem areas when temperature gradients greater than 10 ^{o}C (18 ^{o}F) exist through the building exterior envelope.



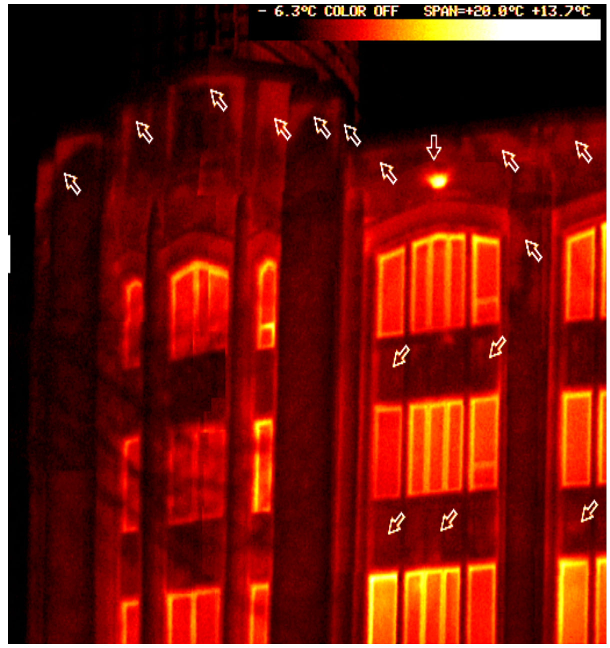


Figure 12. Rain Water Penetration at Parapets. Negative Building Pressure (-20 Pa).

Figure 13. Rain Water Penetration at Parapets. Positive Building Pressure (+35 Pa)

Rainwater penetration patterns are generally associated with the top section of walls and most likely around parapet walls. Most building only experience rainwater penetration at top floors unless located in areas with a high driving rain index, or during hurricanes or tornados. Other areas where rainwater penetration may occur are at sloped or protruding walls or drainage planes from upper wall sections. Window sills and parapets are examples of such drainage features. Sloped relief details in stone masonry walls are another example of such conditions.

EXTERIOR INSPECTIONS; MELT WATER MOISTURE PATTERNING

In winter months, solar gain and thaw conditions result in melt water runoff from roofs, sloped projections and other architectural features. Masonry and other porous cladding materials are affected by the accumulation of surface moisture. These patterns are visible through infrared thermography as a result of conductive heat flow and are more pronounced as the temperature differential between interior and exterior increases.

Melt water patterns are affected by solar heat gain and often dry out on the surface but interstitial moisture remains throughout the winter months. Moisture accumulation due to melt water may often not be visible due to surface drying aided by solar heat gain but subsurface cladding moisture is detectable through the use of infrared thermography. The significance of this moisture is that it can result in increased freeze/thaw potential of the mortar holding masonry together and in some situations results in premature rusting of metal reinforcing and ties within the masonry. Sloped areas on stone and masonry walls are areas that attract melt water throughout the winter months. Often these areas are also characterized by staining and dirt build-up created by the surface water accumulation and adhesion.

EXTERIOR INSPECTIONS; GROUND WATER MOISTURE PATTERNING (RISING DAMP)

Solid masonry walls with stone foundations without ground protection are susceptible to ground water absorption. Ground water wicks its way up the wall at the ground floor of the building through capillarity. Reduced thermal resistance values occur at walls immediately above the ground. This moisture may result in mortar deterioration throughout the wall thickness and be susceptible to freeze thaw on the outer sections. Infrared inspection of these walls can detect moisture accumulation by means of increased conductivity and surface temperatures. Thermal patterns are not mottled as in other types of assemblies but rather consistently warmer throughout the lower sections of the first floor adjacent to grade around the building.

In general, surface temperature variations between the first floor walls and the rest of the building can only be discerned at exterior ambient temperatures below –5 to -20 °C (23 to -4 °F). Inspections carried out during higher temperatures require more sensitive infrared equipment to discern surface temperature variations due to ground water absorption. This type of thermal pattern is not always apparent since it is rather homogeneous in nature rather than mottled and variable.

Figure 14. Ground floor of solid masonry wall assembly illustrates warmer surface temperatures due to rising damp from ground water in foundation wall. Melt water penetration into walls also visible at inside corner on right side of image.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING & NEGATIVE BUILDING PRESSURE

Moisture thermal patterns within building enclosures are generally easier to detect when interior building pressure is negative during heating seasons. These patterns are not overpowered by those created by warm air leakage from the building. Negative building pressures during the heating season, are generally found only at lower floor elevations if mechanical systems do not compensate for the natural stack effect.. Negative building pressures are seldom found in upper floors of buildings during the heating season unless mechanically induced. Thus in many buildings that are not normally pressurized, lower floors enclosures operating under negative building pressures will display moisture patterning due to rain and melt water penetration and condensation due to air leakage better than enclosures experiencing positive building pressures. That said, rain water penetration at lower floors is generally not experienced unless wind conditions are extreme.

During commissioning testing for air leakage, mechanically induced negative building pressure throughout the entire enclosure will allow for easier detection of moisture patterning throughout the entire enclosure and can be used to make a relative comparison between all moisture patterns throughout the enclosure. Moisture patterns due to interstitial condensation occur mostly when temperatures fall below -0 °C (32 °F), but dew point temperatures within enclosures rise when exterior and interior relative humidity increases.

Since heating season conditions generally produce constant positive building pressures at upper floors, residual moisture due to condensation will naturally occur at the top sections of buildings. It generally takes days of negative building pressure along with daytime solar heat gain to dry out interstitial condensation created by constant winter time stack effect. In most situations, exterior infrared thermographic inspections procedures do not allow for the elimination of this moisture and it becomes easy to identify when top sections of the building are under negative building pressure for 2 to 3 hours prior to inspection.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING & POSITIVE BUILDING PRESSURE

Positive building pressures during heating seasons result in warm moisture laden air to condense within the exterior sections of enclosures. Porous claddings absorb this moisture as does most insulation within wall assemblies. Moisture deposition is variable depending on the airflow characteristics, materials used and assembly configurations. Typically these patterns appear as warmer mottled surfaces downstream from the source of the air leak. At the point of air leak, it may appear as a very warm spot due to the increased heat patterns created by the interior escaping air. As the temperature differential between interior and exterior increases, so does the exterior surface temperature at the point of leakage if leakage is direct from interior to exterior. If leakage is diffused due to assembly configuration, increased exterior surface temperatures may not materialize.

Positive building pressures create warm cladding surface temperatures which may obfuscate adjacent thermal patterns created by moisture accumulation within the insulation or cladding materials. Only sustained negative building pressure conditions for a minimum of 2 to 4 hours may eliminate the heat building within the cladding at these locations to the point where only moisture effects are visible. Experience has shown that heat dissipates from cladding materials quicker than moisture. Moisture dissipation from porous cladding materials requires drying potentials to the exterior thus solar heat gain is best employed to dry out cladding materials. This type of testing procedure becomes moot since the source of air leakage needs to be dealt with in the first place to eliminate the source of condensation.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING, DIRECT VS DIFFUSE AIR LEAKAGE

Moisture patterning appears to be more apparent in areas where diffuse air leakage occurs through the exterior walls, rather than at areas where direct air leakage occurs during infrared inspections. One possible explanation for this phenomenon is that in diffuse air leakage conditions, moisture has a greater potential to get trapped into porous materials rather than in situations where direct air leakage occurs from the interior to the exterior. What is generally observed is moisture accumulation at the peripheral areas around direct airflow openings and not immediately at their locations. Again heat and air flow from the exfiltrating air generally will not allow for moisture retention at the immediate opening but rather some distance around the openings where there is less air flow to move the moisture further out of the cladding materials. In very cold conditions (-20 ^{o}C, 4 ^{o}F and lower), visual signs of hoar frosting are visible at these problem areas.

Pre-existing moisture patterning does not seem to be affected to any degree during positive pressure inspections other than to make them less apparent due to the much warmer surface temperatures created by the exfiltrating air at openings within the air barrier assembly. Positive building pressure inspections will result in additional moisture deposition within the wall assembly and thus create additional areas of moisture accumulation within the wall area that may not be present during normal operating conditions of the building. Both significant pressure (between 50 to 150 Pa) and considerable duration (greater than 4 hours of positive pressure) are required before additional moisture patterning is visible due to positive building pressure conditions in building with average to above average leaky air barrier assemblies.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING, EXTENDED POSITIVE PRESSURE

The thermal images in Figures 15 & 16 were taken on subsequent mornings. Figure 15 illustrates positive pressure imagery produced 24 hours prior to the negative pressure imagery in Figure 16. The arrows at the parapet walls of this 24-story building identify the moisture accumulation within the brick cladding as a direct result of positive building pressure imposed on the building for test purposes. The moisture patterns were not present prior to the positive building pressure being induced into the building and did not appear until after 4 hours of positive building pressure.

As seen in Figure 15, leakage areas were random in various section of the building and were not wide spread, but the sustained abnormal positive building pressure during testing did result in additional moisture migration from the building into the masonry cladding. This is a common occurrence in both solid as well as cavity wall assemblies. In cavity wall assemblies, moisture migration often travels from the source of the air barrier opening up to the top sections of the wall cavity due to convection cycles and thus moisture patterns appear more pronounced at the top section of wall cavities and building elevations. Another factor that contributes to the increased build-up of moisture accumulation at top sections of buildings is the increased stack effect pressures generally found at these elevations during winter months.

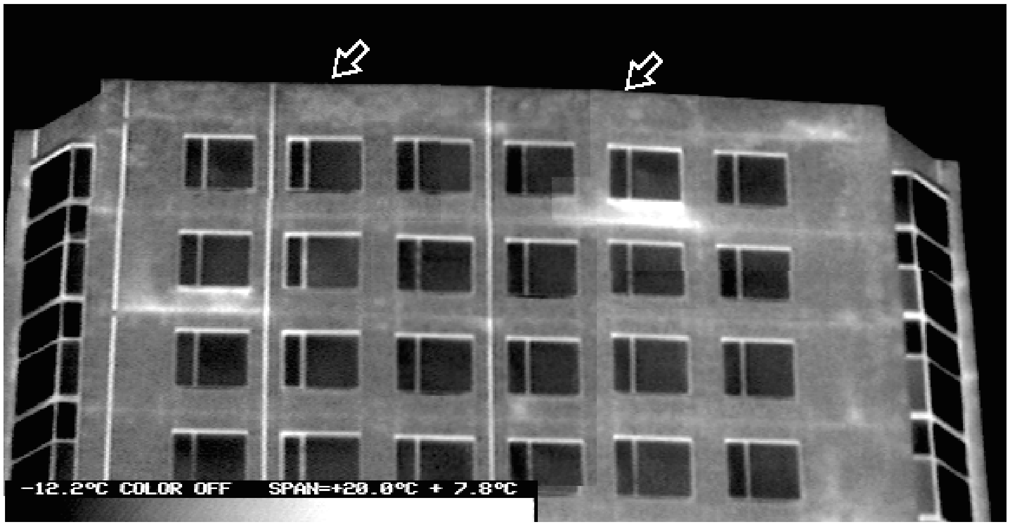


Figure 15. Positive Building Pressure (80 Pa), To = -7 °C (19.4 °F), maintained for a duration of 5 hours prior to inspection.

Figure 16 illustrates the thermal imagery from the same area of this building while being subjected to negative building pressure the following evening. Note that the thermal patterns due to air leakage are absent from this image as are the patterns created by the moisture accumulation within the brick cladding at the upper sections of the elevation from earlier in the day. The thermal bridging patterns are still evident. This image indicates that moisture accumulation, as with heat build-up due to excessive air leakage, given a full 24-hour time period, will dissipate when the driving force of the heat and moisture accumulation within the cladding is not present.

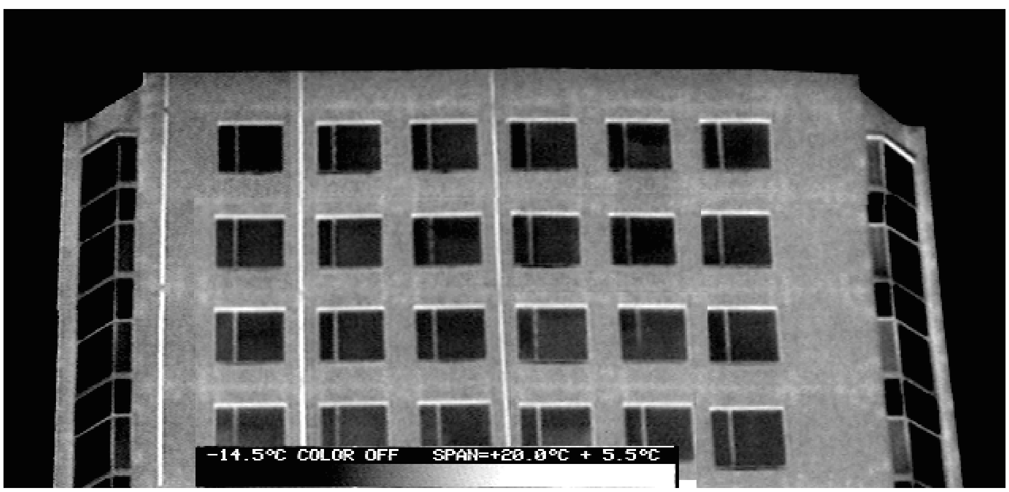


Figure 16. Negative Building Pressure (-60 Pa), To = -7 °C (19.4 °F), maintained for a duration of 4 hours prior to inspection.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO PHASE CHANGE

Phase change of moisture within porous cladding materials from a liquid to a solid occurs at temperatures slightly below freezing. Phase change from a solid to a liquid occurs when temperatures increase above freezing. In the phase change from a solid to a liquid, an endothermic reaction, melting ice within the wall is visible through reduced surface temperatures. Phase change from a liquid to a solid is an exothermic reaction and is visible through increased surface temperatures. These phenomenon occur independent of either positive or negative pressures.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO ENDOTHERMIC REACTION

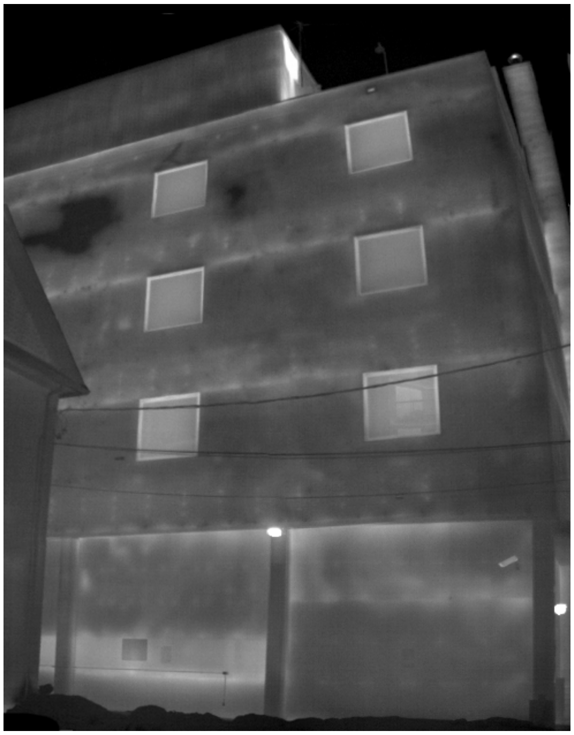


Figure 17. Negative Building Pressure (-140 Pa), To =0 °C (32 °F)

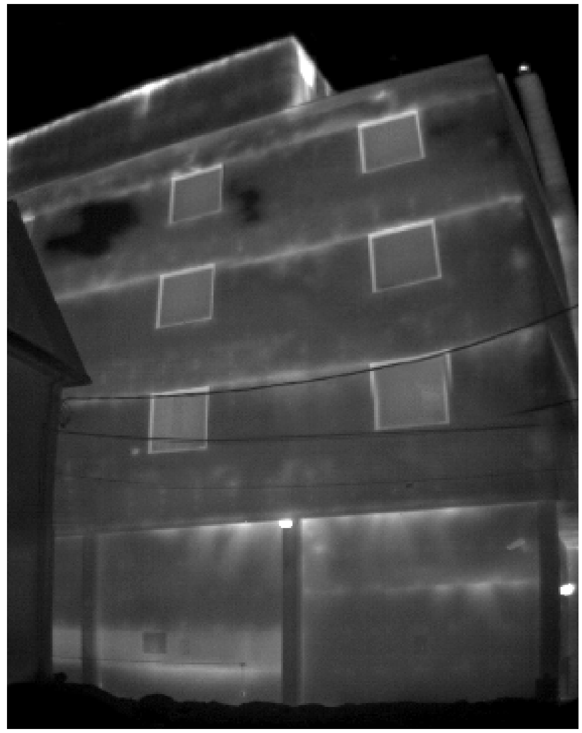


Figure 18. Positive Building Pressure (+40 Pa), To =0 °C (32 °F)

Both images taken during same evening, 4-hour time span between the two images

The dark areas on the 4th floor masonry cladding illustrate the distinctive endothermic pattern generated by the phase change of melting ice within the masonry. It appears reasonably consistent during both negative and positive inspections. The cold areas above the window heads on the third and fourth floor windows are typical of air leakage into the building during negative building pressure conditions.

EXTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO EXOTHERMIC REACTION

Phase changes going from a gas to a liquid or from a liquid to a solid are considered exothermic reactions in that they release energy to adjacent building materials which hold moisture. Therefore, condensation of water vapor or freezing of water within porous building materials produce warmer surface patterns. Condensation will generate a greater thermal signature than freezing of water within porous materials. In winter inspections, it is possible to generate both heat signatures due to condensation of interior warm moist air and cooling patterns due to ice melting within porous cladding.

Much of the mottled surface patterns found in the masonry cladding in Figures 19 and 20 illustrate this heat loss mechanism. The intensity of the thermal pattern is affected by the amount of moisture within the assemblies and the saturation level. In instances of very low exterior temperatures, it is possible to be viewing both phase changes (vapor to water on the inside sections of the enclosure, and water to ice on the exterior sections of the enclosure).

Figures 19 and 20 illustrate exothermic phase change patterns heat at below freezing temperatures. Of special interest is the pattern at the upper roof parapet in Figure 19 where moisture is freezing due to cold air temperatures within the wall assembly due negative pressures.

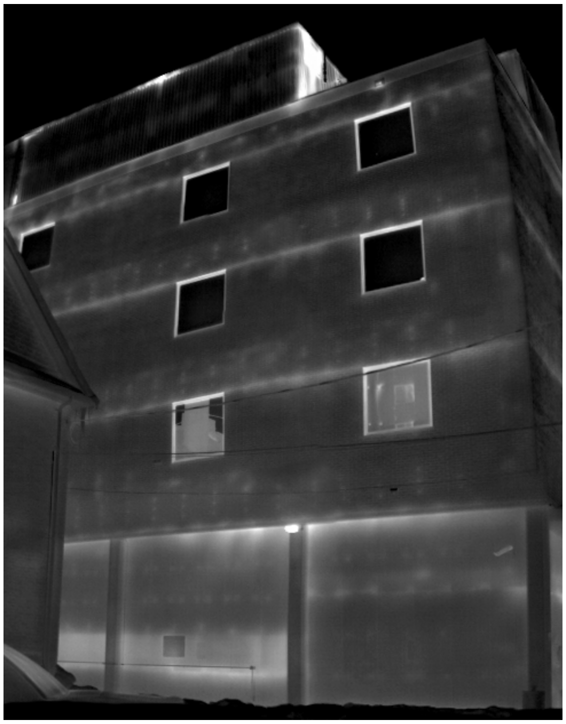


Figure 19. Negative Building Pressure (-8 Pa), To =-11 °C (12.2 °F)

Figure 20. Positive Building Pressure (+25 Pa), To =-11 °C (12.2 °F)

INTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO ENDOTHERMIC REACTION

Phase change of moisture from a solid to a liquid and from a liquid to a gas requires energy. This is considered an endothermic reaction. The energy for these types of phase change is absorbed from building materials holding this moisture. It takes 5 times more energy for water to change to vapor than for ice to change to water. Thus, evaporation of moisture within surface materials results in a considerably greater cooling of surfaces than solid ice melting to a liquid. This is one of the principle reasons that detection of moisture through evaporative cooling is easier to spot than melting of moisture within porous claddings. The amount of surface cooling is directly proportional to the rate of evaporation and the amount of moisture within the assembly. These factors are temperature dependent (both interior and exterior temperatures), vapor pressure dependent and time dependent.

Thermal patterns due to evaporative cooling from interior inspections vary according to the cause of the moisture accumulation within the wall, ceiling or floor assembly. The sources of moisture include but are not limited to: a) rain and/or melt water intrusion, b) condensation due to air leakage, c) water from plumbing & sprinkler systems, d) occupant activities (kitchens, washrooms, wet preparation areas, slop sinks), e) cleaning activities within buildings, f) fire and flood damage and, g) building materials drying out during construction stages (concrete, drywall, masonry). The duration of wetness along with appropriate temperatures results in either material damage or more problematic, development of mold.

Evaporative drying of interstitial moisture within exterior wall assemblies can occur either to the interior or exterior or combinations of both depending on the environmental conditions at the time of inspection and the vapor transmissivity of materials on either side of the embedded moisture. Evaporative drying to the exterior is generally very difficult to see from interior inspections but not impossible. The easiest moisture to detect occurs from evaporative drying of interior surface materials. The presence of moisture within exterior wall assemblies during cold (below freezing) winter months will result in colder interior surface temperatures (a result of reduced thermal resistance) than the temperatures created by evaporative cooling on interior surfaces. During warm summer months, intensity of evaporative cooling thermal patterns may be reduced due to conductive through-wall heat gain. Moisture detection on interior partitions, floors and ceilings is generally easy to detect due to more static base surface temperatures due to stable interior ambient conditions. Variable exterior ambient conditions do not interfere with evaporative cooling thermal patterns on interior surfaces.

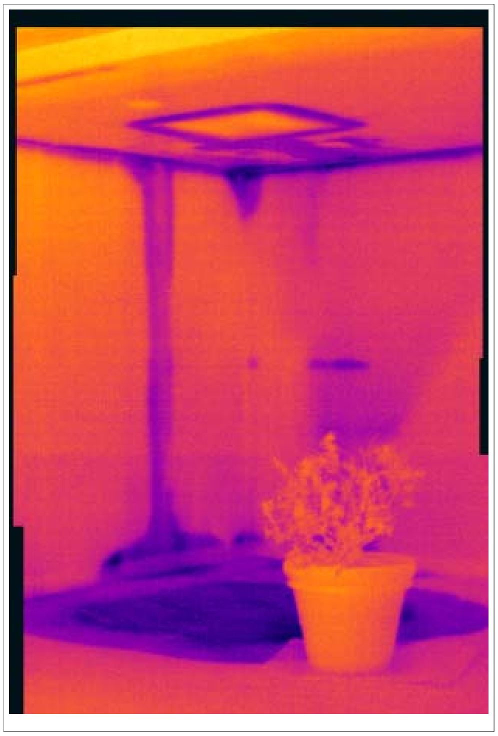


Figure 21. Fire sprinkler system leak observed on an interior painted wall and carpet. Initial wetting and drying appear much defined.

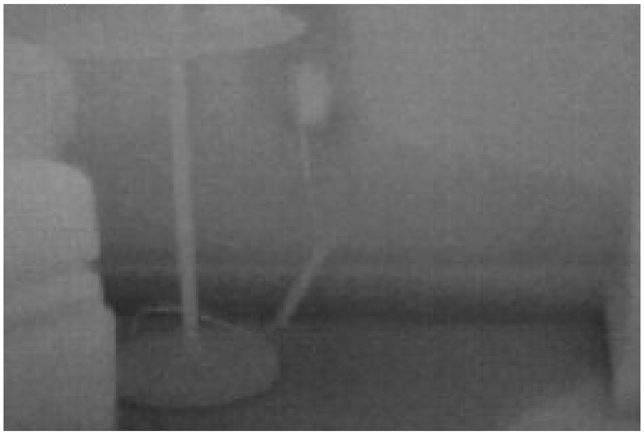


Figure 22. Wetting patterns may be minimal if covered with vinyl wallpaper that inhibits evaporative cooling.

The restoration industry uses infrared thermography to determine when walls are completely dry after floods. Visual inspections cannot always be relied on and moisture meters do not provide a complete picture of potential wet areas. The use of infrared thermography allows for non destructive evaluation of the potential causes and sources of the moisture. The tool is generally used in combination with moisture meters to validate acceptable amounts of moisture at a specific location.

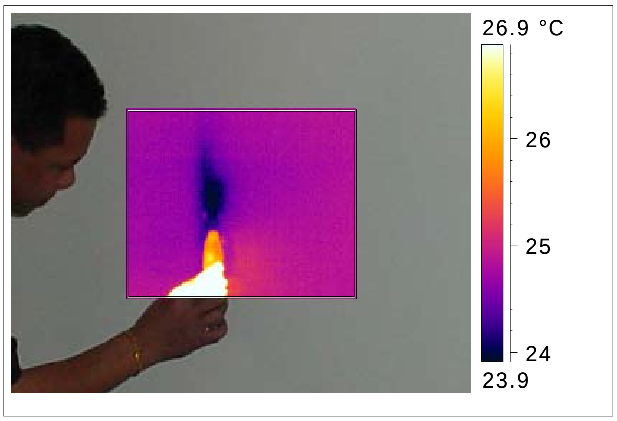


Figure 23. Confirming moisture presence with a capacitance moisture meter.

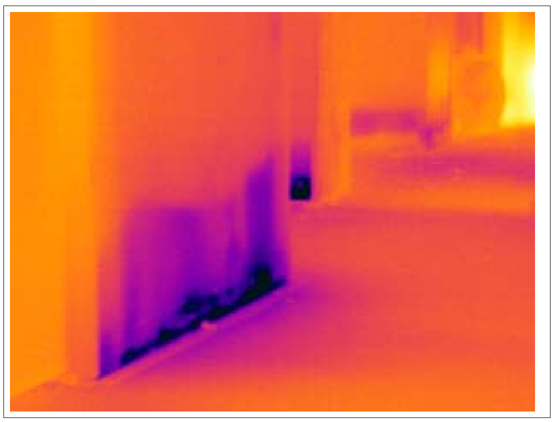


Figure 24. Locating and documenting wet areas.

The issue of limit state moisture detection (with all environmental factors being equal) is subject to both spatial and thermal resolutions of infrared equipment used. Shorter distances to target surfaces address spatial resolution limitations of infrared equipment. Thermal resolution limitations of equipment cannot be compensated for during inspection methodologies for moisture detection. Most medium to low cost imagers provide at least 100 mK thermal resolution. This is generally good enough to see signs of evaporative cooling during initial wetting and drying phase. When trying to determine complete dryness, imagers with considerably better thermal resolution (30 to 50 mK) provide much better limit state information. For this reason, it is recommended that interior moisture detection be carried out with imagers with at least 50 mK thermal resolution.

INTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO RAIN AND MELT WATER

Rain water penetration into exterior wall assemblies show up as a result of either evaporative cooling, or reduced thermal resistance values of saturated materials. The intensity of the thermal pattern will be affected by the rate of evaporation and the amount of moisture within the assembly. These factors are temperature dependent (both interior and exterior temperatures), vapor pressure dependent and time dependent.

Figure 25. Interior surfaces of exterior walls showing no visible wetting other than flooring.

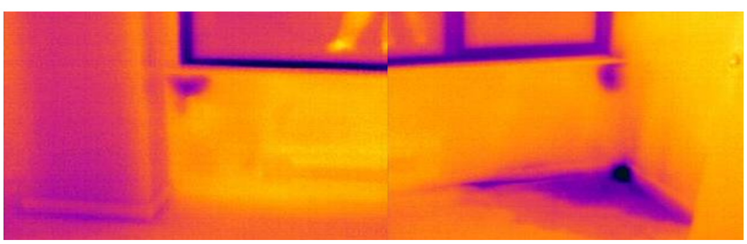


Figure 26. Rain water penetration into wall below corners of windows and on floor area on right side of thermal image.

Figure 26 demonstrates typical wetting patterns found in exterior walls from interior inspections. The primary issue these patterns highlight is that detection is possible but determination of specific defect resulting in water penetration requires additional testing and quite often some form of destructive testing.

INTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO WATER TESTING

Detection of rain water penetration requires inspection during or immediately after rainfall. However infrared inspections cannot always be scheduled or carried out at these times. Water testing is generally required when persistent rainwater penetration issues are experienced in older buildings. In addition, water testing can also be requested as a commissioning test of building envelopes on new buildings. Locating or determining if a water intrusion through the building envelope may be problematic due to the complexities of the building components. The water migration may be close to the exterior intrusion point or some distance from the actual intrusion. Infrared thermography can be used to determine the paths of water penetration thus allowing for better assessment of remediation solutions. Water testing is best employed prior to installation of interior finishes, thus scheduling of this type of commissioning procedure becomes critical to it effectiveness.

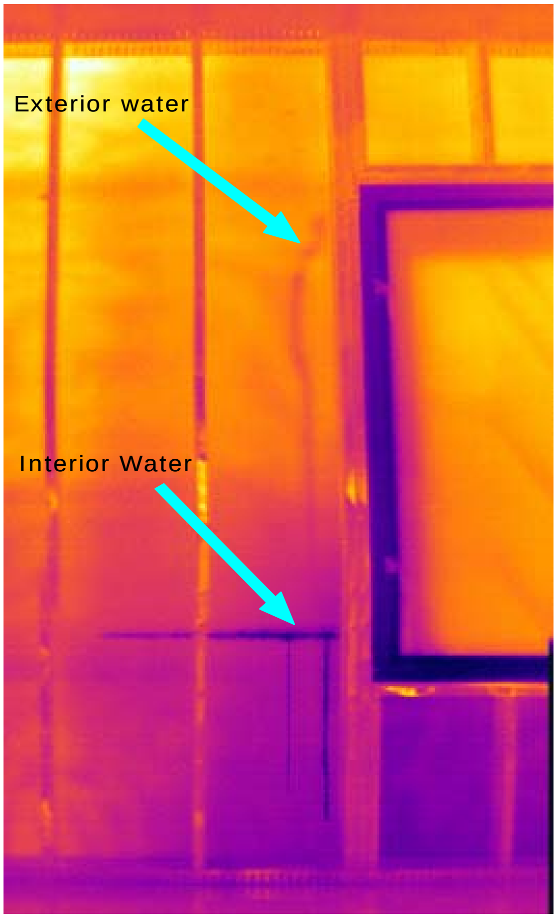


Figure 27. Moisture entering the exterior stucco at the window header, penetrating into the interior at a lower point.

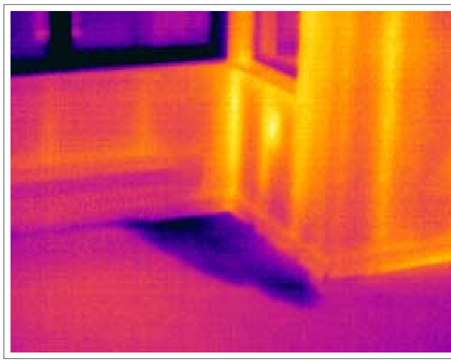


Figure 28. Moisture entering at the window but not showing interior until the floor.

INTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO RISING DAMP

Detection of moisture patterns due to rising damp from interior inspections is made difficult by the limited field of view for most interior inspections. Since this type of thermal patterning is associated with thick high mass walls, interior cavity spaces will almost always negate any potential for moisture detection from this source. Better luck is achieved in detection of moisture from rising damp in interior walls in large open spaces.

INTERIOR INSPECTIONS; MOISTURE PATTERNING DUE TO AIR LEAKAGE TESTING

Interior inspection of residential, large commercial or high rise buildings are generally done after exterior inspections determined that a potential problem exists. They are done to confirm results of exterior inspections. In cold climates, negative building pressure inspections during the heating season could result in condensation potential on interior surfaces or in interstitial spaces or materials close to the building interior. Unfortunately moisture patterning at air leakage points on interior surfaces is overpowered by the mass transfer heat loss pattern of the air leak. The greater the temperature differential between interior and exterior, the less likely moisture patterns are visible in the infrared during leakage testing. If negative building pressure leakage testing is carried out for long durations, it could be possible to detect moisture accumulation after the air testing while the building is in a neutral or slightly positive pressure condition and the mass transfer of warm interior air has not dried out the moisture around the leakage points.

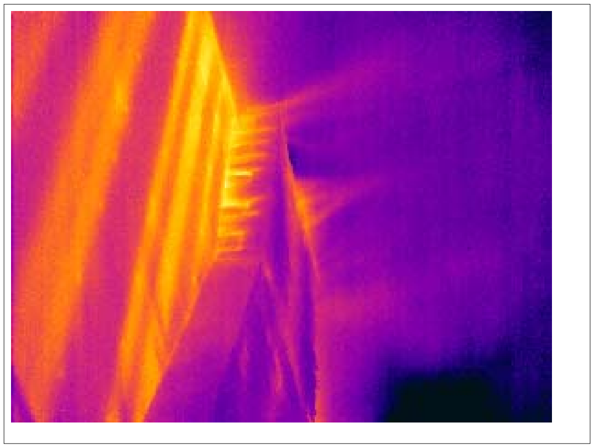


Figure 29. Air infiltration during pressure testing. (Image courtesy of Lee Durstin, BCRA)

Figure 30. Air infiltration during pressure testing. (Image courtesy of Janet Vics, Infrared investigation)

BELOW GRADE INTERIOR INSPECTIONS; EXPOSED FOUNDATION WALLS

Below grade moisture intrusion is generally a result of defects in the damp or water proofing membrane on the exterior face of the foundation wall. These types of moisture intrusion manifest themselves as thermal patterns visible by means of evaporative cooling. Variable conductive heat loss patterns do not disturb the background wall temperatures for these thermal patterns thus they become easily detected.

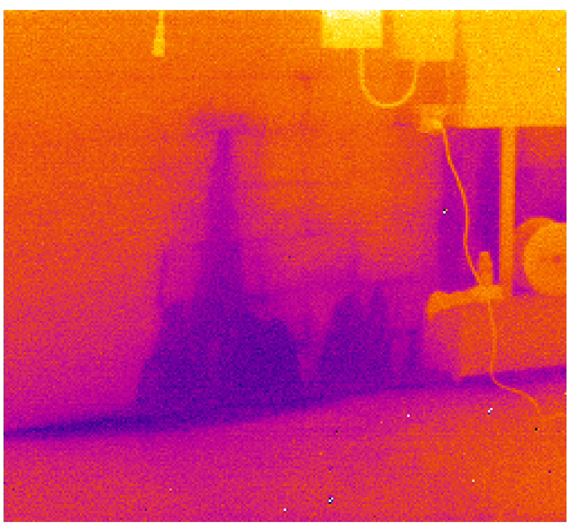


Figure 31. Ground water penetration into hollow core block foundation wall.

BELOW GRADE INTERIOR INSPECTIONS; INSULATED FOUNDATION WALLS

In instances where foundation walls are insulated and finished on the interior, these patterns could still be seen but may look like other interior moisture patterns seen from above ground assemblies. The variable thermal patterning due to studs and possible vapor retarders make moisture patterns on interior inspections of these assemblies more difficult to detect.

SUMMARY

Moisture within low-sloped roof assemblies is detectable by transient or near steady state heat flow methodologies. The window of opportunity for transient condition testing is 2 – 3 hours after sunset following a sunny day. Near steady state condition testing can be carried out from both the interior and exterior providing that there is a sufficient temperature differential to produce a thermal signature and surfaces are unobstructed and easily viewable. Aerial infrared inspections are recommended for large or multiple roofs areas or locations, but walk-on inspections are cost effective for small roof inspections. Spatial resolution becomes an issue when large distance to target object surfaces are encountered. Thermal resolution is less of an issue since moisture effects for transient testing generally produce temperature differences in the 2^{o} C to 4^{o} C (4 ^{o}F to 7 ^{o}F) range.

Moisture patterning due to rainwater and melt water penetration of the building cladding is visible if the cladding is porous and absorbs moisture and there is a thermal gradient through the wall to distinguish dry from wet cladding. This is generally a transient condition and requires inspection after sunset to carry out comparative analysis of patterns from all elevations of the building. Rainwater generally is detected at upper sections of buildings most susceptible to penetration due to wind forces. Melt water patterns are visible at projections and interior corners where ice and snow build up occur in winter months.

Moisture patterning due to ground water absorption in solid masonry buildings generally display as homogeneous higher surface temperatures at the base of the building just above grade. It requires a thermal gradient through the building enclosure of at least 30 ^{o}C (54 ^{o}F) to be visible.

Moisture patterns within masonry cladding created by air leakage from interior sources due to stack effect are most prominent at upper sections of buildings during sub-zero winter months. These patterns are more visible in negative building pressure conditions rather than positive building pressure conditions provided that negative building pressure test conditions do not exist for greater than a 24-hour time period. In conditions where normally occurring exfiltration results in localized increased cladding temperatures and resultant moisture accumulation, a time duration of greater than 24 hours would be needed to eliminate the effect of that normal heat loss pattern. Thus most negative building pressure exterior building inspections often still see these thermal patterns in conjunction with their resultant moisture accumulation.

When conducting exterior large building infrared thermographic inspections during cold winter months, it is advised to conduct the negative building pressure inspection prior to the positive building inspection if both are planned for one evening's work. If the work is spread out over a number of days, then either inspection can be carried out first since the resultant moisture accumulation from internal sources will be allowed to dissipate due to solar gain and natural diffusion of moisture to outdoors through the cladding material.

Phase change of moisture (freeze/thaw cycles) within porous cladding materials is visible only during exterior ambient temperature conditions between 0 ^{o}C and -5 ^{o}C when moisture within the cladding is most susceptible to phase change. Phase change of moisture (condensation) within exterior wall assemblies is visible generally in exterior ambient conditions less than 10 ^{o}C but is subject to relative humidity in both the interior and exterior. Positive and negative building pressure conditions do not affect the formation and detection of moisture within the process of phase change but the mass transfer of hot or clod air through enclosures do make detection of condensation patterns less obvious. The thermal pattern will show up as either much colder or much warmer than adjacent surface areas depending if moisture is freezing to a solid state or thawing to a liquid state.

Moisture is detectable during interior inspections by means of evaporative cooling. The amount of surface cooling is directly proportional to the rate of evaporation and the amount of moisture within the assembly. These factors are temperature dependent (both interior and exterior temperatures), vapor pressure dependent and time dependent. Non-vapor transmissive coatings will affect the rate of drying and thus the intensity of the thermal signature. Imagers with better thermal resolution (50 mK or better) are recommended for this type of moisture detection work.

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ACKNOWLEDGEMENTS

The author wish to thank the Panel for Energy Research and Development (PERD) for their continued funding of field research in the detection of moisture within masonry structures and infrared thermography commissioning methodologies leading to improved building durability and reduction of energy utilization within buildings. He also wishes to acknowledge the assistance of Garry Desroches from PWGSC, Western Region for the capture and data processing of many of the thermal images illustrated within the paper.

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The principle author, Antonio Colantonio (B. Arch 78, Carleton U.), has over 28 years of experience in the area of building science and infrared thermography. He has worked for PWGSC developing non-destructive techniques to evaluate building performance in architectural disciplines in addition to acting as departmental expert advisor on building envelopes. He is an active voting member in over a dozen CGSB standards, VP of the Building Envelope Council Ottawa Region, director of the National Building Envelope Council (Canada) and authored numerous papers on the subject of infrared thermography and building diagnostics.

Scott Wood (B.S. Microbiology 81, Oregon State University) has been involved in building investigations and testing using infrared thermography as an investigative tool for both commercial and residential sectors for 6 years. Currently a Senior Building Science Consultant for BCRA, Inc performing building investigations and evaluations from peer review for architectural planning to final building testing and evaluation. He is the primary instructor/consultant for the Building Science Institute, developing the training curriculum and instructing the building science thermography courses. He is also director of building sciences for the International Association of Certified Thermographers (IACT). Prior to his position at BCRA, Inc. he was involved in the development of training curriculums, project management and investigations for the restoration industry. He has performed hundreds of infrared thermography site evaluations as well as authored numerous papers, provided presentations, clinics and workshops regarding infrared thermography's use in restoration and building science.