Detection of Moisture and Water Intrusion Within Building Envelopes By Means of Infrared Thermographic Inspections

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Abstract

Infrared thermographic imagers have been used in the building industry since the 1980's, mainly for building envelope and heat loss analysis. Infrared imagers have developed significantly over the past 15 years and are now vital tools to determine performance characteristics of walls and roofs for both energy and structural integrity. With interior health issues coming to the forefront - such as mold issues, the infrared imager has again become a vital diagnostic tool. Although infrared imagers do not detect presence of mold, they can be used to detect presence of moisture by means of variances in heat transfer brought on by capacitance of water and phase change heat loss or gain. The infrared camera can be readily utilized to detect the extent of moisture intrusion in building structures in a much faster and convenient way than conventional moisture detection devices. 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 the recommendation for remedial action may 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 infrared wavelengths are different for both interior and exterior inspections. Ensuring optimal inspection conditions is paramount in order to obtain accurate inspection results. This paper discusses 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 are discussed and the importance of timing is stressed regarding detection of moisture within assemblies by non-destructive means.

1.0 Introduction

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.

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

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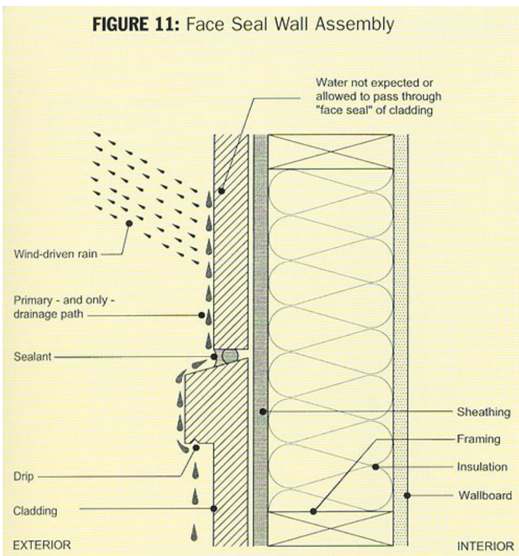
moisture through unintentional openings in the air barrier assemblies than vapor diffusion through the leakiest vapor barrier or retarder. Detection of openings that facilitate moisture migration is critical to the control of vapor flow and moisture accumulation in exterior assemblies.

1.1 Types of Wall Assemblies.

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 loading-bearing or enclose an integral steel or concrete structural frame.



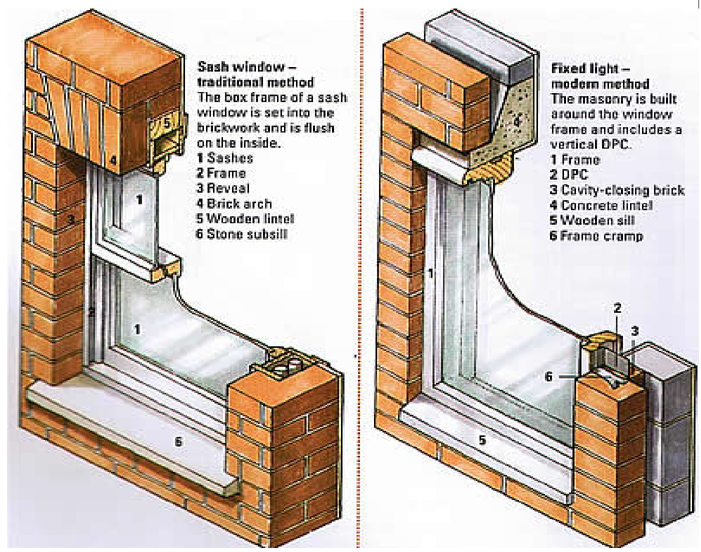


Figure 1; *Typical Face Seal Low Mass Assembly* ***Figure 2;*** *High Mass Face Seal and Cavity Wall Assemblies*

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 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.

1.2 Types of Roof Assemblies.

1.2.1 Sloped Roof Assemblies.

Roofs can be classified into sloped and low sloped assemblies. Sloped assemblies are generally associates 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 10^{o}C and a pressure differential of at least 5 Pa.

Infrared imagers cannot be used to determine presence of moisture within these assemblies from exterior inspections. The resultant effect of roof leaks in sloped roofs is 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 capacitance of the dry roof material and the moisture laden materials), these patterns are most obvious when temperature differentials between interior and exterior are greater than 10^{o}C. Alternatively, if moisture finds its way into the interior gypsum board or plaster, evaporative cooling may be detected during the drying out stage of the roof leak. This option only exists when there has been wetting and drying is occurring within absorptive materials.

1.2.2 Low-Sloped Roof Assemblies.

Low-sloped roofs can be classified into conventional and inverted roof membrane assemblies. Conventional assemblies are where the roof membrane is 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 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 relate to membrane failures. Infrared thermography can only be used to detect moisture within absorptive insulation underneath roof membranes in conventional type assemblies.

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; a) transient method using solar heat gain during day time and inspecting transient conditions during and immediately after 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. The first is exclusively carried out from the exterior while the second type can be carried out both from the exterior or the interior. The static method required a minimum of 10^{o} C

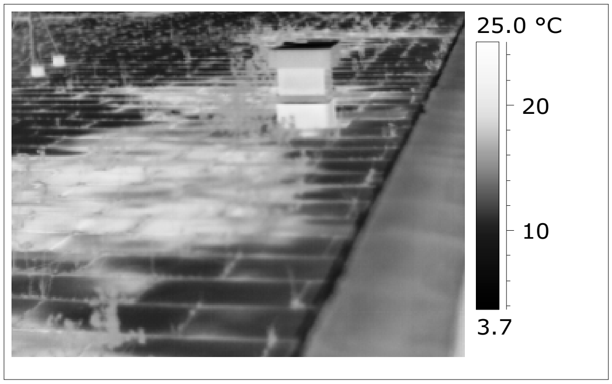
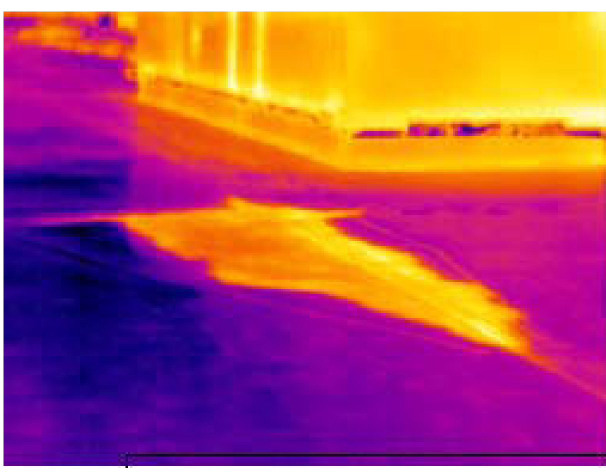


***Figure 3**.Infrared image of moisture within concrete clad Insulation over inverted roof membrane,* $T_o = 20^oC$

***Figure 4**. Visual of concrete clad insulation over inverted roof membrane, no visible wetting on concrete.*
The first sign of lack of drainage within roof assembly could be growth of vegetation within joints. But this does not indicate any deficiency with the actual roof membrane.

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 5^o C produce variable results and are not recommended. If inspections are carried out from the interior, the temperature of the rain water should be at least 5^o C 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 with the roof assembly, and the amount of solar heat gain throughout 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 a tricky activity. Inspections with wind condition greater than 10 kph 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.



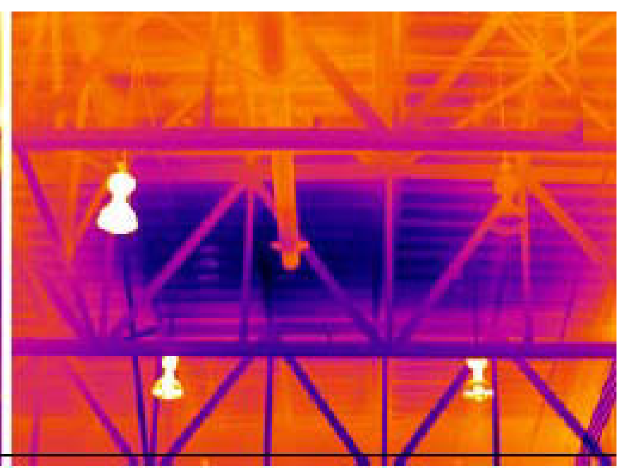


***Figure 5;** Moisture within insulation under one ply sheet membrane roof assembly as seen from exterior (Images courtesy of Paul Frisk, FLIR Systems Canada)*

***Figure 6;** Moisture within insulation as seen from interior of building.*

Temperature resolution is not a critical technical requirement for the transient methodology since the temperature variance between dry and wet insulation is generally in the 2^{o} C to 4^{o} C range. In the static methodology, temperature variance between dry and wet insulation is generally in the 0.2^{o} C to 1^{o} C range for surface temperatures. Most low-cost thermal imagers today come with this level of temperature resolution and are acceptable for use in both methodologies. Better temperature resolution allows for better detection of possible moisture in unfavorable conditions. The difficulty of analysis of data from unfavorable inspection conditions is that many other non consequential thermal signatures also become apparent and need to be evaluated and discounted. These types of thermal signatures include uneven ballast, heavy flood coats, reflective roof surfaces, multiple roof felt layers and membranes, reflected energies from adjacent protrusions and wall surfaces, variable emissivity conditions due to dirt built up.

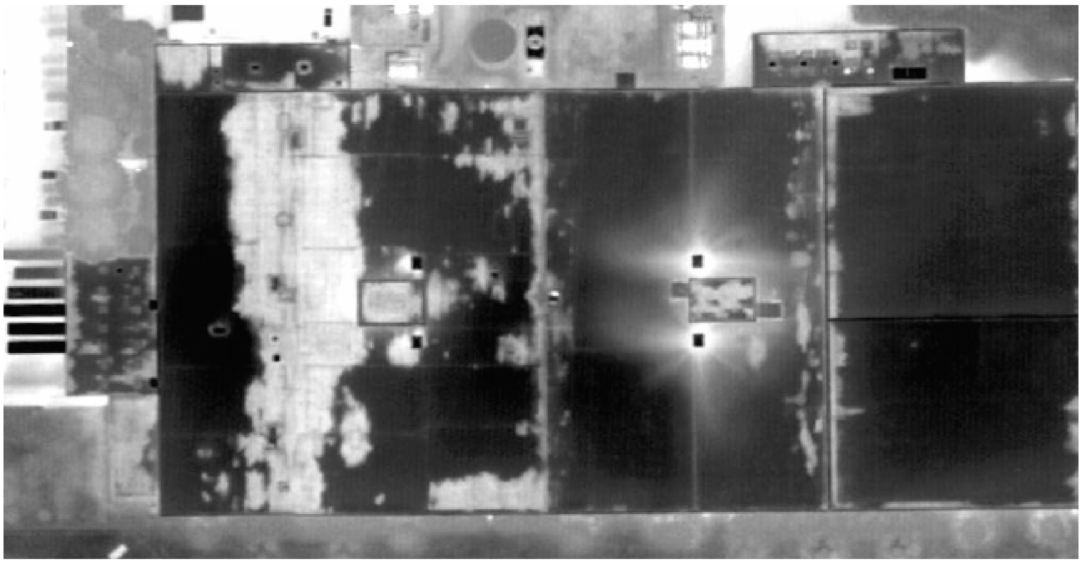


Figure 7; *Aerial infrared image of moisture within insulation of conventional built-up roof. Note only one section of three requires replacement. The other two roof sections display minor roof leaks around curbs and flashings. (courtesy of AITScan and Stockton Infrared, Greg Stockton)*

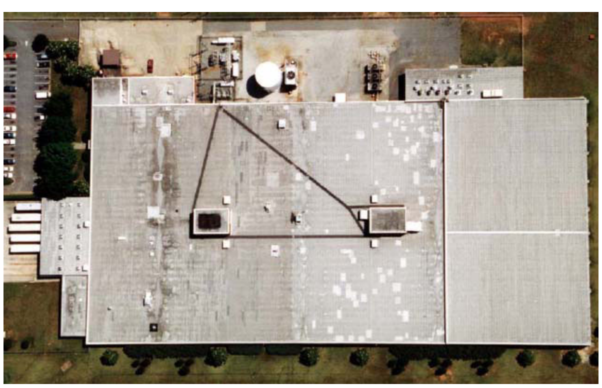


Figure 8; *Visual aerial photo (courtesy of AITScan, Greg Stockton)*

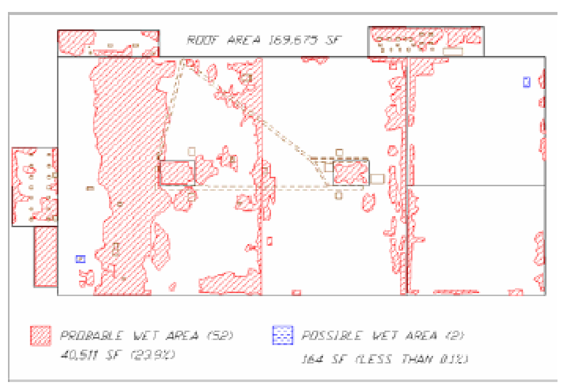


Figure 9; *CAD drawing of suspected moisture (courtesy of AITScan, Greg Stockton)*

Detection of moisture within built-up roofs can be carried out by either walking over the roof assembly, surveying from higher adjacent roofs, or by fixed wing airplanes or helicopters. All are acceptable methodologies when suitable inspection conditions are present and appropriate infrared imagers are used.

Small roofs may be easier and 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 moisture intrusion. Dedicated high spatial resolution imagers (300K pixel or higher) are required to obtain suitable spot size resolution to define moisture patterning and roof features. Focus and high speed vibration are issues that need to be addressed in data collection from aerial fixed-wing or helicopter inspections for both fixed mounted and handheld imagers.

2.0 Exterior Inspections

2.1 Moisture Patterning As A Result Of Rain Water.

In cold climates, commissioning building envelope inspections are not always carried out in sub-zero temperatures. Exterior ambient temperatures between 1°C and 10°C 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 patterns generally affect cladding materials thus thermal patterns are a result of the reduced thermal resistance of the cladding materials. 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° C exist through the building exterior envelope.

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. (See ***Figure 10)***

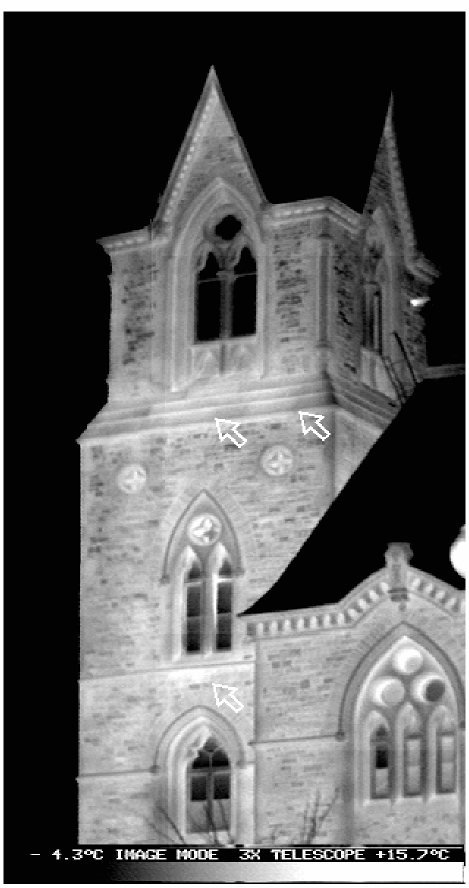


***Figure 10**. Neutral Building Pressure (0 Pa), T_o = -8°C, No precipitation or snowfall for at least 7 days prior to inspection. Arrows point to suspected moisture accumulation within the limestone cladding due to rain and melt water throughout winter.*

2.2 Moisture Patterning As A Result Of Melt Water.

In winter months, solar gain and thaw conditions result in melt water runoff from roofs, sloped projections and other architectural features. In these situations, 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.

2.3 Moisture Patterning As A Result Of Ground Water.

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 the stone walls immediately above the ground during the heating season. 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 the 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^{o} C. 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 11**. Ground floor of solid masonry wall assembly illustrates warmer surface temperatures due to rising damp from ground water in foundation wall.*

3.0 Air Leakage Testing & Resultant Moisture Patterning

3.1 Negative Building Pressures and Ambient Temperatures.

Figures 12 & 13 demonstrate the amount of moisture accumulation that can occur within masonry cladding as a result of stack effect brought on by low winter exterior ambient temperatures. Both images taken during negative building pressures are void of air exfiltration patterns but ***Figure 13***, taken at a lower ambient temperature (-11^{o}C), displays greater amount of moisture accumulation within the masonry cladding at the top of the building than ***Figure 12*** taken at temperatures approximately 10^{o}C higher.

The only other variable in this image is significantly increased negative pressure in the higher temperature situation that could have resulted in slightly modifying existing moisture patterns. The increased negative pressure combined with the time prior to inspections that this condition existed may have reduced the amount of moisture within the wall cladding. In addition, due to reduced exterior ambient temperatures, stack effect would have been reduced for the period prior to capture of image in ***Figure 12***, thus reducing the amount of moisture especially at the top of the building envelope.

3.2 Positive Building Pressures and Ambient Temperatures.

The thermal images in ***Figures 14 & 15*** demonstrate the amount of moisture accumulation that can occur within masonry cladding as a result of stack effect brought on by reduced exterior ambient temperatures. Both images, taken during positive building pressures, display thermal patterns created by air exfiltration patterns in addition to previously accumulated moisture patterns due to stack pressures. These air leakage patterns overpower the moisture induced thermal patterns in both exterior ambient temperature conditions.

The image taken at the lower ambient temperature illustrates greater amount of moisture accumulation within the masonry cladding than the image taken at temperatures of approximately 10^{o}C higher. This is consistent with the thermal patterns produced during the negative building pressure inspections. The only other variable in this image is slightly increased positive pressure in the higher temperature situation that could have resulted in the slight modification of existing moisture patterns.

3.3 Moisture Patterns Resulting From Direct and Diffuse Leakage.

The thermal images seen in ***Figures 16 to 19*** demonstrate the variances between moisture patterns created by both direct and diffuse air leakage. These images also illustrate the variations during both positive and negative pressure conditions during inspections.

Moisture patterning is most visible during negative building pressure inspections since air leakage patterns do not overpower those created by moisture within the cladding or insulation. If conducting inspections within an hour or so after initializing negative building pressure, then moisture patterning created by normal operating conditions become most visible in the infrared. 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 these 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 has been generally observed is that moisture accumulation around areas of direct airflow paths occur at the peripheral areas of the 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 (-30^{o}C and lower), visual signs of hoar frosting is visible at these problem areas.

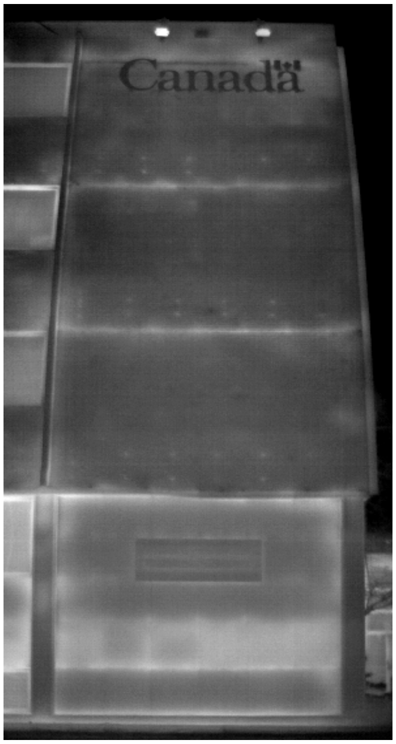


Figure 12. *Negative Building Pressure (-140 Pa), $T_o = 0^oC$*

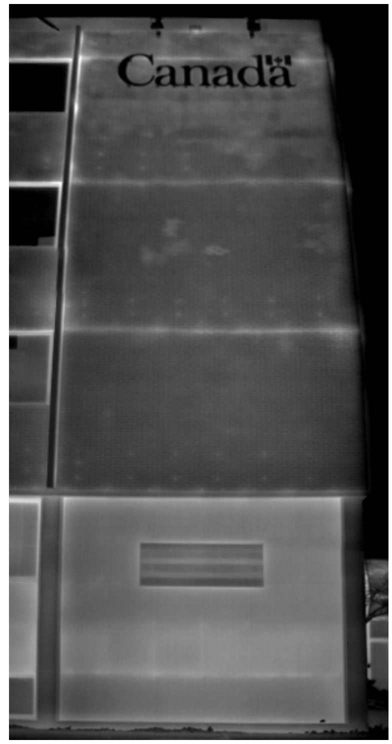


Figure 13.*Negative Building Pressure (-8 Pa), $T_o = -11^oC$*

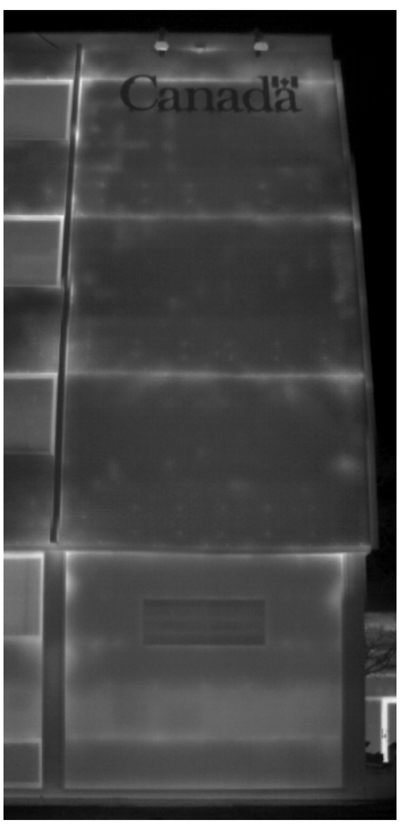


Figure 14. *Positive Building Pressure (+40 Pa), $T_o = 0^oC$*

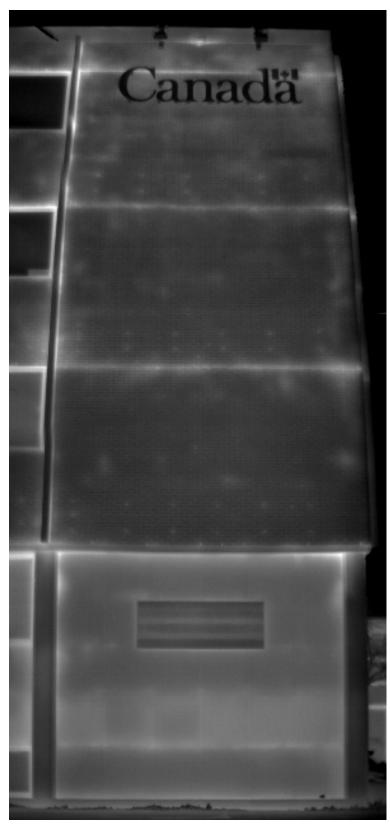


Figure 15. *Positive Building Pressure (+25 Pa), $T_o = -11^oC$*

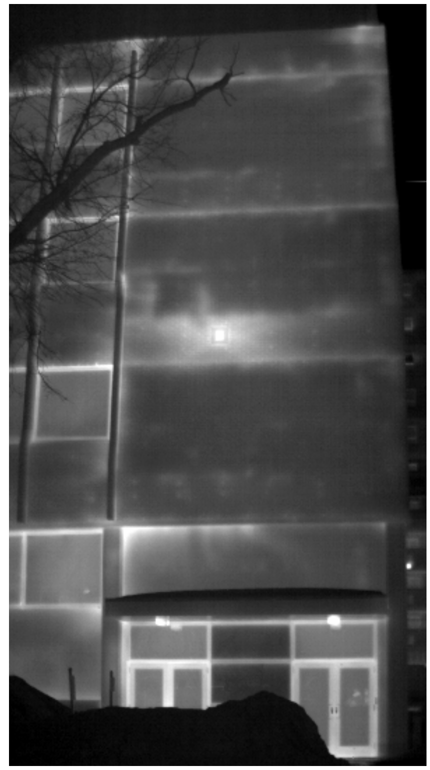



Figure 16. *Negative Building Pressure (-140 Pa), T_o = 0^{o}C* ***Figure 17***. *Positive Building Pressure (+40 Pa), T_o = -0^{o}C*

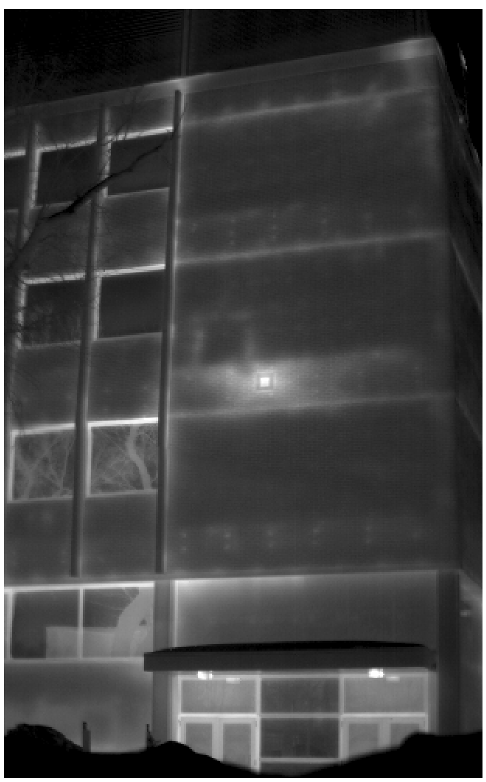
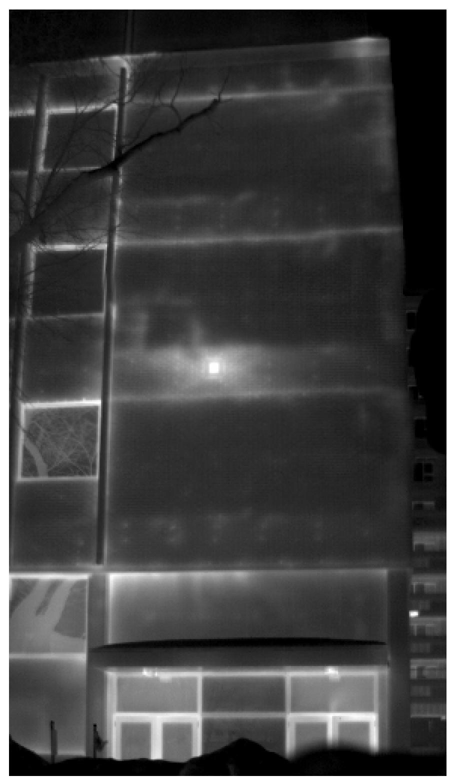



Figure 18.*Negative Building Pressure (-140 Pa), T_o = -11^o* ***Figure 19***.*Positive Building Pressure (+40 Pa), T_o = -11^{o}C*

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.

When looking at buildings during cold weather conditions, variations in the thermal signatures created by naturally occurring conditions will take considerable time to be modified and in some conditions, may not be modified at all. In ***Figures 16 to 19*** the masonry areas around the vent located in the central section of the third floor appears warm in the negative pressure inspections, even through negative pressures were imposed for more than 2 hours prior to each inspection. Exterior ambient temperature seems to have little effect on the dissipation of stored heat and moisture within the masonry around these locations. In these conditions, greater time is required under negative building pressure to eliminate the stored heat from air leakage within the masonry cladding.

3.4 Duration of High Building Pressure and Moisture Accumulation.

The thermal images in ***Figures 20 & 21*** were taken on subsequent mornings. ***Figure 21*** illustrates positive pressure imagery produced 24 hours prior to the negative pressure imagery in ***Figure 20***. 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.

Figure 20 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.

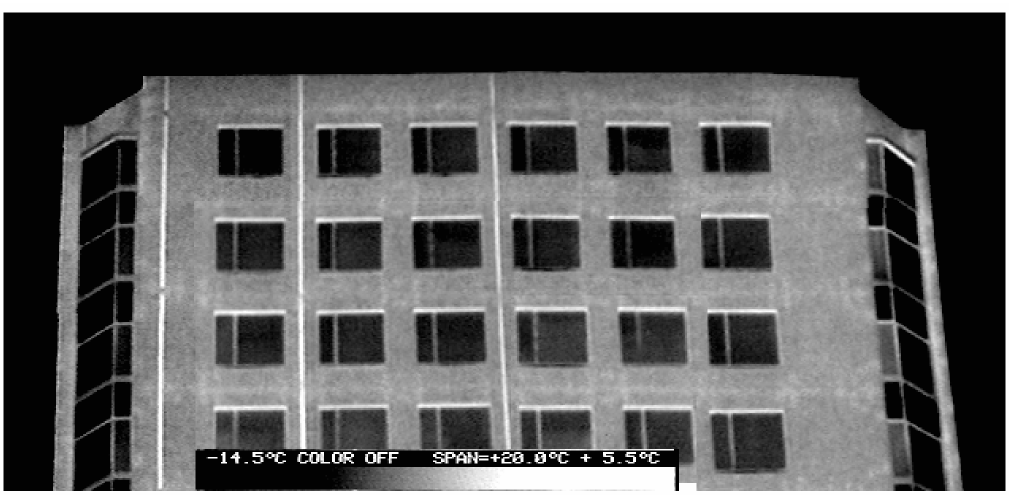


Figure 20*. Negative Building Pressure (-60 Pa), T_o = -7°C, maintained for a duration of 4 hours prior to inspection.*

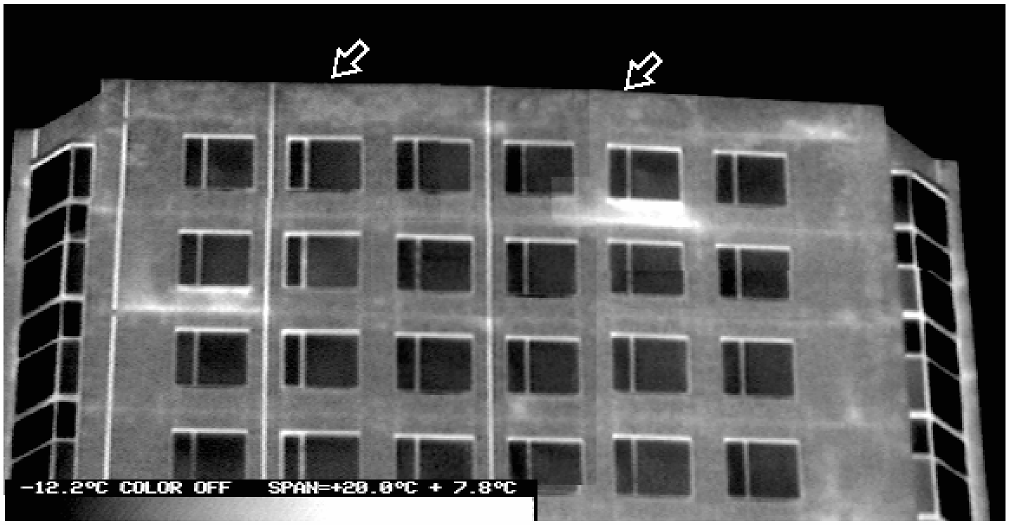


Figure 21. *Positive Building Pressure (80 Pa), T_o = -7°C, maintained for a duration of 5 hours prior to inspection.*

As seen in ***Figure 21***, 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.

4.0 Moisture Patterning and Phase Change

4.1 Exterior Inspections (Freeze Thaw Cycles).

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. The accompanying thermal images in ***Figures 22 to 23*** illustrate the endothermic effects of melting ice within the building cladding.

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 the negative and positive inspections during the same evening. 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.

The moisture patterning in the wall due to accumulated moisture over the winter months appears warm around the floor slabs and is present during both the negative and positive pressure inspections. During the positive building inspection, these moisture patterns appear to be overpowered by the thermal patterns created by the air leakage through the walls from the building interior. Both images were taken during same evening, 4 hours between the two settings. Due to the lower exterior ambient temperatures, phase change phenomenon is not visible at low outside temperatures. Moisture accumulation is visible during both inspections, but more during positive building pressure inspections than slightly negative pressure inspections.

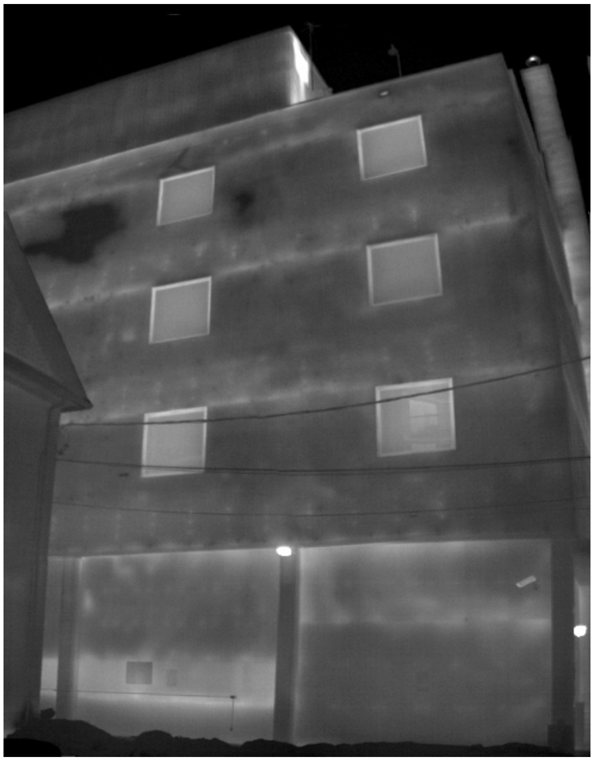
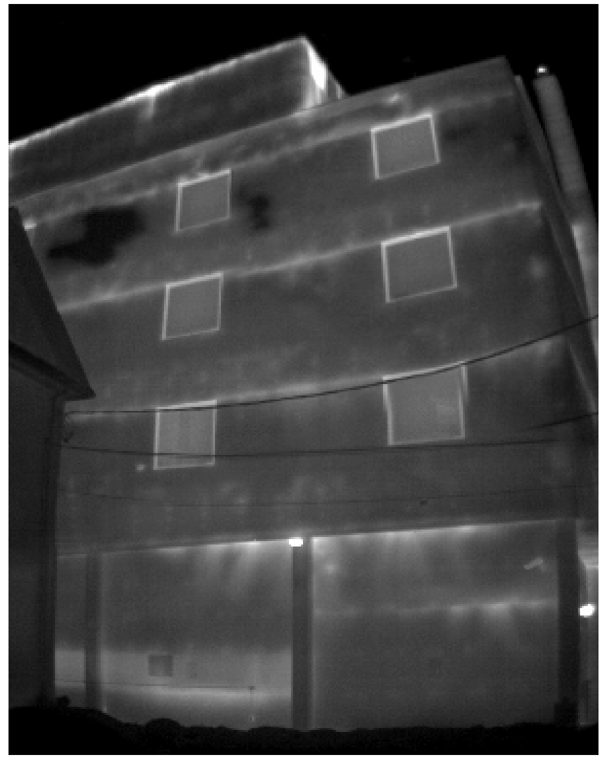



***Figure 22**. Negative Building Pressure (-140 Pa), T_o = 0^{o}C* ***Figure 23**. Positive Building Pressure (+40 Pa), T_o = 0^{o}C*
Both images taken during same evening, 4-hour time span between the two images.

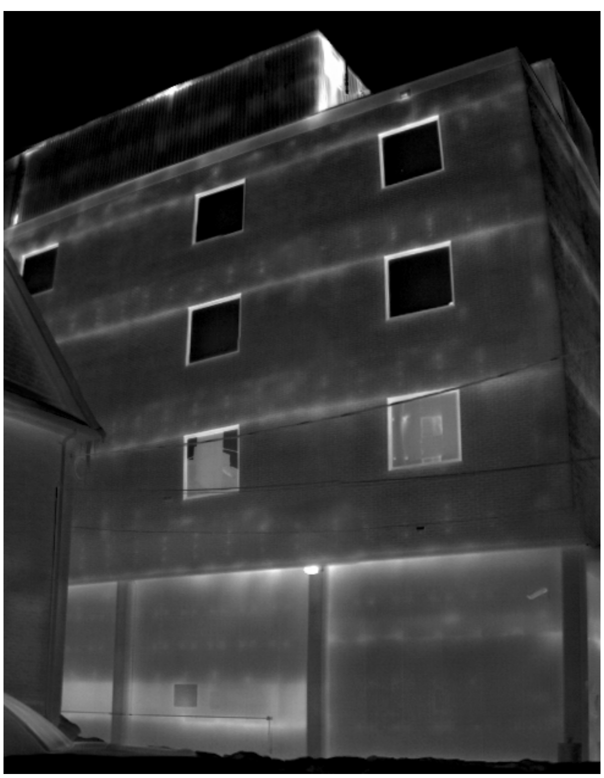



***Figure 24.** Negative Building Pressure (-8 Pa), T_o = -11^{o}C* ***Figure 25.** Positive Building Pressure (+25 Pa), T_o = -11^{o}C*

4.2 Interior Inspections (Evaporative Cooling).

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 phase changes is absorbed from the 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.

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 the 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 that 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.

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 temperature ranges 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 winter months will result in colder interior surface temperatures of exterior walls 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.

The insurance 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.

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.

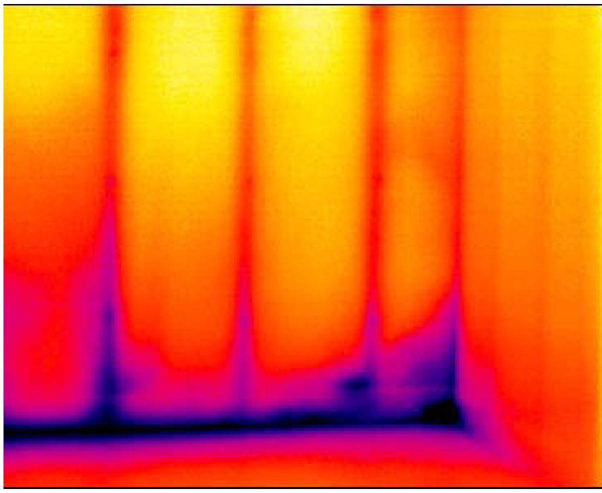


Figure 26; *Moisture within base of wall and wet studs.* *(Images courtesy of Paul Frisk, FLIR Systems Canada)*

Figure 27; *Visual of interior partition with no visible wetting.*

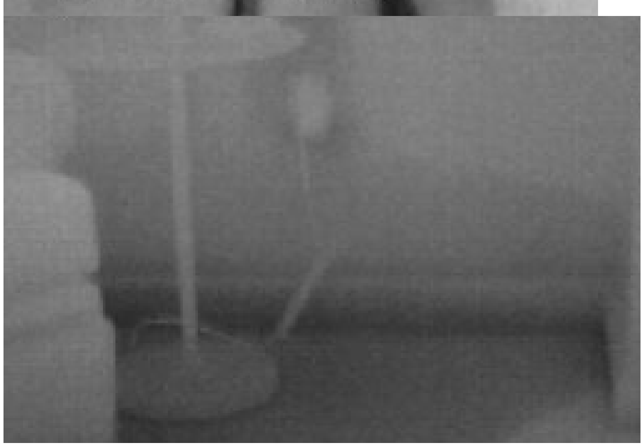


Figure 28; *Plumbing leak within interior painted wall. Initial wetting and drying appear very defined. (Images courtesy of Paul Frisk, FLIR Systems Canada)*

Figure 29; *Wetting patterns may be minimal if covered with vinyl wallpaper that inhibits evaporative cooling.*

5.0 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 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 between the 2^{o} C to 4^{o} C 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 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 building 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. Positive and negative building pressure conditions do not affect the formation and detection of moisture within the process of phase change. 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.

6.0 References

1. Colantonio, Antonio and Desroches, Garry: "Thermal patterns on solid masonry and cavity walls as a result of positive and negative building pressures", pp 176 – 187; Proc. Thermosense XXVII; SPIE Vol. 5782, March 2005.

7.0 Acknowledgements

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