Thermal Patterns Due to Moisture Accumulation within Exterior Walls

Antonio Colantonio, Garry Desroches
Public Works And Government Services Canada

ABSTRACT

In cold climates, air leakage is accompanied by moisture transport. When migrating through dew point temperatures, a considerable amount of moisture accumulation may occur depending on variables such as the duration of sub-zero exterior temperatures, building pressurization, wind effects and the level of interior relative humidity. Moisture accumulation may result in premature deterioration of wall assemblies and the formation of mold. 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 since the recommendation for remedial action will vary considerably. This paper will define 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. Various types of exterior building envelopes will be discussed along with their hygro-thermal performance characteristics and how these affect thermal patterns during various inspection procedures.

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 and 4) insulated steel assemblies. For low rise and residential buildings there is an additional type of generic wall assembly; 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. In these climates, 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 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.

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.

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 and 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 completion of 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 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. Once 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 air barrier assembly breach. Variability of location and size of air barrier breaches 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.

MOISTURE PATTERNING AS A RESULT OF RAINWATER

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 the 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. Unless buildings are located in areas with a high driving rain index, most only experience rainwater penetration along the top floors. 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. (Refer to ***Figure 1)***

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 the temperature differential between interior and exterior.

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. In many of the buildings investigated there was a correlation between the dirt build up on stones and moisture accumulation within the wall and the specific stones.

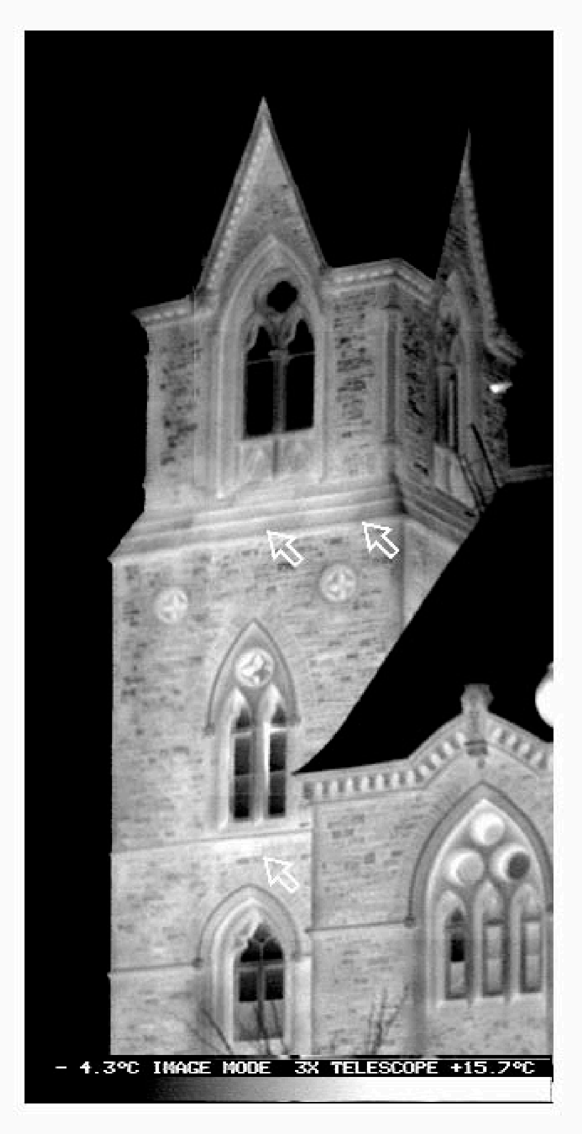


Figure 1*. Neutral Building Pressure (0 Pa),* $T_o = -8^{o}$*C, No precipitation or snowfall for at least 7 days prior to inspection.*

Arrows point to suspected moisture accumulation within the limestone cladding due to rain and melt water throughout winter months.

MOISTURE PATTERNING AS A RESULT OF GROUND WATER

Solid masonry walls with stone foundations without ground protection are susceptible to ground water absorption, and through capillarity this ground water wicks it way up the wall at the first floor of the building. 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 due to freeze thaw. Infrared inspection of these walls can detect moisture accumulation by means of increased 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 -10°C. Inspections carried out during higher temperatures require more sensitive infrared equipment to discern surface temperature variations, and they are not always apparent since thermal patterns are rather homogeneous in nature rather than mottled and variable.

NEGATIVE AIR LEAKAGE TESTING AND EXTERIOR AMBIENT TEMPERATURES

The two images below (***Figures 2 & 3***) 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 3***, taken at a lower ambient temperature (-11°C), displays a greater amount of moisture accumulation within the masonry cladding at the top of the building than ***Figure 2*** taken at temperatures approximately 10°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 2***, thus reducing the amount of moisture, especially at the top of the building envelope.

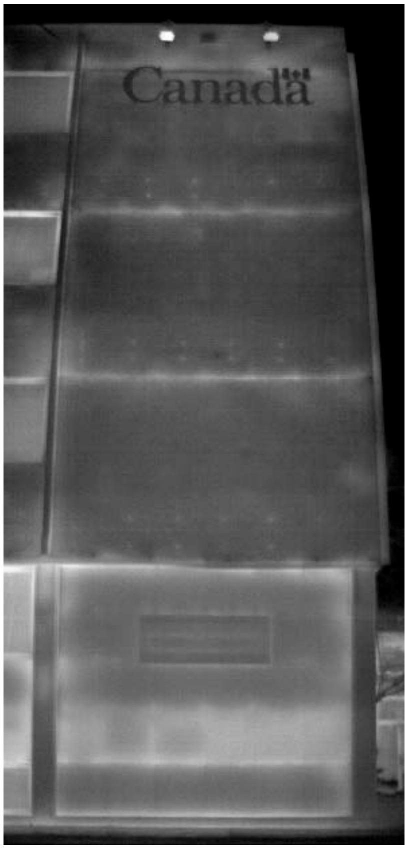


Figure 2*. Negative Building Pressure (-140 Pa), $T_o = 0^oC$*

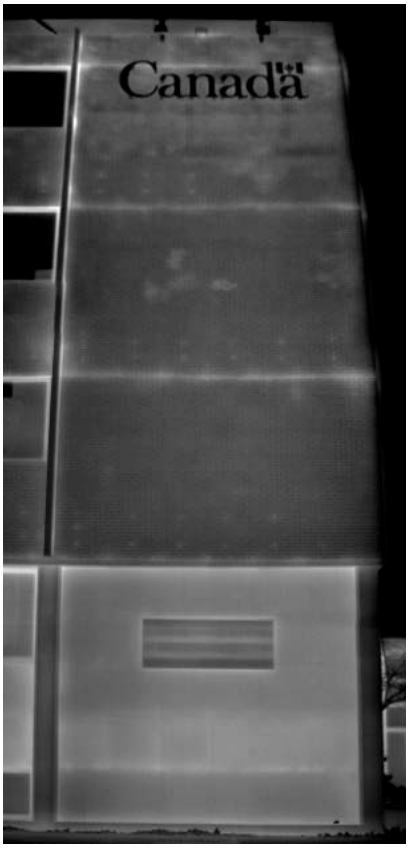


Figure 3*. Negative Building Pressure (-8 Pa), $T_o = -11^oC$*

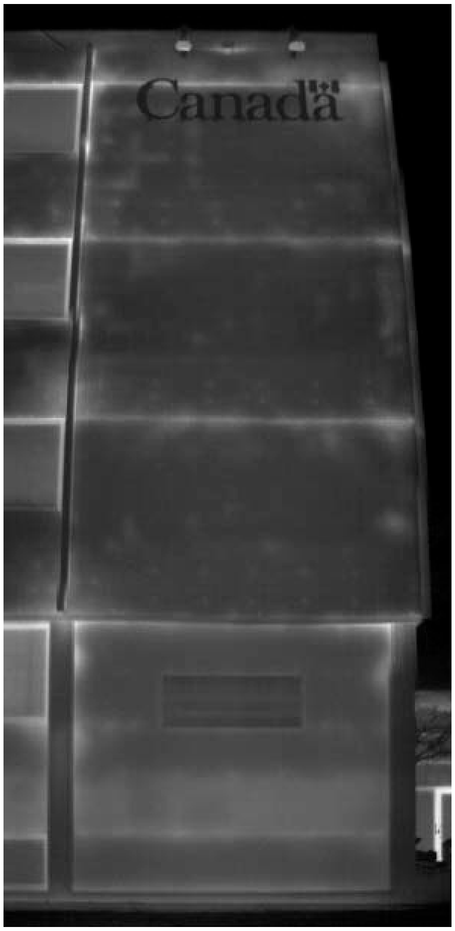


Figure 4. *Positive Building Pressure (+40 Pa), $T_o = 0^oC$*

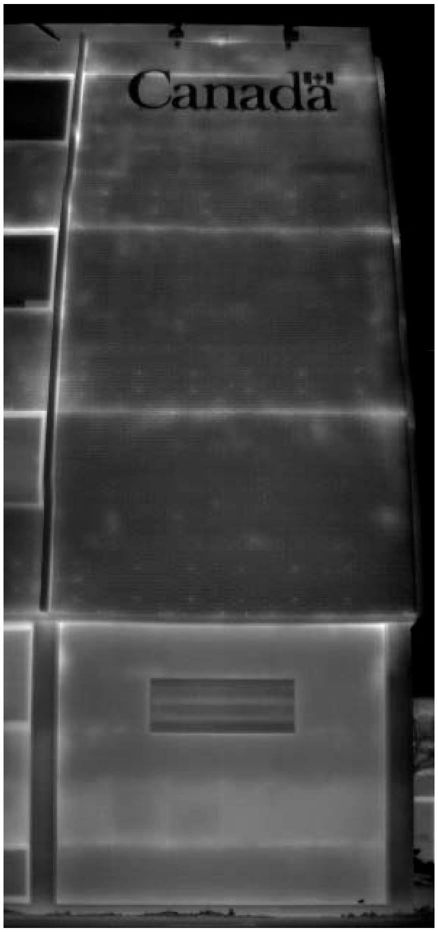


Figure 5. *Positive Building Pressure (+25 Pa), $T_o = -11^oC$*

POSITIVE AIR LEAKAGE TESTING AND EXTERIOR AMBIENT TEMPERATURES

The two images in ***Figures 4 & 5*** above 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 a greater amount of moisture accumulation within the masonry cladding than the image taken at temperatures approximately 10^oC 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.

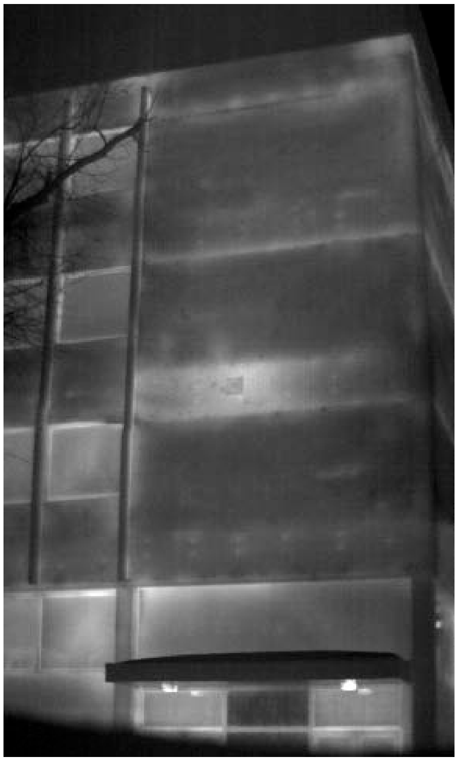


Figure 6. *Negative Building Pressure (-140 Pa), $T_o = 0^oC$*

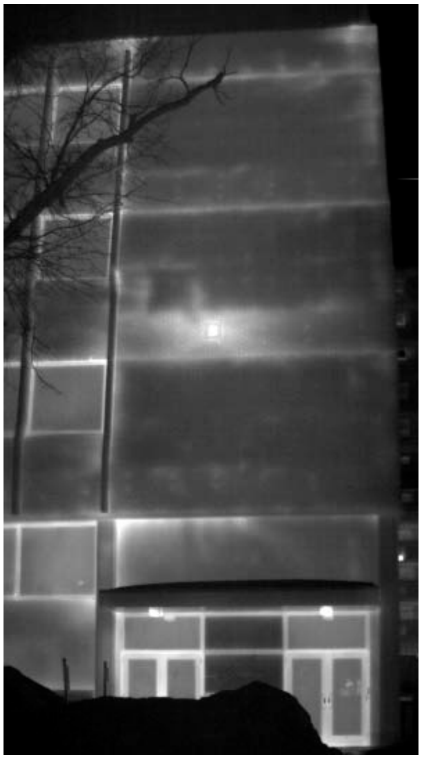


***Figure 7**. Positive Building Pressure (+40 Pa), $T_o = -0^oC$*

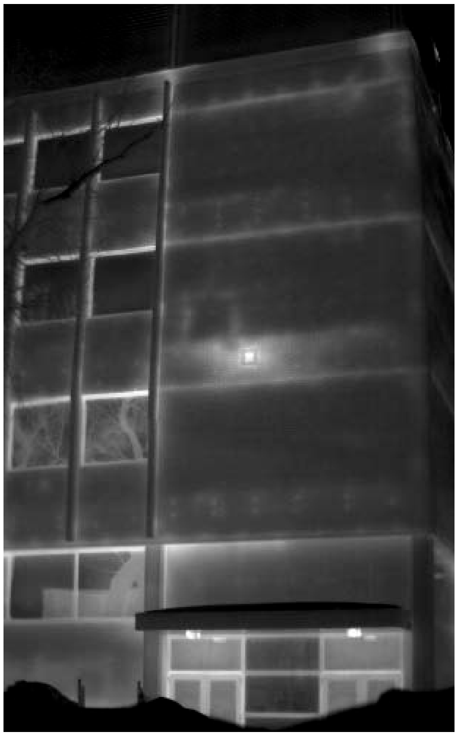


***Figure 8**. Negative Building Pressure (-140 Pa), $T_o = -11^oC$*

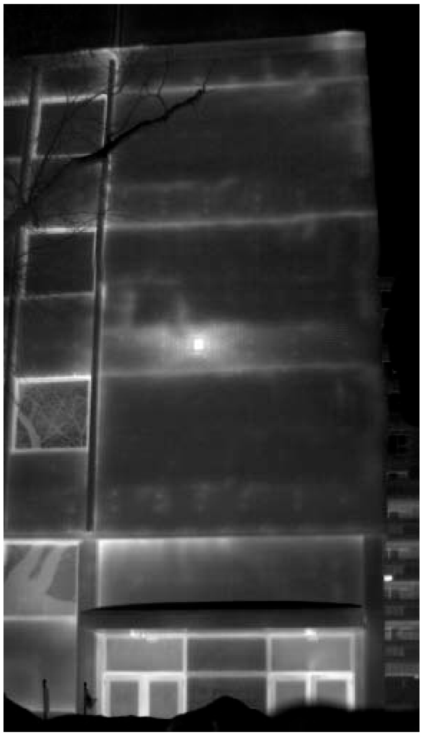


***Figure 9**. Positive Building Pressure (+40 Pa), $T_o = -11^oC$*

DIRECT AND DIFFUSE AIR LEAKAGE AND RESULTANT MOISTURE PATTERNING

The thermal images seen in ***Figures 6 to 9*** 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 image. 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 occurs 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.

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 structures 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 6 to 9*** the masonry areas around the vent located in the central section of the third floor appears warm even 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 affect 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.

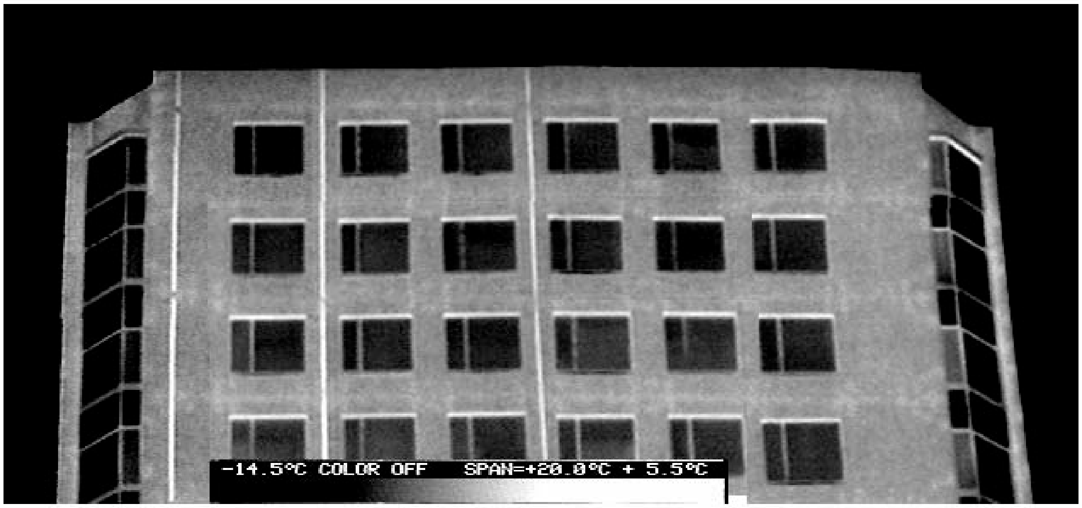
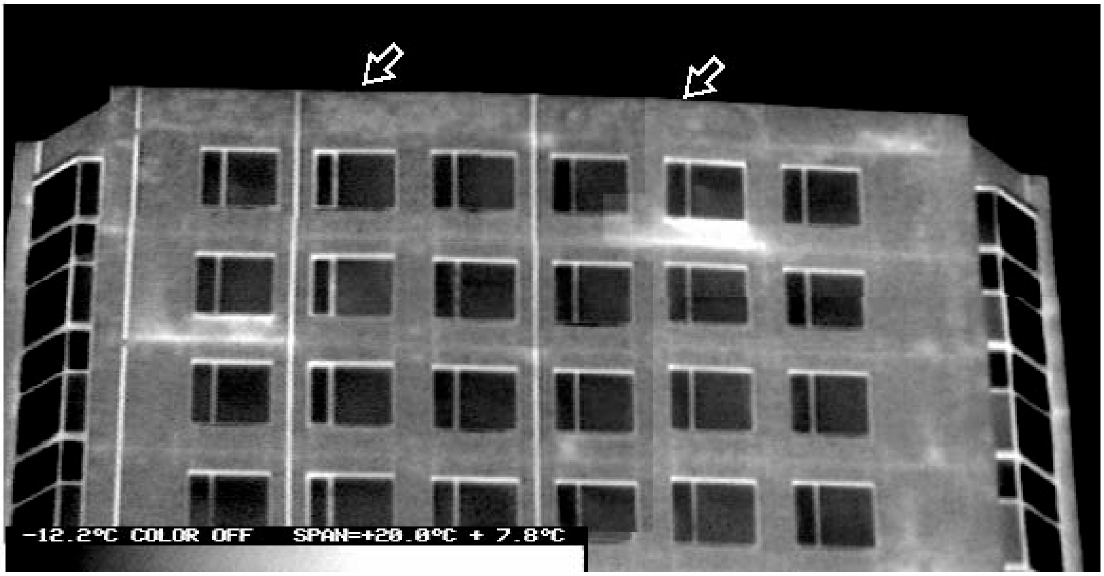


***Figure 10**. Negative Building Pressure (-60 Pa), T_o = -7^{o}C, maintained for a duration of 4 hours prior to inspection.*



***11**. Positive Building Pressure (80 Pa), T_o = -7^{o}C, maintained for a duration of 5 hours prior to inspection.*

DURATION OF HIGH BUILDING PRESSURE AND MOISTURE ACCUMULATION

The composite thermal images in ***Figures 10 & 11*** were taken on subsequent mornings, but in ***Figure 11*** positive pressure imagery was produced 24 hours prior to the negative pressure imagery. The arrows at the parapet walls of this 24-storey 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 11***, leakage areas were random in various sections 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 10 illustrated 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. 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.

EXTERIOR AMBIENT TEMPERATURES AND PHASE CHANGE OF MOISTURE

Phase change of moisture within porous cladding materials, from a liquid to a solid, occurs at temperatures slightly below freezing. In these conditions frozen surface moisture is visible through reduced surface temperatures. This phenomenon occurs independent of either positive or negative pressures. The accompanying thermal images in ***Figures 12 to 14*** illustrate this point.

The dark areas on the 4th floor masonry illustrate the thermal pattern generated by the phase change of masonry moisture. It appears reasonably consistent during both the negative and positive inspections of this building during the same evening. Note the cold areas above the window heads on the third and fourth floor windows typical of air leakage into the building during negative building pressure conditions.

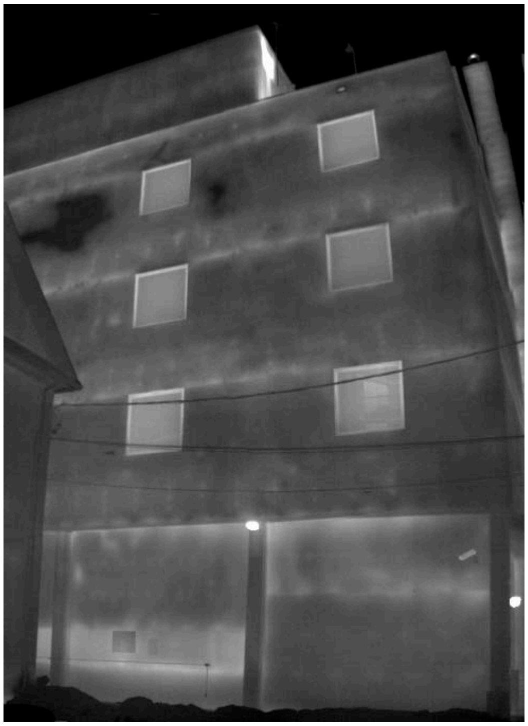


Figure 12*. Negative Building Pressure (-140 Pa), $T_o = 0^oC$*

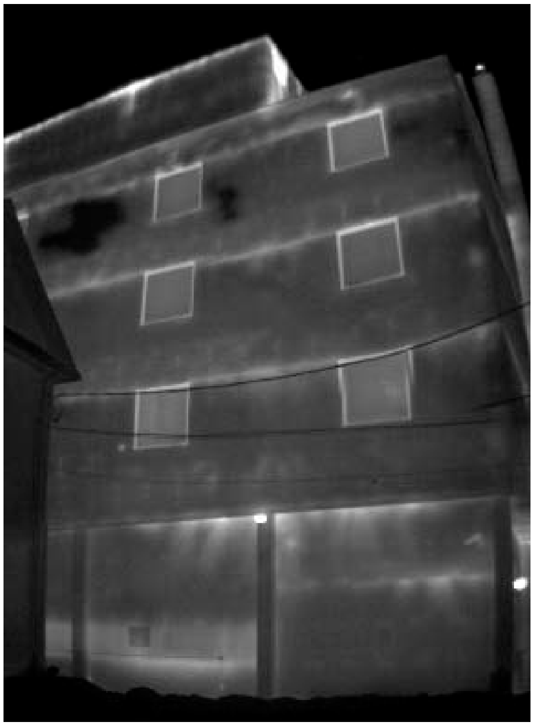


Figure 13*. Positive Building Pressure (+40 Pa), $T_o = 0^oC$*

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

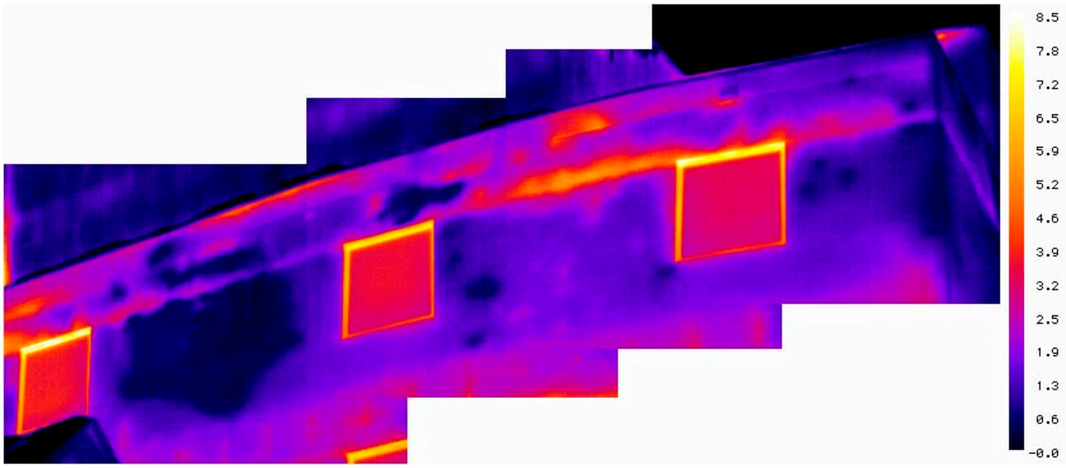


Figure 14. *Positive Building Pressure (+3 Pa),* T_o *= -1°C, Close up thermal image of previous images in* ***Figures 12*** *and* ***13*** *showing phase change of moisture within masonry. This image was taken a year earlier than previous images but generates the same type of imagery.*

The moisture patterning within the wall due to accumulated moisture over the winter months appears warm around the floor slabs and is present during both the negative inspections as well as the 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.

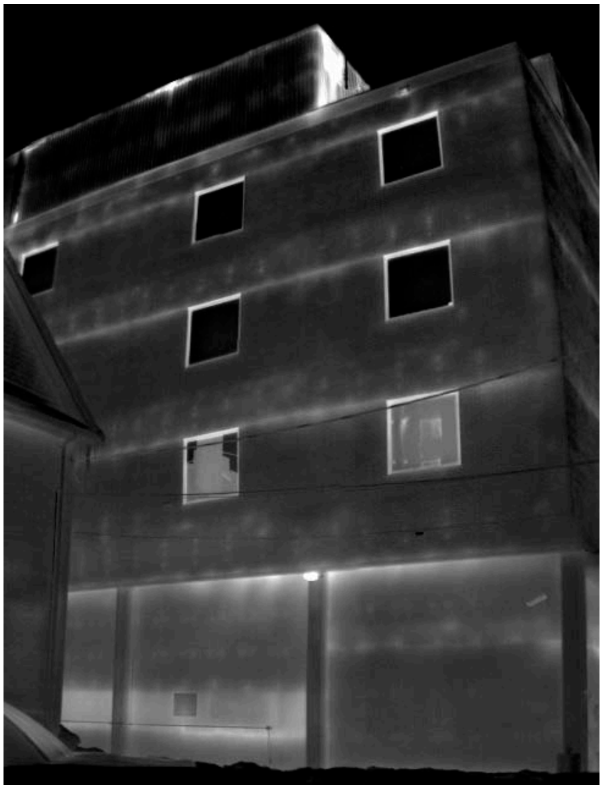


Figure 15. *Negative Building Pressure (-8 Pa),* T_o *= -11°C*

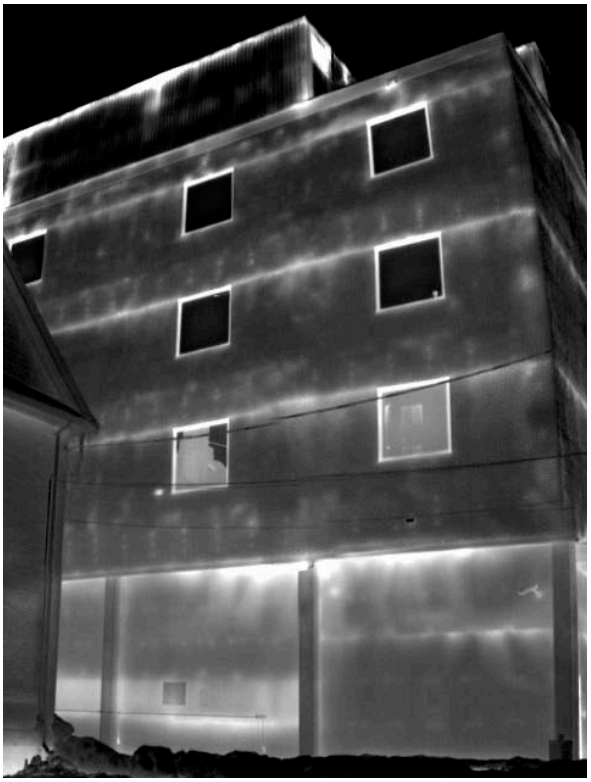


Figure 16. *Positive Building Pressure (+25 Pa),* T_o *= -11°C*

Both images were taken during the 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.

SUMMARY

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 presents itself as a homogeneous higher surface temperature 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 in the infrared spectrum.

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 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 continue to see these thermal patterns in conjunction with their resultant moisture accumulation.

When positive building pressure inspections are carried out in sub zero ambient conditions, there is risk that moisture from interior sources is driven into porous cladding materials. When these conditions are maintained for greater than 4 hours, moisture accumulation is visible on masonry cladding. If positive building pressure conditions are not normal, then this resultant moisture accumulation dissipates over a 24 hour time period.

When conducting exterior large building infrared thermographic inspections during cold winter months, it is advisable 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 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.

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.

ACKNOWLEDGEMENTS

The authors 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 reduction of energy utilization within buildings and resultant green house gas emissions.