

Nondestructive Testing of Building Envelope Systems Using Infrared Thermography

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ABSTRACT

The structures we live and work in are susceptible to quality and performance problems during construction and maintenance that can impact performance and may, in some cases, render them dangerous. Regardless of the building type involved, infrared thermography also known as thermal imaging can provide remarkable, nondestructive information about construction details and building performance.

This paper discusses the numerous applications for the technology currently being used to inspect building envelopes. These include validation of structural details, verification of energy performance (conduction and air leakage), location of moisture intrusion, and the identification of structural and system degradation of roofs and facades. Examples will be given for each application and the basic conditions required will be discussed.

1. INTRODUCTION

Buildings of all sorts, from homes to factories to high rises, can be troubled by problems related to design, construction and maintenance that can be difficult to diagnose and resolve. The major problems found in buildings include:

- excessive energy use due to missing or damaged insulation, insulation that is performing inadequately, and excessive air-leakage across the thermal perimeter
- moisture damage due to leaks or condensation, especially in the walls or roofs
- ice damage to sloped roofs
- poor HVAC distribution or performance
- inadequate verification of construction details or structural performance
- delaminations of façade materials
- “sick building syndrome,” mold growth and other health related issues

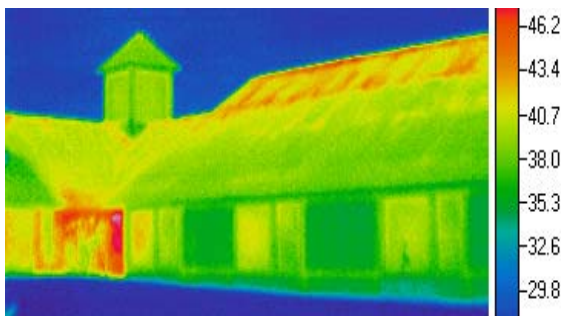


Image 1. Excessive heat loss and poor ventilation resulted in costly ice damage to this large roof.

Often the problems—as well as their causes and consequences—simply cannot be seen until after costly damage has been done. At that point the only recourse may be extensive, costly reconstruction. The commercial building in **Image 1**, a nursing home, had extensive problems resulting from a poorly designed roof/ceiling insulation system; these included excessive heat loss during the winter months and, as a result, extensive ice damage due to snow melt. Hundreds of thousand so dollars were spend in various, poorly planned attempts to correct the underlying causes. In the end the owners simply lived with the continued problem because corrective actions were deemed too expensive. Despite this unfortunate resolution, the thermograms helped the owners negotiate a financial settlement with the architects and contractors.

A great value of infrared thermography is that it provides a means of seeing the invisible thermal signatures related to many of these problems in building. When properly used, thermography enables building owners, architects, contractors and inspectors to locate problems, verify building performance, and validate solutions. When people act on this information, significant savings result and buildings are more comfortable!

All surfaces radiate invisible heat energy. You've felt this energy emitted by the sun or a stove burner. Infrared cameras also known as thermal imagers are specially-designed electronic devices that detect thermal radiation. They convert this radiation into thermal images, or thermograms, which visually portray temperature differences as small as 0.05°C.

These portable, battery-operated instruments record the thermal data either as still, digital images or on conventional videotape or digital video. The image is displayed live in a viewfinder or on an LCD view screen. Different radiant temperatures are shown as different colors or shades of gray. Although it may sometimes be useful to display temperature values, this is often not required in building work. Rather the differences are what is usually of interest.

Given the right conditions most buildings exhibit characteristic thermal patterns that can be interpreted by a qualified person. The infrared systems themselves are quite easy to operate and, thus, a number of thermographers conduct building inspections. The tasks of interpreting the imagery, understanding the root cause problems, and finding solutions are all more difficult. Because of this, thermographers often work closely with a team consisting of building specialists, architects, and contractors.

The key to using thermography successfully is understanding what thermal patterns are associated with the problems being studied and knowing when those patterns will become visible in the infrared image.

2. BUILDING APPLICATIONS FOR THERMOGRAPHY

Thermography has been used since the mid-60s to solve building problems. During the late 70s and early 80s, a time when fuel prices rose dramatically, thermography was embraced widely as a tool to help determine building performance. Since then other applications have been developed and refined, especially related to verification of structural performance.

The major building-related applications for the technology are detailed below.

• Insulation checks

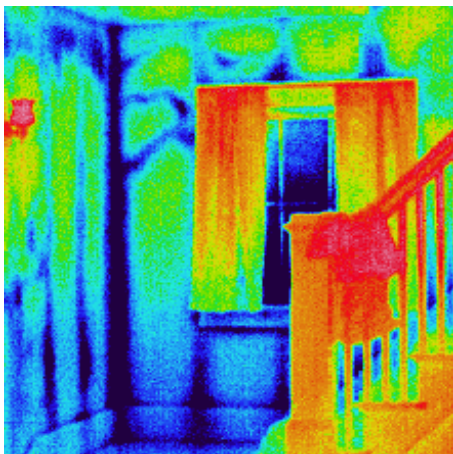


Image 2. When conditions are right, it is possible to locate missing or damaged insulation, such as this poorly installed injected foam in a residential building.

Missing, damaged or non-performing insulation will stand out clearly in a thermal image when there is at least a 10°C (18°F) stable temperature difference between the conditioned space and the outside air. It is often possible to do work with less of a temperature spread due to differences in the thermal capacitance of the building materials. The inspection is typically done from both inside and outside. Often the best results are gained from inside because of fewer influences, but a better overall understanding of the building can often be gained from larger views of the outside elevations.

It is essential to know the type of insulation in the building and construction details, including how the insulation was installed. Insulation may be in place but not performing; often a destructive evaluation is warranted to establish baseline conditions or understand the exact construction detail. Each type of insulation has a characteristic thermal pattern. **Image 2** shows a classic pattern associated with injected foam insulation in a wood-framed wall. This particular insulation, a soft ureaformaldehyde foam, is susceptible to shrinkage and cracking when poorly installed.

Many factors impact the image you will see. When work is done in the daytime or early evening, the impact of solar loading must be considered. The affects of the sun can easily last 6-8 hours on both the inside and outside after a wall has been exposed. This often results in the direction of heat flow being reversed, making for confusing images

and misdiagnosis. Wind must also be reckoned with, as it can both quickly eliminate the thermal difference on a surface as well as enhance others. If building problems are wind-related, i.e. “we are cold on windy days,” then it is wise to conduct the inspection with a wind load.

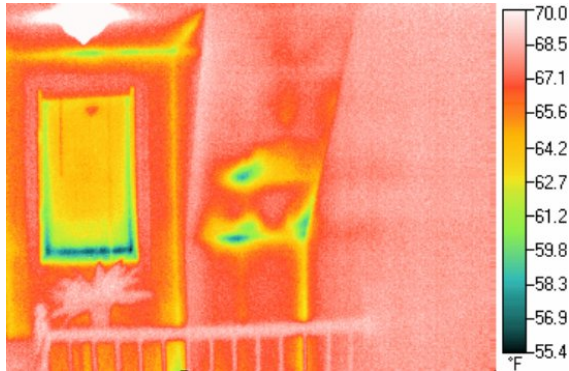


Image 3. The improperly installed fiberglass yields an irregular thermal pattern. The resulting cold spots commonly host wall stains or mold growth.



Image 4. Properly installed cellulose is an excellent insulation. Unfortunately it is often poorly installed with missed areas and settling the most common quality problems.

The costs of poor performance of insulation are huge. In addition to excessive energy consumption, there may be costly freeze-ups of water pipes or fire sprinkler systems; health issues associated with mold growth in cold spots, damage to roofs and interiors caused by ice dams, condensation, and water intrusion.

• **Air leakage location**

Excessive air leakage can account for up to half of the energy consumed to condition buildings. Of course adequate air exchange is essential for the occupants’ health and safety, but most buildings have a far higher rate of air exchange than is necessary. The root cause is often poor design and/or construction which allows air to move across the thermal perimeter. The problems can be as straightforward as a failed door weather seal or as complex as an air pathway through a plumbing chase in an interior wall or ceiling plenum. The leakage pathway is often complex and, without thermal imaging, extremely difficult to visualize.

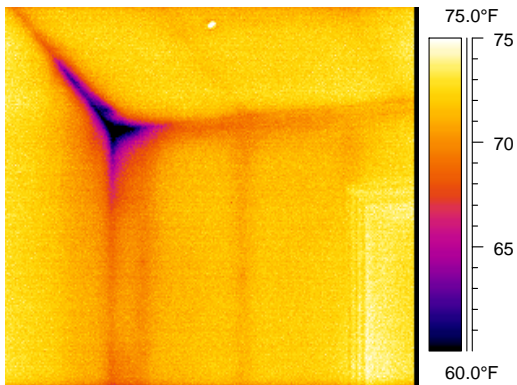
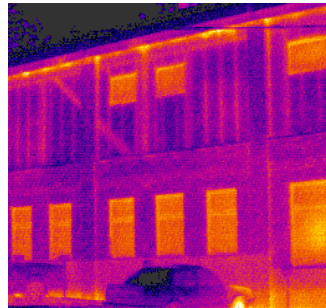


Image 5. Many types of insulation are susceptible to air infiltration. The fiberglass shown here does not stop air flow through the wall section.

Air leakage inspections are best conducted when air flow is directed and controlled. This can be accomplished with exhaust fans, specialized blower fan door, or, in larger buildings, by temporarily altering the HVAC system, to create a negative pressure inside. During the heating season the resulting sites of air infiltration appear cooler. The work can be done any time of year the indoor/outdoor temperature difference is greater than a few degrees. Blower door fans can also be used to quantify air leakage rates. This technique is invaluable in predicting building performance and monitoring air sealing work.

Image 6. All the framing and insulation is clearly visible in this commercial building. Normal pressure differences on the top floor result in air leaking past the envelope through various pathways.



Most types of insulation are not effective at reducing air movement through the thermal perimeter. Good construction practice includes interior air sealing; if this is not in place effectively, air can move through the interior and exterior surfaces and through the insulation. Unfortunately, fiberglass is particularly susceptible to this problem. Thus, while the insulation may be present, it does not perform as expected when the building is under a pressure gradient. **Image 6** shows the impact of warm air

leaking out of this commercial building. This will typically go unnoticed until the fuel bill is paid.

• Moisture intrusion or condensation

As building designs and techniques produce tighter thermal envelopes, moisture (from leaks or condensation) has created more and more problems. The water can intrude through a small crack but it is then trapped between the relatively impermeable building materials. Good building techniques typically must deal with both air sealing and moisture retarders to keep moisture from accumulating inside the wall sections.

Locating moisture with thermography is often simple because water has both a high thermal conductivity and a high heat capacitance. Determining the source of the moisture, however, can be difficult. Condensation, rather than leakage, is often the culprit so it is important to identify sources of air leakage that can transport moist air into the wall sections and the cold spots that can result in it condensing. The classic case is that of warm moist air leaking past the insulation in a metal building or mobile home; as it contacts the cold underside of the metal roof it condenses, and often freezes, causing the occupants to think, mistakenly, that the roof is leaking. Damage in building from condensation includes mold growth, brick spawling, roof membrane fastener corrosion and reduced insulation values.

• EIFS construction

The growing popularity of buildings using Exterior Insulation and Finish Systems (EIFS) has been accompanied by numerous cases of moisture-related structural damage. Although often attributed to leaking windows, water typically intrudes where sealing or flashing systems were inadequate or have begun to fail (**Image 7**). Moisture is then trapped under the relatively impervious foam. In warm climates the decay of structural wooden elements, which can occur very rapidly, is a major problem. Mold growth also often accompanies the moisture resulting in health concerns.

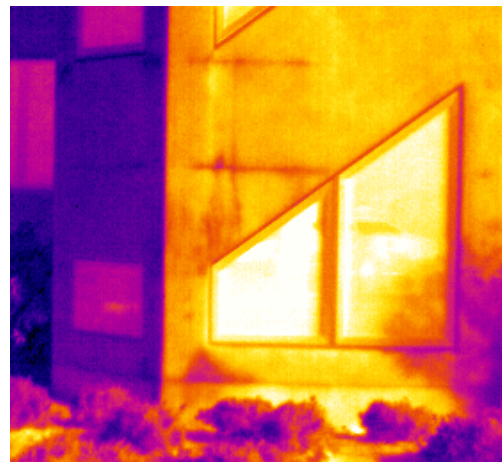


Image 7. EIFS construction is particularly susceptible to water intrusion resulting in both mold growth and wood rot problems.

Thermography is an invaluable tool to locate moisture in EIFS systems. Inspections are best conducted in the early evening from the outside after a sunny day with little or no wind. It may also be possible to locate moisture from inside during cooling or heating conditions. The expanded foam insulation boards tend to become more absorbent to water over time.

• HVAC performance

HVAC systems can be plagued by design and installation problems resulting in excessive energy use and/or uncomfortable buildings. Thermography helps building specialists visualize the otherwise invisible impact of this poor performance as indicated by excessively hot or cold areas. Once these have been located, the root causes can be

determined; these may include reversed or misdirected airflow or poorly placed supply ducts, leading to short-circuiting of air directly to the return ducts.

Unfortunately many of these problems result from poor design; by the time the thermographer spots them, it may be too late to correct some of them. On the other hand, some, such as reversed diffusers, are very easy to correct.

It is also possible to visualize air flow itself! Several thermography studies have been conducted by hanging layers of plastic netting in a room. As the air flows through it, the temperature of the netting can be imaged. In most comfort-related cases it is probably as useful to simply image the walls and objects in the room a technique that is much easier.

• **Subsurface heat sources**

Heating coils are being used more and more either to keep outside walkways or entrance ramps snow free or to provide heat to areas and rooms via hot water or electric cables. Thermography provides a quick way to verify location and performance of these subsurface devices. Typically the thermal pattern shows up very clearly even when the heat source is embedded in several inches of concrete (**Image 8**). Similarly, water pipes in wall sections can usually be located quite readily.



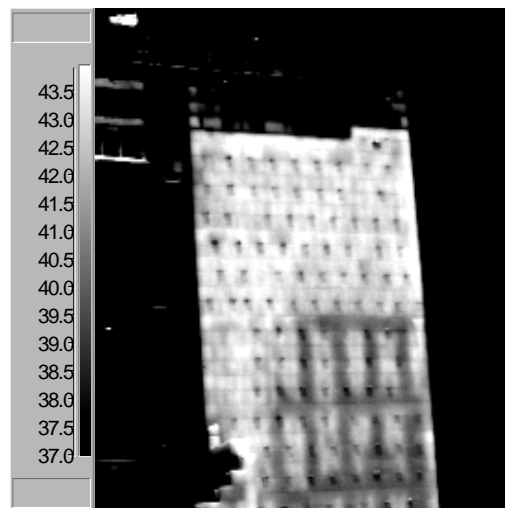
Image 8. Hydronic heating coils embedded in a concrete floor show up clearly in this thermal image.

Water leaks from pipes, whether in a wall section or under a slab, may also be located using IR, although airborne ultrasonics may be a simpler method. To use IR a temperature difference must be induced generally by simply running hot water through the pipe. Leaks under concrete slabs may not express themselves because the water if the water is drained away in the sand/gravel base layer.

As a side note, thermographers are often asked to locate reinforcing steel in buildings. This is much more difficult. Heating the steel is not a simple task, usually accomplished with an inductive coil or direct DC-powered heating. Secondly, the heat is often insufficient to express itself on the surface. Other methods, based on sending and receiving radio signals, are probably more useful.

• **Verification of construction detail**

No area of application is more important these days, particularly in commercial buildings, than the verification of construction details and performance. Thermography is being used with great success to verify bond beams and placement of reinforcing in concrete masonry unit (CMU) walls as well as structural elements of pre-cast, tip-up walls. How? The solid portions of the wall change temperature more slowly than the rest. The inspection can be conducted anytime the wall is in a thermally transient condition—typically in the early evening as it cools down. Because the inspection is conducted during construction, deficiencies can be corrected prior to occupation with relatively minor inconvenience.



Verification of placement of insulation in masonry unit walls is also more important than in the past due to high energy costs and health concern regarding mold growth in cold wall cavities.

Image 9. This block wall is not uniformly grouted as was specified, leading to severe structural problems —image courtesy Phil McMullen

- **Sick-building syndrome**

When buildings are too tight or too moist, health-related problems quickly come to the forefront. Grouped together as “sick building syndrome,” these can stem from inadequate HVAC performance, moisture trapped in walls, mold growth on cold, damp surfaces and inadequate air change rates. Many of these can be visualized and diagnosed, at least in part, with thermography to help solve these very serious—and common—problems. Diagnosing these problems is often a very complex process and, given the fact that litigation may be involved, it is not something to be entered into lightly.

- **Facade delaminations**

A great deal of work has been done in SE Asia inspection the facades of large buildings for delaminations. Failures of these materials can result in serious personnel injury. The masonry tiles used to face the buildings tend to change temperature rather quickly when they begin to delaminate compared to the underlying structure to which they were affixed. The diurnal cycle is typically the driving heat source and inspections are best done in the early evening hours after a warm sunny day.

- **Roof moisture inspections**

The inspection of flat roofs, especially built-up roofs (BUR) has been proven for a number of years. The technique allows for the detection of moisture trapped in a roof system; over time this moisture leads to the pre-mature degradation of the roof. The moisture appears warmer at night after a sunny day due to its greater thermal capacitance.

The roof surface must be dry and the technique works best on roofs with absorbent insulation. Inspection work can be accomplished either in a roof-top survey or an aerial survey conducted from a helicopter or fixed-wing craft.



Image 10. The wet insulation in the roof system shows up clearly due to its greater thermal capacitance.

3. STANDARDS AND REFERENCES

Several important standards exist to support the work of thermographers conducting building inspections. These include, among others, the following:

- ASTM C 1060-97 Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings
- ASTM C-1153-97 Practice for the Location of Wet Insulation in Roofing Systems Using Infrared Imaging
- ISO 6781 Thermal insulation, qualitative detection of thermal irregularities in building envelopes, Infrared Method
- American Concrete Institute Design Standard 530 / American Society of Civil Engineers Standard 5, Masonry Building Code and Specification

Another excellent reference, although not a standard, is the Canadian General Standards Board Manual for thermographic analysis of building enclosures (149-GP-2MP). Numerous building related papers have been published over the years; many are collected on a CD-ROM from SPIE, entitled Selected Papers from the Proceedings of Thermosense, edited by John Snell and Doug Burleigh, available from <http://www.spie.org>.

4. QUALIFICATIONS OF THE THERMOGRAPHER

Although building applications may appear simple, successful use requires qualified personnel with related experience. Both training and experience are essential. An intimate knowledge of construction techniques, practices, materials, and failures is also important. It is also not unusual for the thermographer to work with other building scientists who have expertise in other areas. Failure to conduct an inspection in a professional manner can result in serious damage to the building and/or harm to the occupants.

5. CONCLUSION

When properly used by qualified individuals, this remarkable technology can play a powerful role in visualizing otherwise invisible building problems and conditions. Contractors and architects alike are both using thermography to assure the performance of their buildings. Building specialists count on thermography to help them diagnose tough problems that, left unsolved, are costly or dangerous. Owners rely on thermography as a tool for commissioning a new building.

While a foundation of expertise must underlie the successful use of thermography for building diagnostics, getting started with most of the applications is often not difficult. An appropriate infrared system is required, with proper training and experience for the operator as well. Having supplementary knowledge of building sciences or access to that information is also vital. The primary return on an investment in building thermography is gaining a higher level of assurance buildings will perform as intended and occupants will be more comfortable, often at a lower cost.

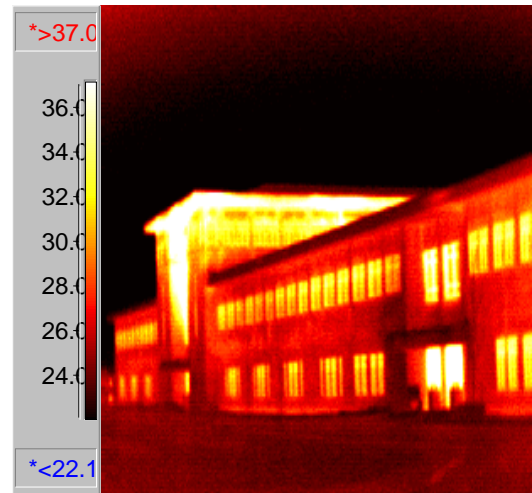


Image 11. During the commissioning of this building thermography revealed an extreme problem involving exfiltration through the soffit. Courtesy Phil McMullen

