Thermal Imaging as a Forensic Tool in Coating Failure Investigations

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Abstract

This paper discusses the use of thermal imaging as an analytical tool in forensic investigations of moisture-related coating failures applied over hollow core building walls. The success of thermal imaging depends upon detecting subtle temperature differences arising from differences in thermal conductivity of the coated wall surfaces. The method is a valuable adjunct to contemporary failure investigation methodology.

Background

In 1800, the astronomer, Sir William Herschel, while conducting experiments into the spectral distribution of sunlight, discovered infrared. Herschel is recognized as the pioneer in the science of thermography. Sir William designed and created his own telescopes and became very familiar with lenses, mirrors and light refraction. His research led to the knowledge that sunlight was made up of all the colors of the spectrum, and was also a source of heat. Research with sunlight passing through prisms established that there was an increase in temperature as a thermometer was moved from violet to red components of the rainbow created by the light. Herschel noted that the hottest temperature was beyond red light, and that the radiation causing this heating was invisible. He called this invisible radiation "calorific rays." Today, the light/energy is called infrared. The science of measuring the heat emitted by infrared is called thermography.

Infrared thermography is a form of non-contact, non-destructive testing used to detect and document thermal patterns and associated temperatures across a surface. Today the science has largely adopted thermographic video cameras to detect radiation in the infrared range of the electromagnetic spectrum (roughly 900–14,000 nanometers or 0.9–14 µm) and produce images of that radiation. A distribution of the wavelengths within the IR spectrum is depicted below.

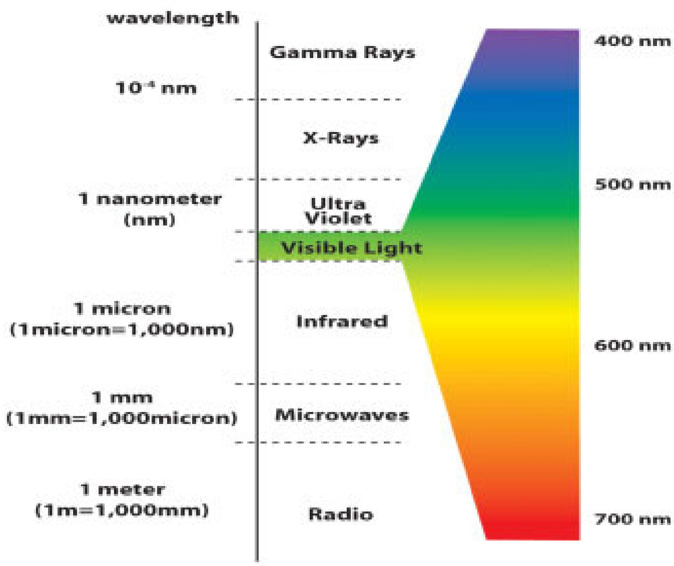

Figure 1

Forward Looking Infrared (FLIR) devices are sophisticated imaging systems that operate in the 0.4-1.0 µm range. They detect infrared energy emitted from an object and convert it into a digital image displayed on a monitor screen. Because infrared energy is a direct and proportional function of temperature, the video image depicts temperature levels on the monitor in either black and white or color. The displayed image is called a thermogram.

FLIR Display Modes

In the black and white mode the thermographic image contains various shades of gray that represent different temperature levels throughout the chosen temperature range. Black corresponds to a lower temperature, and white indicates a higher temperature.

In the color mode, the thermographic image contains a range of colors that are matched to a reference temperature bar at the side of the thermogram. Colors appearing closer to the top of the reference bar correspond to higher temperatures. Colors appearing closer to the bottom of the reference bar correspond to lower temperatures. The FLIR equipment has the capability to sense object temperatures from -10°C to +1500°C (14ºF to 2730ºF), with sensitivity of 0.07 ºC (0.13 ºF)

Analyzing Building Envelopes

Infrared thermography is frequently used as a diagnostic tool to find latent failures or defects within the building envelope. Heat loss surveys using FLIR are now routinely applied to locate heat energy loss from building roofs and walls.

Two types of energy loss can occur within a building envelope; conduction and infiltration/exfiltration losses. Air infiltration/exfiltration can occur at numerous locations within a building envelope through seemingly insignificant cracks and uncaulked openings. Air infiltration is detected through an interior building survey, while air exfiltration is detected through an exterior survey.

Conduction losses are most often due to missing or damaged insulation within the building walls and/or roof. Conduction heat losses caused by entrapped moisture within the building walls are also detectable by FLIR.

Construction Types and How They Relate to IR Inspection

The presence of moisture in a material increases its thermal conductivity, producing a correspondingly higher surface temperature than when the same material is dry. As heat flows from within the building to the exterior surface, more heat is transferred through the wall areas with contained moisture, resulting in higher surface temperatures.

The thermal imaging process is sensitive to structural and material anomalies that produce differences in thermal conductivity and surface temperature. It is transparent to both the color and composition of thin surface coatings.

Material anomalies are sometimes created by the building construction. Block walls that contain cavities created by hollow core masonry block will create a thermographic pattern due to the difference in heat transfer between the solid and hollow sections.

Precast wall panels, frequently used in tilt-up construction, can be fabricated to include integral thermal insulation in a layered arrangement, with expanded polystyrene (EPS) foam billets inserted directly into the wet concrete, or internal cavities that are filled with thermal insulation following their erection.

The latter is a two component system consisting of a two-part amino-plast or open-cell, urea-formaldehyde resin reacted with a foaming agent/surfactant. The resin component is supplied as a concentrated liquid. It is diluted at the job site with water and pumped under pressure into the wall cavity. As wet foam, the insulation has a density in the range of 2.7 to 5.5 lb/ft^3. It begins to cure immediately after injection, expands to fill the voids, and dries through evaporation of water through the building wall. After a period of approximately 24 hours, the dry foam achieves a density in the range of 0.7 to 0.9 lb/ft^3. The cured foam is a thermal insulator (R=4.0/inch).

Moisture Effects on Wall Panel Construction

Neither type of wall construction is immune to moisture infiltration and deterioration of insulating characteristics.

The cellular structure of the molded expanded polystyrene (EPS) foam is essentially water-resistant and provides zero capillarity. However, due to the fine interstitial channels between the molded beads, EPS may absorb moisture when it is completely immersed.

Also, while molded foam is nearly impervious to liquid water, it is moderately permeable to water vapor under pressure differentials. Closed cell materials resist the flow of liquid water between cells; however, the cell walls transmit measurable quantities of water vapor. As the temperature of the foam drops below the dew point, the water vapor condenses, and it trapped within the closed cell as liquid water. In addition, water will also condense within the myriad of interstitial channels between the expanded foam particles.

As environmental heating warms the foam within the wall cavity, the vapor pressure of the trapped water increases and the vapor pressure differential drives water toward the panel surface. In this manner, a cycle is set up that drives moisture toward the path of least resistance. The path to the inner wall of the panel is less permeable because it contains an additional layer of embedded foam cells, offering more resistance to vapor flow.

Moisture Entry During Construction

Moisture can also infiltrate the foam cavities during the construction period when the walls are erected, but the protective coverings, flashing, and roof caps incomplete. Walls at the low point in the drainage pattern of the roof slope will experience the greatest exposure to moisture.

The subsequent sealing of the wall cavities and installation of surface coatings on both sides of the wall will limit the vapor permeability, and reduce the ability of the moisture to escape from the wall system. Radiant solar energy and elevated ambient temperatures will cause an elevation of water vapor pressure within the wall cavity, triggering the movement of entrapped moisture to the exterior wall surface.

Post-Construction Moisture Entry

There also exists a source for continued water infiltration into the wall cavities when there is backside water vapor flow to the exterior wall surface. Degraded seals at the wall caps, metal fascia and flashing are potential water entry points. When the flood level of the rain gutters is at or near the critical seal areas, a hydrostatic head exists to cause water infiltration. Water movement by capillary action may also occur where the sealant between overlapped cap and flashing elements is missing or has deteriorated.

Gutters filled with ice and snow also have the potential to affect drainage patterns and extend periods of water exposure. Water entry into the panel cap areas, if allowed to freeze, causes a wedging action to further deteriorate the watertight integrity of the seal area. This situation can result in a chronic water entry problem that is exacerbated during periods of winter freeze-thaw cycles.

Failure Modes in Exterior Wall Coatings

Coatings lose adhesion and delaminate from masonry surfaces from a variety of reasons. Among possible failure modes are:

- Surface anomalies related to level of cleanliness and profile prior to painting.
- Incompatibility caused by pre-treatment chemicals or sealers.
- Chemical incompatibility between existing and new coating systems.
- Susceptibility of one or more of the coating system components to moisture.
- Anomalies in coating composition introduced during manufacturing.
- Adverse environmental conditions during application and cure (drying).
- Adverse environmental conditions from weathering exposure.
- Water vapor transmission arising from conditions inside the structure.

When a comprehensive failure investigation has eliminated all but moisture-related causes, the use of infrared thermography may be an effective tool for analyzing the coated surfaces.

CASE STUDY

The following case study demonstrates the use of infrared analysis to determine the cause(s) for coating adhesion failures in a large northeastern warehouse facility.

The acrylic-based surface coatings placed on the bare walls in the summer of 2003 displayed disbondment within weeks of application. Attempts to repair the coating during 2004-2004 resulted in similar coating losses.

The facility consisted of a single building with a total wall area of approximately 83,000 ft^2. It was constructed upon a concrete slab at grade using prefabricated concrete wall panels containing an embedded slab of expanded polystyrene (EPS) foam billets inserted directly into the wet concrete during prefabrication.

The walls of the building were built from prefabricated concrete panels. The panels contained a series of embedded foam cores (billets) fabricated from expanded polystyrene beads. Six cores, each 12" wide by 5" thick, ran the length of the panel from top to bottom, and were surrounded by 1-½" of concrete. The wall panels were completed with a 2-½" thick polystyrene foam board that covered the full panel area and was embedded in the panel just to the front of the six, parallel foam cores. The foam panels were covered on both faces by approximately 1-½" of concrete.

Approximately 31% of the interior building space was used for cold food storage and maintained at a temperature of 40ºF and 50% relative humidity (RH). The remainder of the building was maintained at 70ºF and 55% RH. There appeared to be no connection between the observed coating failures and interior wall temperature. Areas of the east and/or west walls were exposed to the same temperatures as the north and south walls. Only the north and south walls display coating failures.

The north and south sides of the building front contained random areas of exposed concrete panel where the applied coating had peeled from the underlying substrate. The areas ranged in size from approximately 2 ft^2 to 36 ft^2. The areas of coating damage appeared over the panels from ground level to the gutter that ran along the roof eave. However, the areas of coating loss were larger and more dominant on the upper half of the panel walls.

A review of project documentation and physical measurements revealed that the specified coating system was applied at the dry film thickness recommended by the manufacturer.

Coating chips removed from the walls were tested using Attenuated Total Reflection Fourier Transform Infrared Spectroscopy (ATR-FTIR). The ATR-FTIR was used to differentially scan the front and underside of the delaminated coating chips to detect the presence of foreign materials with the potential to affect adhesion. The testing revealed the presence of efflorescence, but no organic-based contaminants capable of defeating coating adhesion.

The nature of the coating loss on the north and south walls was characterized by a nearly total adhesive-type failure where the applied coating had separated from the underlying concrete surface. There was no visible appearance of a cohesive failure with the separation occurring within the actual coating layer. In contrast, when the same test was applied to locations on the east and west wall with no visible coating loss, the adhesion of the coating system was good. It resisted removal at the "X" cut, and could only be removed after aggressive probing from a sharp knife.

Because of indications that the coating adhesion problems were moisture related, a total thermographic building survey, incorporating an FLIR digital video camera was conducted on an evening in August 2005.

The infrared survey of the facility exterior identified 29 specific wall locations that displayed surface temperature anomalies. Among the total, 6 were on the east wall, 18 on the south wall, 3 on the west wall, and 2 on the north wall.

For the purpose of explanation and illustration of the analysis techniques employed, only three thermographic images produced along the building south wall are included in this paper. However, they are typical of the 18 images produced along the south building wall.

Figure 2, below is a thermogram for a sequence of three adjacent panels on the south wall of the building. The picture depicts three large yellowish-brown panel areas with elevated temperature. The two panels to the right also contain isolated red-brown areas that are at a higher temperature. The thermogram indicates that that the three-panel area exhibits temperature anomalies typical of moisture infiltration, with the color range of yellow-brown to red-brown attributed to increasing moisture content.

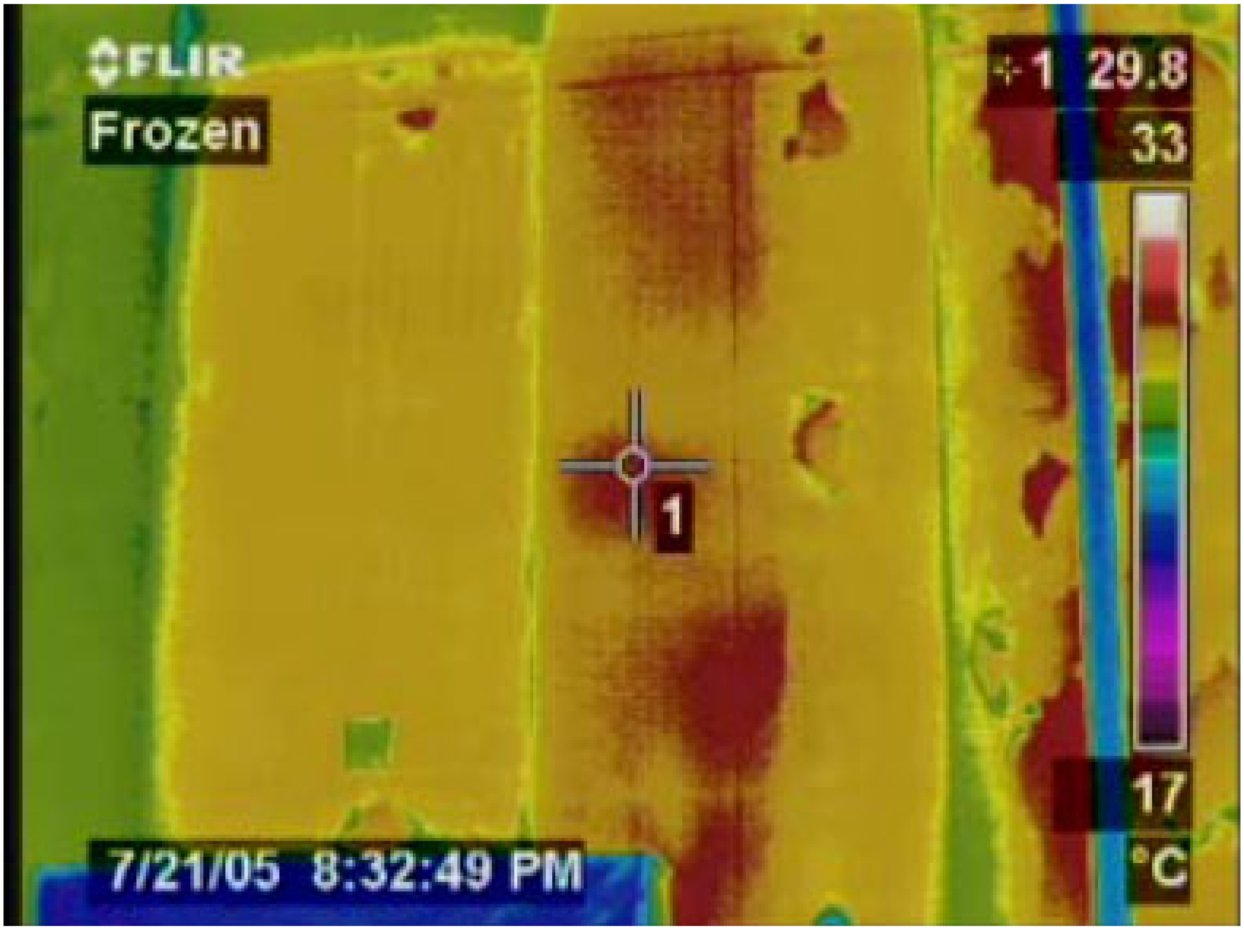

Figure 2

Figure 3, below, displays the thermogram produced by the south wall panels between a series of loading dock truck portal doors. The panels display elevated temperatures in areas that range in color from light green to yellow, yellow-brown, and red-brown. In the displayed wall areas, the warmest wall areas are directly below the roof gutter/roof flashing line and trend vertically downward from the roof line. As in Figure 1, the warmest areas are indicative of the areas with the highest moisture content.

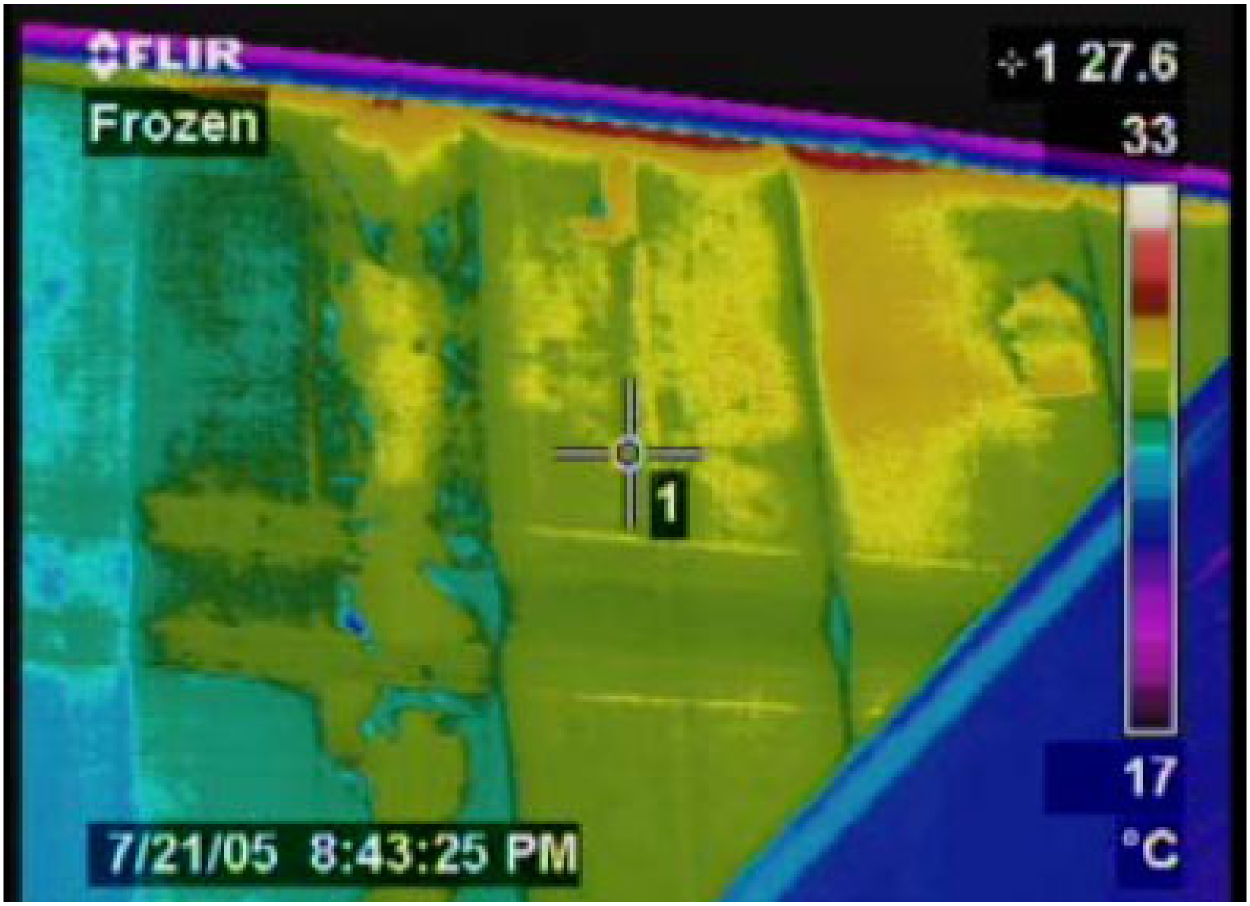

Figure 3

The following Figure 4 displays the thermogram produced by the south wall panels above and to the left of another truck portal door. The panels display elevated temperatures in areas that range in color from light green to yellow, yellow-brown, and red-brown. In the displayed wall areas, the warmest wall areas are directly below the roof gutter/roof flashing line that trend vertically downward from the roofline and concentrate in the panel area at the center of the thermogram. There is a significantly warm (red-brown) area that is at the upper portion of the center panel. Additionally, there is an extended warm area in the panel areas below the horizontal bond beam. As in the preceding thermograms, the warmest areas are indicative of the panel areas with the highest moisture content.

Figure 4

The total thermographic survey identified 20 locations on the north and south building walls that displayed thermal conductivity anomalies typical of moisture infiltration. The survey of the east and west building walls identified 9 thermal conductivity anomalies. Most of the nine locations were more typical of structural anomalies than moisture infiltration.

The failure investigation produced the following conclusions:

- The FLIR survey confirmed that there were significant areas of moisture infiltration within the north and south wall panels.
- The heaviest moisture concentration was at the roof level and extended downward to grade level.
- The coating delamination was in panel areas infiltrated by moisture.
- The heaviest moisture concentration was within the drainage pattern of the roof.
- The condition of roof flashing, perimeter seals, and gutter drain capacity appeared to be possible sources for chronic water entry into the cavity walls.

CONCLUSIONS

The results presented in the described investigation demonstrate the value of an infrared thermographic survey in failure investigation work. FLIR represents a qualitative testing technique that can confirm the suspected presence of moisture in concrete cavity walls. The methodology can lead to a rationale for determining the cause for the lack of adhesion and delamination of coatings applied to masonry surfaces.

Other IR Applications in the Coatings Industry

The thermal sensitivity of FLIR technology has also been used by researchers[1] as a non-destructive technique to identify heat transmission anomalies arising caused by blistered and detached coatings. Coatings that contain underfilm voids will contain localized areas where the heat transmission rate will be different than the surrounding bulk coating area. FLIR digital cameras, with sensitivity of 0.07 ºC (0.13 ºF) can detect the anomalies. Other researchers at the Wright Patterson Institute [2] have used passive infrared thermography to detect corrosion and structural defects under aircraft coatings. In addition to detecting hidden corrosion, thermography has provided additional information on the microscopic nature of the corrosion area, its roughness, material loss levels and pitting sharpness.

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[1] Issues Impacting Bridge Painting: An Overview, FHWA/RD/94/098 –August 1995, Infrastructure Technology Institute, Northwestern University, Evanston, IL

[2] Blackshire, Dr. James L. and Meltzer, Dr. Pete, "Passive Thermographic Imaging Shows Promise For Detecting Hidden Corrosion", Air Force Research Laboratory Materials and Manufacturing Directorate, Wright Patterson Air Force Base, 2005