Passive Infrared Thermography—A Qualitative Method for Detecting Moisture Anomalies in Building Envelopes

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ABSTRACT

The presence and detection of moisture in building envelopes may best be described as an elusive phenomenon in a heterogeneous medium. When normal (parabolic-shaped) moisture content gradients exist in the material or when the material is uniformly equilibrated, traditional moisture instruments (conductance and dielectric types) perform adequately. However, these instruments may not be ideally suited to cope with a wet building envelope anomaly that can change its shape, location, and content as conditions dictate. Infrared thermal imaging is a more versatile tool for in-situ moisture detection because it can rapidly scan a surface to determine if irregular thermal patterns, "*thermal anomalies*," are present that suggest an excessive moisture condition. Investigations of moisture intrusion through the masonry-veneer envelope of a commercial and a residential structure are presented, as well as the resultant microbial colonization in the interstitial wall space. An infrared inspection was performed in accordance with International Standard ISO 6781-1983 (E) using a FLIR Systems Thermovision® 550 infrared imaging system. Based on a qualitative interpretation of the thermal scans, wall areas were selected for invasive examination and correlated with moisture-meter readings. The masonry veneer was removed to expose the method of brick installation and the composition of the envelope. In addition, the interstitial wall cavity of the commercial building was inspected from the interior using negative air pressure glovebag containment. Observations were photographed and the free water content of building components was measured. Microbial colonization of the interstitial wall space was observed and, in some cases, with deteriorating building components. Air sampling for culturable fungi was conducted three times over a 2-year period in the commercial building to determine whether fungi that were present in "*visually inaccessible spaces*" migrated into the occupied space. These investigations demonstrate that qualitative infrared thermography coupled with an informed visual inspection and quantitative substantiation using moisture meters is an effective method to detect moisture anomalies in building envelopes.

INTRODUCTION

Irregularities in the thermal properties of the components constituting a building envelope result in temperature variations over the surfaces of the structure.[1] The energy emitted by a surface at a given temperature is the spectral radiance and is defined by Planck's Law.[2] Surface temperature distribution can thus be used to detect thermal anomalies. A *thermal anomaly* is defined as a thermal pattern of a surface that varies from a uniform color or tone when viewed with an infrared imaging system.[3]

Infrared thermography is a process in which an infrared imaging system (an infrared camera) converts the spatial variations in infrared radiance from a surface into a two-dimensional image, in which variations in radiance are displayed as a range of colors or tones. As a general rule, objects in the image that are lighter in color are warmer and darker objects are cooler. Pertaining to the thermal imagery of building envelopes, the atmosphere (in most cases) is considered transparent in the spectral bands of interest where absorption is limited to 3 to 5 µm (short waves) or in the 8 to 12 µm (long waves).[2]

Infrared thermography locates moisture anomalies in building envelopes by exploiting the thermal properties of water. The greater the specific heat (the amount of heat required to raise the unit mass of material one unit of temperature), the more energy is required to heat or cool a particular material. For example, water has a higher specific heat (4,180 J kg^{-1} $^{o}C^{-1}$) than pine (2,800 J kg^{-1} $^{o}C^{-1}$) used as framing lumber or common building brick (840 J kg^{-1} $^{o}C^{-1}$). Consequently, water loses or gains heat much slower than wood or brick under similar conditions. Because the heat capacity of a water-damaged material is greater than that of a dry material and air (700 J kg^{-1} $^{o}C^{-1}$), areas of high-moisture content appear either warmer or colder than the surrounding infrastructure. The difference in temperature can be imaged and measured using an infrared camera. The recorded visual image is a thermogram or thermal scan.

An infrared thermal imaging system has advantages that conventional instruments (conductance- and dielectric-types) do not have. Such a system is fast, meaning that all areas (not just suspected areas) can be quickly scanned to determine if moisture anomalies are present. It produces a two-dimensional image of the scanned area which gives a moisture mapping capability. Surveys can be conducted from ground level, which avoids potentially expensive access arrangements outside as well as inside buildings. It is non-contact, which means that metallic materials in or near the location to be measured do not alter or attenuate its performance.

The objectives of these investigations include using infrared thermography to locate areas of probable moisture anomalies in the building envelope to pinpoint areas for intrusive study; verifying the moisture condition by direct measurement and invasive examination; determining the extent of resultant microbial colonization; and establishing a theory as to the cause(s) of the moisture.

METHODS

Thermographic Examination

To minimize the effects of solar radiation, *passive infrared thermography* was performed on the building envelope 2 to 3 hours after sundown. Passive thermography test materials are naturally at a different temperature than the surrounding materials; in active thermography, however, an external stimulus (e.g., heat gun) is necessary to induce relevant thermal contrast. Passive thermography is rather qualitative since the goal is simply to locate thermal anomalies. Prior to the inspection of the structures, no precipitation occurred for at least 24 hours. The thermography was performed using a FLIR Systems Thermovision® 550 infrared imaging system. A visual record (photograph) was made of each area surveyed.

Intrusive Inspection of Building Envelope

Based on the qualitative interpretation of the infrared thermograms, intrusive inspections were conducted of the exterior of the building envelope to verify the potential presence of moisture observed by the thermograghic scans and detected through critical observations. Additionally areas with visible fungal growth were identified. This procedure was accomplished by removal of the brick veneer to expose the method of installation for the brick and the composition of the envelope. Subsequently, the exterior sheathing was removed to expose framework, insulation, vapor retarder, and the backside of the gypsum wallboard. Access to interior inspection locations in the commercial building was provided by a negative air pressure glovebag containment to prevent the potential release of aerosolized fungal spores into the occupied space. A hose from an operating high-efficiency absolute particulate (HEPA)-filtered vacuum was used to provide negative air pressure in the glovebag. Invasive tests were not conducted from the interior of the residential structure.

A GE Protimeter MMS Moisture Measurement System was used to measure the moisture in wood and wood-moisture equivalent (WME) in building materials other than wood (e.g., batt insulation or gypsum board). When materials other than wood are tested, the instrument measures the WME value of the material. WME is the moisture level that would be attained by a piece of wood in equilibrium with the material being tested. Our observations were photographed and microbial testing was conducted.

Microbial Samples

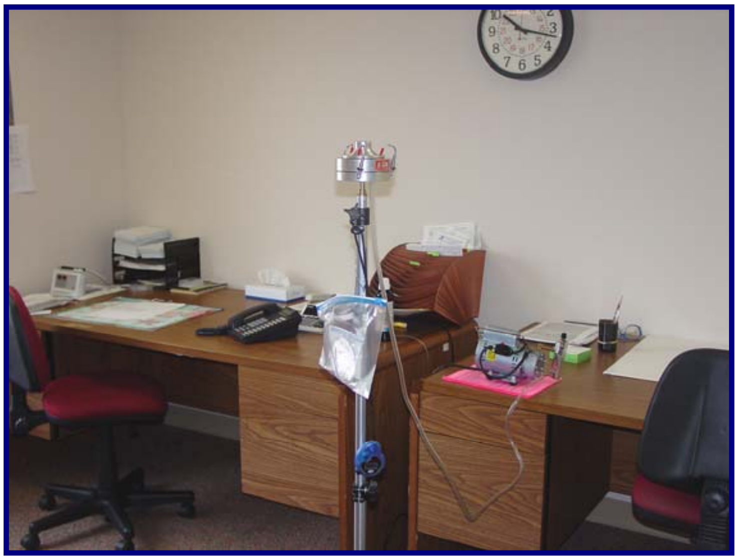
The samples were collected in accordance with procedures specified in *A Field Guide for the Determination of Biological Contaminants in Environmental Samples,* 2^{nd} ed. (AIHA 2005). A laboratory accredited by the American Industrial Hygiene Association (AIHA) Environmental Microbiology Laboratory Accreditation Program (EMLAP) prepared and analyzed the samples. Sample chain-of-custody and accountability were in accordance with ASTM Standard D 4840-95.

Airborne Mycobiota

Air samples for culturable fungi were collected using an Andersen N-6 single-stage microbial sampler (Figure 1). Immediately prior to collecting the samples, the sampler was sterilized by deluging the sampler with 70% isopropyl alcohol and air-drying. The sampler was set at a flow rate of 28.3 liters per minute (L/min) with an in-line calibrated flow meter. The airflow meter (a secondary calibration standard) was calibrated with a primary airflow calibration standard. The indoor and outdoor sampling periods were 10 minutes and 2 minutes, respectively.

Collection was made on approximately 30 ml of sterile 2% malt extract agar (MEA) contained in 100-mm x 15-mm polystyrene Petri plates. The samples were sent to the laboratory by 1-day courier service for further processing. Upon arrival, the culture plates were incubated at approximately 25 ^{o}C for 7 days. Culturable fungal colonies were identified and enumerated in concentrations of colony forming units per cubic meter of air sampled (CFU/m^3). Cladosporium, *Aspergillus*, *Penicillium*, and other species were identified to group-species level and enumerated. Yeasts and sterile hyphae were also enumerated as CFU/m^3.

Figure 1. Single-stage multi-orifice viable air sampler (Andersen N-6).



Mycobiota in Bulk Samples of Building Materials

Bulk samples were collected of batt insulation and gypsum wallboard paper facer. The samples were placed in a clean labeled zip-lock bag for subsequent analysis in the laboratory to determine type and quantity (colony forming units per weight of sample) of fungi. Serial dilutions of the prepared samples were plated to two nutrient growth media for identification and enumeration of fungi: malt extract agar (MEA) and dichloran glycerin agar (DG18). MEA is a general growth media; DG18 is a growth media used for the enumeration of low-moisture-tolerant fungi. Mature sporulating fungal colonies were identified to genus level and enumerated in CFU/g of material. *Cladosporium*, *Penicillium*, and *Aspergillus*, and some other fungi were identified to species level and enumerated.

RESULTS

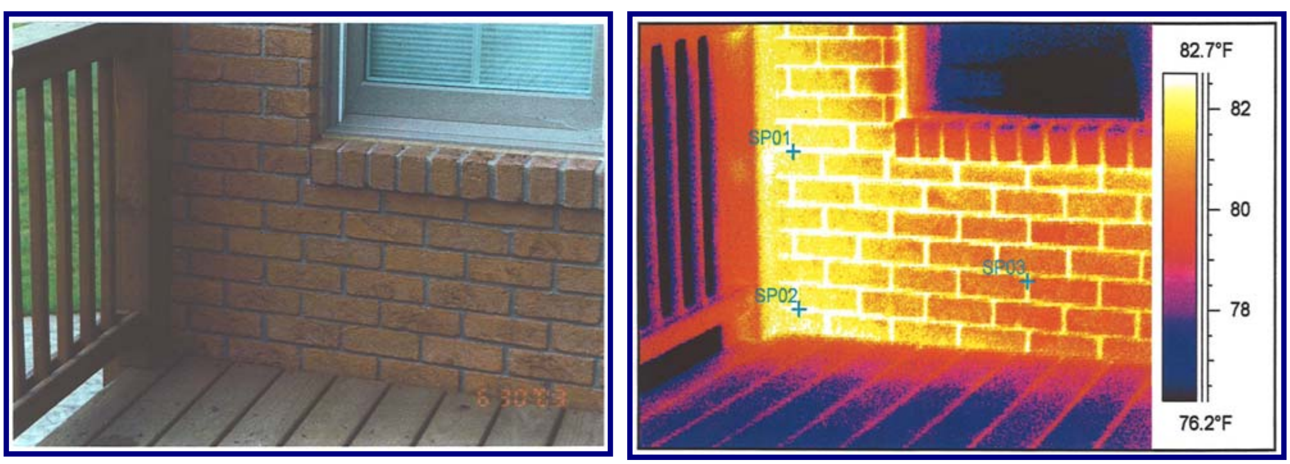
Residential Structure

Thermographic Observation

Infrared thermographic observations of the building exterior were conducted to identify moisture anomalies in the exterior facade. Eleven test locations were chosen for invasive examination. Representative thermograms and the corresponding photographs are shown in Figures 2 and 3.

Figure 2. This thermographic image taken at the south side of the north elevation on June 25 showed thermal anomalies in the brick veneer. The suspected wet areas are relatively warm and clearly visible in this thermogram as white and yellow areas. Cooler, dry areas are red, purple, and black. The color bar shows the measured temperature range of 76.4 to 82.2 °F. The ambient temperature was 76 °F and the object distance was 50 ft. See Figure 4 for observations made during the intrusive inspection of the wall cavity.

Figure 3. This thermographic image taken at the south end of the north elevation on June 25 showed thermal anomalies in the brick veneer. The suspected wet areas are relatively warm and clearly visible in this thermogram as white and yellow areas. Cooler, dry areas are pink, purple, and black. The color bar shows the measured temperature range of 76.2 to 82.7 °F. The ambient temperature was 76 °F and the object distance was 6 ft. See Figure 5 for observations made during the intrusive inspection of the wall cavity.



Intrusive Inspection

The results of the moisture measurements and microbial samples are summarized in Table 1. Seven of the test locations chosen based on the thermographic scans revealed moisture levels above 20%. Generally, moisture levels greater than approximately 18 to 20% is considered sufficient to support microbial growth. Overall, the measurements show that the moisture levels measured in the components of the building envelope are conducive to microbial growth. The observations made during the intrusive inspection of the sites identified in Figures 2 and 3 are shown in Figures 4 and 5, respectively.

The inspection concluded that the moisture gained access through capillary action at the various openings in the exterior (i.e., windows, etc.) and that the water shedding ability or weatherproofing of the mortar and brick had been compromised by excessive acid cleaning of the masonry. Further, the presence of moisture within the wall cavities is attributable to improper installation of the brick veneer.

Table 1. Moisture measurements and microbial analyses of residential structure.

Site	% Moisture Content[a]		% WME		Culturable Fungi, CFU/g	
	Wood Framing	**OSB Sheathing**	**Batt Insulation**	**Gypsum Board**	**Batt Insulation**	**Gypsum Board Paper**
South Elevation						
1	21	-	-	-	-	-
2	-	13	-	-	-	-
3	12	16	10-12	17	1,240-2,000	1,220
4	52	31	61	-	5,850	-
5	16	19	-	15	1,257,00	-
East Elevation						
6	57	17	66	21	96,000	-
7	-	18-19	15-100	-	11,160-64,420	-
8	44	19	87	-	53,120	-
9	25	38	37	-	58,000	121,500[b] 58,800[c]
North Elevation South Side						
10	61	28	54	-	18,680	-
North Elevation East End						
11	20	-	26	-	971,000	-

[a] Readings above 25 to 27% (the nominal value of the fiber saturation point) are indicative only and do not imply reliability of the readings above the fiber saturation point.[4]

[b] OSB sheathing.

[c] Tyvek® wrap.

Figure 4. Intrusive inspection of the wall cavity at the south side of the north elevation; see corresponding thermogram in Figure 2. Elevated moisture levels were measured in the building materials. Fiberglass batt insulation was colonized by fungi (18,680 CFU/g) and was dominated by *Aspergillus versicolor* (91%).

Figure 5. Intrusive inspection of the wall cavity at the south end of the north elevation; see corresponding thermogram in Figure 3. Elevated moisture levels were measured in the building materials. Fiberglass batt insulation was colonized by fungi (9.71E+05 CFU/g) and was dominated by *Acremonium strictum* (76%) and *Aspergillus versicolor* (22%).

Commercial Structure

Thermographic Observation

Infrared thermographic observations of the masonry-veneer were conducted to identify moisture anomalies in the exterior facade. A representative thermogram of the brick veneer and the corresponding photograph is shown in Figure 6. Thermographic images were also obtained of the roof (Figure 7).

Figure 6. This thermographic image taken at the southeast elevation on April 16 showed thermal anomalies in the brick veneer. The suspected wet areas are relatively warm and clearly visible in this thermogram as white and yellow areas. Cooler, dry areas are pink, purple, and black. The color bar shows the measured temperature range of 64.4 to 71.1 ^{o}F. The ambient temperature was 73.4 ^{o}F and the object distance was 10 ft. See Figure 8 for observations made during the intrusive inspection of the wall cavity.

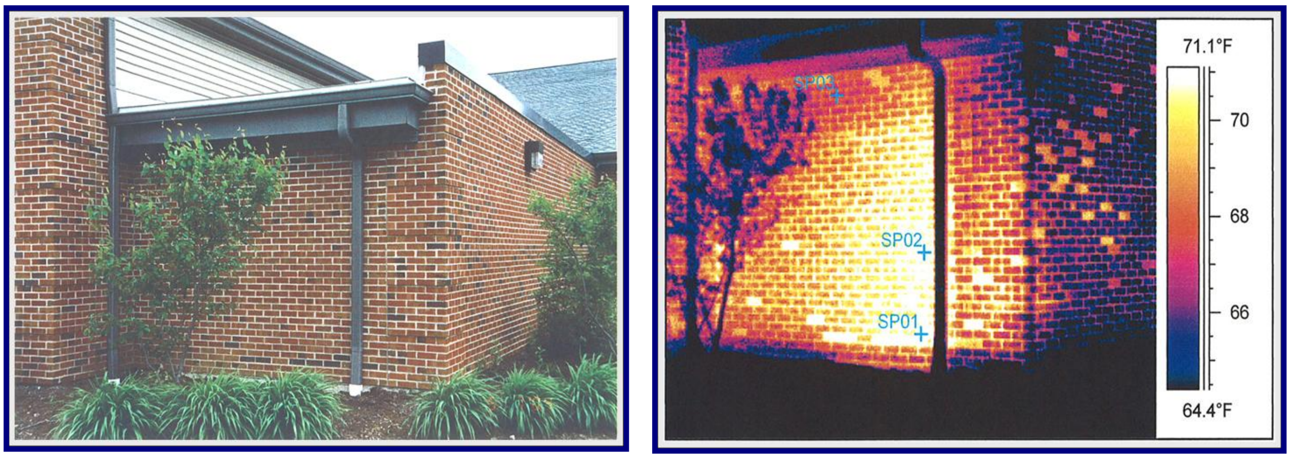
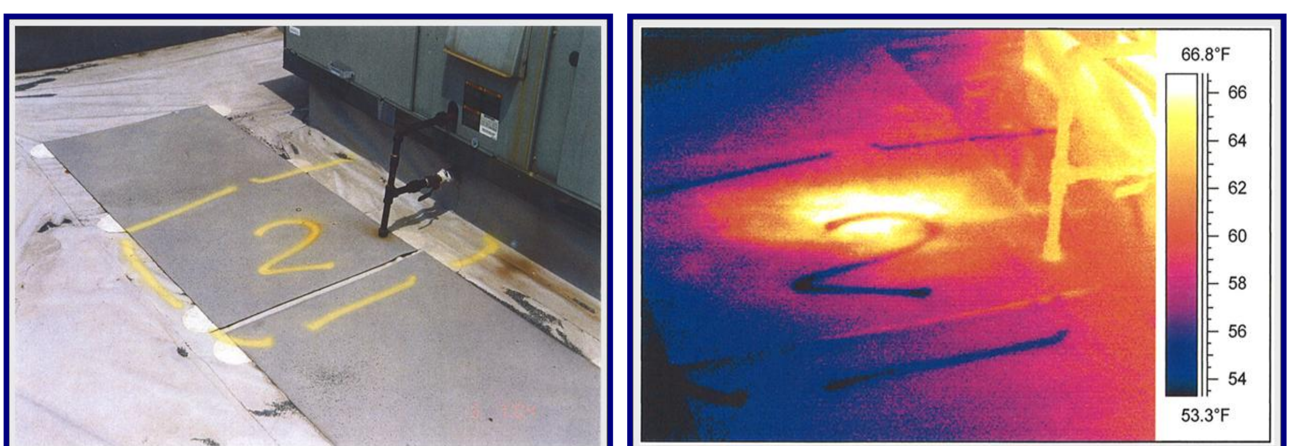


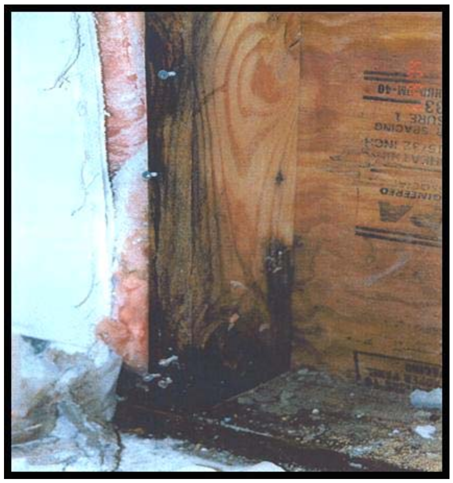
Figure 7. This thermographic image was taken of a section of the roof on April 16. A leak in the roof membrane allowed overflow moisture from the air-handling unit to enter the roofing system, resulting in roof-entrapped moisture. The suspected wet areas are relatively warm and clearly visible in this thermogram as white and yellow areas. Cooler, dry areas are pink, purple, and black. The color bar shows the measured temperature range of 53.3 to 66.8 ^{o}F. The ambient temperature was 73.4 ^{o}F and the object distance was 2.3 ft. The location of the finding is marked on the roof.



Intrusive Inspection

At the location shown in Figure 6, the intrusive inspection of the building envelope was conducted from the interior of the structure. A section of gypsum wallboard was removed to expose the vapor retarder, batt insulation, framework, and backside of the plywood sheathing (Figure 8). The lower portion of the gypsum wallboard was saturated with moisture and broke when handled. The presence of a mold-like substance was present on the lower 4 inches of the gypsum wallboard. Visible condensation was observed on the insulation side of the vapor retarder. Prior to removal of the insulation, a moisture measurement made of the batt insulation showed a reading of 22% wood-moisture equivalent. The 2 x 6 framing member was wet and water-stained, as was the sill plate (Figure 8). The excessive moisture caused the sill anchorage to corrode.

Figure 8. Water staining of framing members.



Because the masonry was not removed from the exterior, a 4-inch-diameter hole was cut in the exterior plywood sheathing just above the membrane flashing (Figure 9). The view (Figure 9) shows that the band of mortar running horizontally would obstruct the flow of water to the base flashing. The cavity between the brick and sheathing is <½-inch and was found to be occluded. The brick veneer should be installed with a minimum of a 1-inch airspace.[5] This air space must be clear of mortar and should be open at the top of the brick veneer wall, as well as at its base.

Figure 9. The band of mortar running horizontally would obstruct downward migration of moisture to the flashing and not be expelled to the exterior.

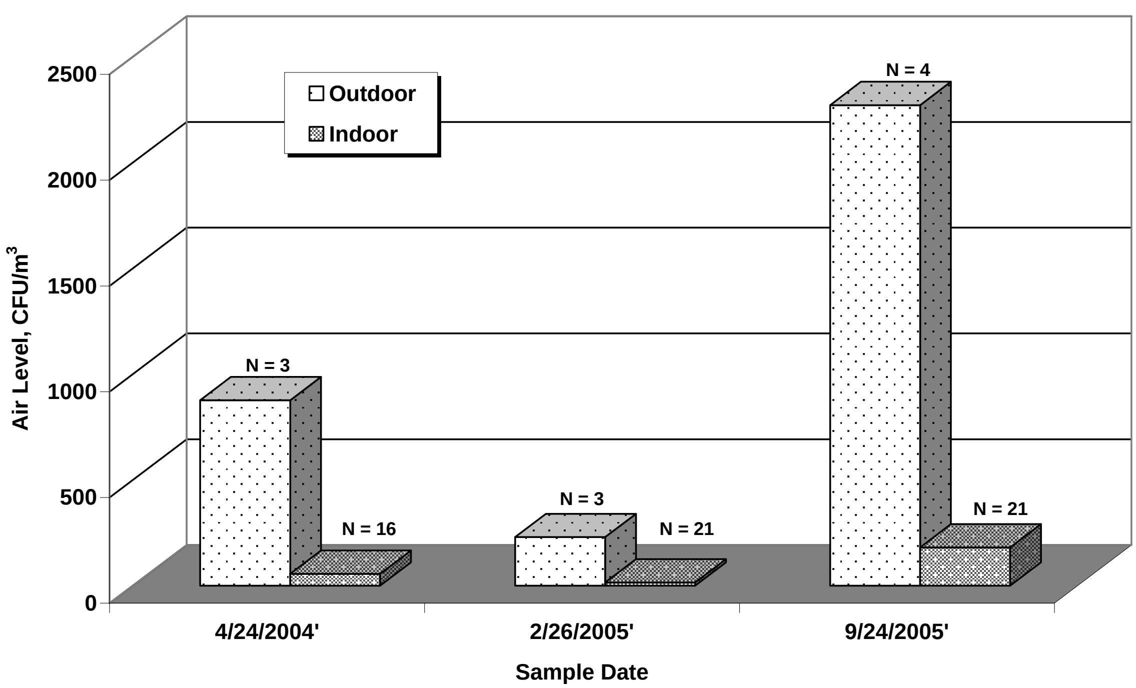
Airborne Culturable Fungi

Air sampling for culturable fungi was conducted three times over a 2-year period to determine whether the fungi that were present in "*visually inaccessible spaces*" (e.g., interstitial wall cavity) had migrated into the occupied space of the building. The air samples were collected under normal conditions of air movement and without intentional disturbance of the air. The heating, ventilation, and air-conditioning (HVAC) system was operating in normal mode.

A graphical summary of the airborne concentrations of total culturable fungi is presented in Figure 10. The air concentrations are reported as colony forming units per cubic meter of air sampled (CFU/m^3). The corrected colony count used to calculate CFU/m^3 is based on the positive-hole correction count (PHC).[6] The PHC is used to adjust colony counts from an impactor (in this case a 400-hole impactor) for the possibility of collecting multiple particles through a hole, which could underestimate the bioaerosol concentration.

The average concentration of airborne culturable fungi measured outdoors was consistently higher than that present indoors (Figure 10). The indoor-to-outdoor ratio of total culturable fungi was consistently <0.1. The dominant fungi present outdoors were qualitatively similar to those present indoors. Typically, the normal air mycoflora outdoors are quantitatively higher than that indoors (i.e., indoor-to-outdoor ratio <1) if the primary source of the fungi is the outdoor air. This data suggests that the fungal colonization of the interstitial wall space is not migrating into the occupied space or has not been detected by these three sampling events.

Figure 10. Average airborne level of total culturable fungi in occupied space.



CONCLUSIONS

Infrared thermography is a useful and effective tool for the detection of moisture anomalies in building envelope systems; because of the complexities of building construction and performance of infrared detection and measurement, however, considerable care must be exercised in both collection and interpretation of thermographic data. These investigations demonstrate that qualitative infrared thermography coupled with an informed visual inspection and quantitative substantiation using moisture meters is an effective protocol to detect moisture anomalies in building envelopes. Infrared thermography provides a means of *seeing* the invisible thermal signatures that are related to many building enclosure problems and conditions.

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