

Practical Issues Associated with the Use of Infrared Thermography for Detection of Heat, Air and Moisture Deficiencies in Building Envelopes

Irrespective of whether it is an inside or outside inspection, transient environmental conditions, particularly those caused by solar loading and wind, may confuse actual insulation conductive performance, and/or cause conductive deficiencies to go undetected.

Thermography can and has been utilized in the discovery of otherwise undetectable heat, air and moisture anomalies in buildings. Unfortunately, thermography only is applicable when these anomalies affect detectable surface temperature patterns. It therefore requires suitable thermodynamic conditions sometimes unique to the environment, materials, assembly, or operation of the building in order to discover an anomaly related to a specific heat, air, or moisture deficiency. This creates limitations on the time, location, camera detection capabilities, and operator expertise required for suitable, reliable and repeatable detection. This paper will discuss practical considerations for detection of thermal anomalies in each of three categories. For each topic we will discuss the limitations, challenges and requirements for the use of this building diagnostic tool.

Detecting Thermal Anomalies Related to Conductive Heat Transfer

Thermographic evaluations for conductive thermal anomalies (e.g.: insulation quantity, quality, deficiency, thermal bypasses) may be conducted in heat loss (winter) or heat gain (summer) conditions so long as there is a minimum steady state temperature difference maintained between the inside and outside of the structure. Evaluation is based upon Fourier's law of conduction: heat flux, $Q = (k/L) \times \Delta T$ (Incropera, et al, 1996). Hence any thermal anomaly detected as a surface temperature variance under constant steady state temperature difference (ΔT) must be attributable to a variance in material conductivity (k) or thickness (L). ASTM C1060, ISO 6781, and RESNET standards specify a minimum of 10°C *difference* across the enclosure. The Canadian National Master Specifications NMS 022713 requires a minimum difference of 15°C, although NMS standards are aimed more towards commercial and institutional buildings where buffer spaces (e.g. ceiling plenums, vented rain-screens) and thicker more complex construction is common. All standards require steady state conditions lasting at least 3 to 4 hours (longer in some standards under certain conditions) to eliminate transient surface thermal patterns influenced by material thermal capacitance storing or releasing energy. Most standards require the inspection be conducted from both interior and exterior perspectives, although most note that an interior inspection will usually provide better, more stable information, particularly in conventional construction where the insulation is typically placed closer to the interior than the exterior surfaces. Irrespective of whether it is an inside or outside inspection, transient environmental conditions, particularly those caused by solar loading and wind, may confuse actual insulation conductive performance, and/or cause conductive deficiencies to go undetected.

Most standards refer to thermographic assessments as being qualitative in which different types of insulation anomalies and construction deficiencies related to thermal conduction will exhibit unique surface temperature patterns. Most standards refer to the use of a known thermal conductivity bypass (e.g. wood studs) as a qualitative thermal performance reference. In conventional wood frame construction the wood studs will

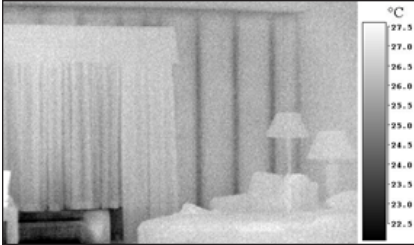


Photo 1a. Winter Heat Loss

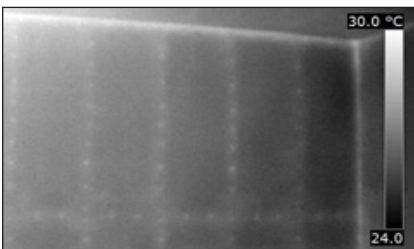


Photo 1b. Summer Heat Gain

Thermal bypasses (in this case wood studs in conventional residential construction) of known conductivity can be used as a qualitative “calibrator” for a wall experiencing steady state heat flow. (McIntosh)

exhibit a regular consistent pattern of lower performance relative to the insulation. In a normal insulated wall, when an inside wall is viewed under heat loss conditions the studs will appear cooler than the insulation (Photo 1a), while in summertime the polarity will be reversed and the studs will appear warmer than the insulation (Photo 1b).

Accurate quantitative heat transfer performance (conductance or equivalent R value) cannot be derived from a thermal image and/or temperature values alone. If this is desired it should be done in accordance with ASTM C1046 – 95 and ASTM C1155 – 95. The only part that thermography plays in ASTM C1046 is to determine the placement of the heat flow devices and measurements. Since the total enclosure heat loss is affected by the total surface area multiplied by the unit heat flux, then thermography can also be useful for estimating the total area affected by either one localized conductive anomaly, or the sum of repetitive anomalies. RESNET, however, is the only standard which suggests a quantitative approach of determining approximate area affected. In addition to being a difficult and time-consuming practice however, a specific threshold of surface temperature difference must be specified to define an “anomaly” to be included in the area calculation.

Some thermographers approximate wall performance based upon the principle of Temperature Index (Mill, P.A.D., 1979). This index is derived from dividing the drop in temperature from the inside surface (T_{is}) minus the outside ambient (T_{oa}) by the total drop in temperature from the inside ambient (T_{ia}) minus the outside ambient (T_{oa}), i.e.: $\text{Temperature Index} = (T_{is} - T_{oa}) / (T_{ia} - T_{oa})$. It is based upon the principle that in steady state the unit heat flux transferred from the interior space to the inside wall should be equal to the heat flux conducted through a unit wall area (assuming an infinite plane). Therefore, the ratio of temperatures should be equal to the ratio of wall thermal resistance (L/k) value to the overall heat flow resistance inclusive of the inside surface resistance. Temperature Index produces a graph with a variable range of possible wall performance, since the actual field value for the inside surface resistance, (which ultimately determines T_{is}) may vary significantly at the time of the inspection. While ASHRAE handbook of fundamentals Table 4 suggests a design resistance value for a vertical wall of $0.120 \text{ m}^2 \times \text{K/W}$ ($0.68 \text{ hr} \times \text{ft}^2 \times \text{F/Btu}$), the actual field value can vary significantly depending on air velocity, surface emissivity, orientation, and variance in the air temperature and radiant environment. On a low emissivity wall, for instance, the ASHRAE value changes to $0.238 \text{ m}^2 \times \text{K/W}$ ($1.35 \text{ hr} \times \text{ft}^2 \times \text{F/Btu}$). Or, if there is a 5 ft/sec air flow across the inside wall the design value changes to $0.044 \text{ m}^2 \times \text{K/W}$ ($0.25 \text{ hr} \times \text{ft}^2 \times \text{F/Btu}$). Another major assumption in the use of Temperature Index is that the all components of the wall are in steady state, i.e. no part of the wall is storing or releasing heat due to the material’s heat capacitance or to a phase change (e.g.: moisture within the wall enclosure). An additional error is created when there is three dimensional heat transfer taking place within the wall. This will occur on or close to thermal bridging (e.g. wood or metal studs), when there is air movement within the wall, or when there are highly diffusive materials within the wall. Due to this cumulative uncertainty, Temperature Index is not an accurate or reliable method to predict an actual quantitative performance or for calculating an accurate R value (Stainton, W.D. 1978). It is however, a reasonable method for classifying the thermal performance of a light construction (e.g. wood frame, fiberglass insulated) wall. If the wall is in steady state there can be a high confidence that the wall is in a performance category,

All standards specify a minimum theoretical detectable difference (sensitivity) for an IR camera to be 0.1°C or 100mK (Noise Equivalent Temperature Difference or NETD).

(e.g.: very poor, poor, acceptable, good) which could justify further investigation of an anomaly, such as heat flow measurement or destructive testing respectively.

Qualitative pattern assessments imply that training and experience is required in order to identify deficiencies from normal patterns, and all standards refer to training and experience requirements, although only the RESNET and NMS standards specify ASNT SNT-TC-1A compliant Level 1 thermographers for the data collection stage. NMS further requires an ASNT compliant Level 2 for the assessment stage. ISO 6781/DIS-3, a revision to the current ISO 6781 standard, is a new training and certification document which specifies comprehensive training and experience requirements for detection of heat, air and moisture anomalies in residential, commercial and institutional buildings.

All standards specify a minimum theoretical detectable difference (sensitivity) for an IR camera to be 0.1°C or 100mK (Noise Equivalent Temperature Difference or NETD). Attainment in the field of this number is doubtful however, due to operator control and material emissive properties. Most standards also refer to the minimum spatial detection capabilities for interior inspections of approximately 3 milliradians (the angle subtended by an object 3mm in size at a 1m distance) specified as Instantaneous Field of View (IFOV). NMS 022713 is the most rigorous by defining the minimum detectable object size as 150mm² (approx 12.5x12.5mm) within minimum physical minimum Field of View requirements. For interior work this approximates a minimum 160 x 120 pixel camera with a 20 to 30 degree lens used at a distance not exceeding 5m. RESNET has a similar spatial requirement, although somewhat relaxed in the minimum Field of View requirement. For normal exterior work NMS requirements translate to a 320 x 240 pixel camera used at a distance of up to about 20m, although it specifies that higher resolutions of lenses and/or pixel count may be necessary to achieve the minimum 150mm² resolution at longer stand-off distances. Unfortunately there is a proliferation of low cost (under \$500) thermal imagers which do not even come close to meeting these specifications, yet are being utilized for thermographic assessments.

Detecting Thermal Anomalies Related to Air Movement

Unintentional air movement within, around, and through an enclosure may result in significant energy, thermal comfort, moisture, durability and environmental issues. As shown in the table below, air movement with respect to a building enclosure can take 7 different types. (Mill, P.A.D. et al, 1982)

Interior	Interstitial	Exterior
1. Surface convection	3. Interior to exterior (exfiltration)	1. Exterior open loop
2. Interior open loop	4. Interstitial closed loop	7. Surface convection
	5. Exterior to interior (infiltration)	

TABLE 1. TYPES OF ENCLOSURE AIR MOVEMENT AFFECTING SURFACE TEMPERATURE

Air movement types 1, 2, 4, 6 and 7 will transfer heat via surface to air convection, while types 3 and 5 are air leakage and have additional heat transfer associated with mass transfer (note: any latent heat related to phase change during mass transport will be discussed next section). Under some environmental conditions and certain types of wall assemblies the thermal patterns associated with types 2, 4 and 6 can be misinterpreted as either uncontrolled air leakage, or even at times missing insulation (when in fact adequate insulation and/or an adequate enclosure air barrier is present).



Photo 2a.



Photo 2b.

Uncontrolled air leakage is best performed under two pressure conditions. When observed from the inside under slightly positive pressure conditions (2a) no evidence of air movement can be detected. Under negative pressure (2b), the interior surfaces temperatures are affected by the air leakage. (McIntosh)

The use of thermography to detect the effect of air leakage requires that there is both a pressure and temperature difference between the inside and outside air. It does not detect the air directly, but rather the heat transfer that the air movement has upon the surrounding surface. Investigations into air related thermal anomalies may be conducted in heat loss (winter) or heat gain (summer) conditions as long as minimum temperature and pressure differences exist across the enclosure. When air movement studies utilizing a single pressure condition are conducted in conjunction with conductive insulation studies confusing and ambiguous patterns can result, particularly from diffuse air movement through some types of porous insulation. Definitive air movement testing relies on multiple pressure conditions, preferably both positive pressure and negative pressure. Identification of air movement types 3, 4, 6 and 7 must be done by exterior evaluation and positive pressure while identification of types 1, 2, 4 and 5 must be done by interior evaluation and negative pressure.

Natural pressure differences across the enclosure are created by three means: stack effect; wind; and by mechanical systems (e.g.: fans and combustion equipment). Unfortunately the thermographer is at the mercy of the natural conditions creating the pressure differences at the time of the survey. This often leads to a poor evaluation since parts of the building may be under positive pressure, others negative pressure, and even others nominal pressure. To overcome this limitation the thermographer can pro-actively create a pressure condition by one of two means: 1.) in smaller buildings utilize a blower door which can create a positive or negative air pressure differences within the entire structure or 2.) in larger or commercial buildings adjust the inlet and exhaust fans and/or their dampers to vary pressure differential. A blower door has the advantage of being able to characterize the air leakage curve for building and provide a quantitative estimation of the amount of air leakage under average and extreme conditions. For larger buildings where blower door use is not possible, air leakage quantification will typically be limited to evaluation via tracer gas depletion method.

ASTM E1186-03, RESNET and NMS 022713 standards do not agree on the pressures and temperatures differences across the enclosure required for reliable thermographic detection of air leakage. It varies from a difference of 1.7°C @ 10 Pa (RESNET) to 5°C @ 10 to 50 Pa (ASTM) to the most stringent requirements of NMS which requires a minimum of 20°C difference when pressures are between 5 to 10 Pa and 10°C minimum when pressures are between 10 to 25Pa.

The NMS standard describes an ideal two-step procedure for qualitative air leakage evaluation of larger commercial buildings. The building is first placed under entire positive pressure and the outside surfaces are inspected. Once all surfaces have been mapped, then the building systems are reversed and building is placed under negative pressure. After waiting a sufficient period of time, typically at least 2 hours, the surfaces are re-scanned to see if the pattern has changed. If it has, it is likely due to air leakage. In order to resolve the small areas of air leakage it is often necessary to use a narrow angle lense, map the exterior surface with a set of images, and then assemble them into one large image. In winter, air exfiltration will create warm patterns on the exterior surface. In general, the more diffuse the leakage, the larger the affected area and the less dramatic the exterior thermal patterns. The more direct the leakage and size of hole, the smaller and hotter the pattern will be.

Relying on water detection through the natural drying process only, will result both in false negatives (non-detection of moisture) and false positives (the thermal anomaly is not moisture).

The extreme sensitivity of modern cameras (e.g. better than 50 mK) can be such that even a relatively tight building may *appear* to be extremely leaky when tested under large delta temperatures and pressures. Therefore thermography should not be used to estimate the amount of air leakage (e.g. air changes per hour or effective leakage area). If the surface temperature approaches the air temperature on the opposite side of the wall, however, it is often indicative of a direct air leakage pathway (as opposed to diffuse pathways). If this is an isolated case of a small hole, in extreme conditions of pressure difference and temperature the resultant direct air leakage may cause damage (e.g. an interior pipe could freeze) yet a blower door test could indicate a relatively tight building. Thermography could identify this, even under non-extreme test conditions, because the surface temperature on the negative pressure side would be only slightly different than the air temperature on the positive side.

Camera performance requirements specified by all standards for air leakage detection are identical to those for detection of conductive anomalies, with the NMS specifications being the most detailed and rigorous. (refer to the previous section on conduction for camera specifications)

Detecting Thermal Anomalies Related to Moisture

Water, may be detected thermodynamically for three reasons: when a material contains water it can affect the thermal conductivity (k); when a material contains water it can alter the volumetric heat capacity ($\alpha \cdot c_p$); or when water changes state latent heat is absorbed (evaporation, melting) or released (condensation, freezing). Many thermographers, however, believe that the only mechanism for detection of moisture is evaporation. Under the right conditions, free air evaporative cooling on a surface can indeed be very thermodynamic, and easily detected with a modern infrared camera: 1 droplet of water (e.g. of a mass of 0.45gms (0.001 lbs) can theoretically extract approximately 1.05kJ (1 Btu) from the surroundings in order to provide the latent heat required for evaporation. After a flood in a building, the restoration industry will usually attempt to dry the interior by significantly lowering the vapor pressure (relative humidity) and using IR has brought with it the concept of water 'always appearing cool'. The dramatic surface temperature depression easily detectable during high vapour pressure difference, however, has led a very wrong general assumption by building investigators for passive moisture detection. Relying on water detection through the natural drying process only, will result both in false negatives (non-detection of moisture) and false positives (the thermal anomaly is not moisture). Even near-surface moisture can go undetected if the vapor pressure (RH) is too high in the free air condition adjacent to the surface. An infrared camera does not directly detect evaporation: rather it may detect a surface temperature depression due to the rate of evaporation which is determined by the vapor pressure difference between the saturated condition of the material and the free air space adjacent to it as well as the vapor retarders present in between. If the free air condition is warm and dry (low RH) it may create a high rate of cooling. Conversely, if the free air condition is cool and/or humid (high RH) it could easily go undetected because the evaporative cooling rate will be very low. In fact if condensation is occurring within a wall behind a vapor barrier then latent heat will be released and surface warming may occur and completely be ignored or misinterpreted as a non-moisture condition by an unsuspecting and untrained inspector.

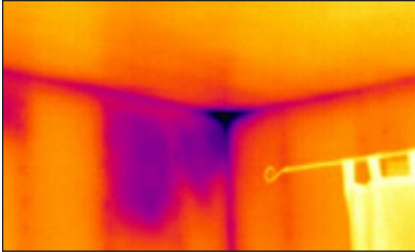


Photo 3a.

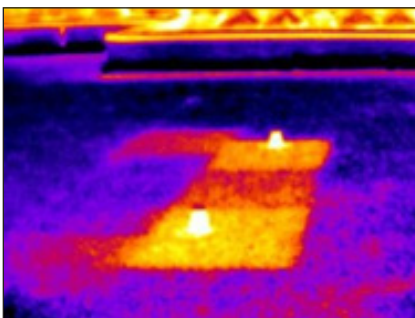


Photo 3b.

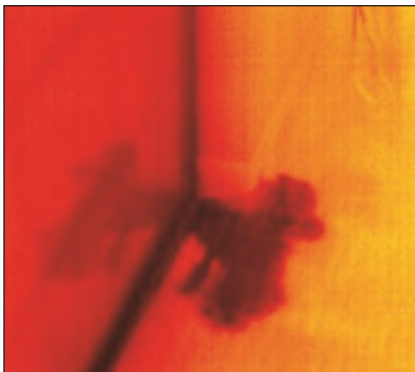


Photo 3c.

Moisture may be detected by: increased conductivity in steady state heat transfer (3a); increased thermal capacitance when undergoing transient heat transfer (3b); and through release or absorption of latent heat one when undergoing a phase change. In this case (3c) evaporative cooling when relative humidity is low. (McIntosh)

Detection of interstitial water within a wall or roof assembly is much more complex than the process of water evaporating from an exterior or interior surface exposed to free air. Many wall and roof systems have unintentionally created two or more vapor retardant barriers which inhibits the drying process. This raises the vapor pressure within the assembly, and inhibits evaporative cooling as a means of detection. Ironically this situation creates enclosure issues which the investigator is often tasked with finding. In this case, the thermographer must rely on a steady state conductivity change between wet and dry material; a heat capacity change between wet and dry material (under transient state); or the special thermal and moisture conditions required for one of the four phase changes.

Thermographic cameras are extremely sensitive, often able to detect differences less than 0.05°C (50mK). But while this may create a clearer, more defined pattern when the thermal conditions are right, it is not a viable substitute for moisture detection under poor thermodynamic conditions, and/or when moisture is buried deep within an enclosure. High sensitivity cameras used under less than ideal conditions can lead to a large number of false positives, and/or lengthy field time for verification using other methods. False negatives lead to credibility issues of both the inspector and the thermographic industry as well as the possibilities of litigation, particularly when mold or other damage associated with the moisture is present but not detected.

Since moisture detection is not covered in much detail by any standard, a general assumption could be that the requirements for camera performance are at least equal to those for detection of conductive anomalies. The current consensus in the industry however, is that moisture detection necessitates a higher level of thermal sensitivity. Most manufacturers have accommodated this by producing “building” model of IR cameras with an NETD of at least 0.08°C (80mK) or better. It is likely that any future standards developed for moisture detection will require at least this level of sensitivity. Spatial requirements are likely to remain the same as for conductive anomaly detection. The NMS standard is the only specification which itemizes certain conditions for the detection of moisture. The standard requires a minimum 20°C (temperature) and 25Pa (pressure) difference from the inside to the outside and 30°C difference when the pressure difference is less than 10Pa.

The Special Case of Low Slope Roof Moisture Detection

Both ASTM C1153-10 and NMS 022716 standards detail the conditions necessary for detection of moisture trapped in conventional low slope built-up roofing systems. Interstitial moisture is detected using the capacitive method of detection by observing the outside roof surface under transient conditions. Ideal conditions are a warm sunny day with low wind, and no moisture on the roof surface. Inspection takes place 1 to 2 hours after the direct sunlight has left the roof surface and is conducted into the night. Potential wet areas are identified as warm areas that have retained the solar heat gained during the day. Both standards also permit investigations to be performed using the conductive method of inspection under steady state heat loss conditions with a minimum differential of 10°C (ASTM) or 15°C (NMS) across the enclosure. In all cases, and with both standards, the thermographer must be aware of inside conditions, fixtures and appliances and no standing water should be present on the roof surface.

	Conduction (insulation) IR Test Method	Air Leakage IR Test Method		
		Infiltration Only	Exfiltration Only	Infiltration and Exfiltration
Temp. Difference	10°C minimum	5°C minimum	5°C (min) across wall	5°C (min) across wall
Wind Dependent	Yes for exterior	No unless affects pressure	Yes	Yes for exterior
Steady State/ Transient Heat	Steady State	Steady State for Thermal Transient for Pressure	Steady State Thermal Transient Pressure	Steady State Thermal Transient Pressure
Time of day dependent	No, so long as no solar gain present	No, so long as no solar gain present	No, so long as no solar gain present	No, so long as no solar gain present
Pressure difference	Not required	Neutral/Normal then Minimum -12 Pa	Neutral/Normal then Minimum +12 Pa	Minimum +12 Pa then minimum -12 Pa
Interior/Exterior	Both. Interior is usually more reliable	Interior	Exterior	Interior and Exterior
Thermal anomaly polarity	Warm or Cool	Winter: Cool Summer: Warm	Winter: Warm Summer: Cool	Warm or Cool
Best Conditions	Walls under steady state heat loss or gain	No initial natural pressure difference	No initial natural pressure difference	

TABLE 1. SUMMARY OF CONDITIONS FOR CONDUCTION AND AIR LEAKAGE INVESTIGATIVE METHODS UTILIZING THERMOGRAPHY

	Conductive Method	Capacitive Method	Phase Change Method			
			Evaporation	Condensation	Freezing	Thawing
Temperature Difference	10°C (min) across wall	Yes (Varies)	No	No	Yes and sub-zero	Yes
Wind Dependent	Yes for exterior	Yes for exterior	Yes for exterior	Yes for exterior	Yes for exterior	Yes for exterior
Steady State/ Transient Heat	Steady State	Transient	Varies	Varies	Transient	Transient
Time and duration dependent	No	Yes	Varies	Varies	Yes	Yes
Vapour Pressure dependent	No	No	Yes	Yes	No	No*
Moisture content dependent	Yes	Yes	No	No	No	No
Interior/Exterior	Both	Both	Both	Both	Exterior	Exterior
Depth dependent	No	Varies	Yes	Yes	Yes	Yes
Thermal polarity	Warm or Cool	Warm or Cool	Cool	Warm	Warm	Cool
Specific temperature dependence	No	No	Yes, as it affects RH	At or below dew-point	Above then below 0°C	Varies with solar gain

TABLE 2. SUMMARY OF CONDITIONS FOR VARIOUS MOISTURE DETECTION INVESTIGATIVE METHODS UTILIZING THERMOGRAPHY

*may affect the conditions for sublimation

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Conclusions

Thermography can play a significant role as a non destructive and rapid screening tool to identify potential heat, air, and moisture related anomalies in large and small buildings, but *only if the thermodynamic conditions are right*. Thermographic results alone cannot quantify excessive heat flow, air flow, or moisture content. The primary use for thermography should be as a qualitative investigative tool, identifying potential areas for further investigation, validation and quantification by other means. Any quantitative thermographic analysis should be limited to that of temperature measurement and/or potential percentage area affected. Thermographic investigations should be limited to those environmental conditions, procedures, and methods specified and recommended by various standards established by recognized independent bodies. Standards for utilizing thermography for conductive and air leakage studies are well established and should be adhered to. These are summarized in Table 1. But, because of a lack of current standards for moisture detection, it should be done carefully and with a specific methodology for detection (conduction, capacitance or phase change) appropriate for the materials, assembly and environmental conditions. This is summarized in Table 2. Home inspectors, for example, could apply a thermal camera in a limited scope for free-air detection of water related anomalies, so long as they have a specific Standard of Practice detailing the method and conditions necessary for doing so and a means (e.g. a moisture detector) for immediate field confirmation of the suspected anomaly.

IR cameras suitable for building investigations are now inexpensive, lightweight and easy to use. There are, however, cameras available which do not even come close to meeting the requirements of the current well established standards for detection of heat, air and/or moisture anomalies. One should ensure that before a camera is purchased, or a contract for services engaged, that a camera and thermographer suitable meet the minimum requirements of the appropriate standard for the task.

All standards emphasize the importance of training and certification related to not just the camera and infrared detection principles, but more importantly knowledge of building construction, performance, and sound building science principles. The proliferation of readily available low cost cameras used by unqualified persons unaware of the underlying thermodynamic principles, appropriate methods, and limitations however could jeopardize the legitimate value of thermography as a valuable tool for the building diagnostic industry.