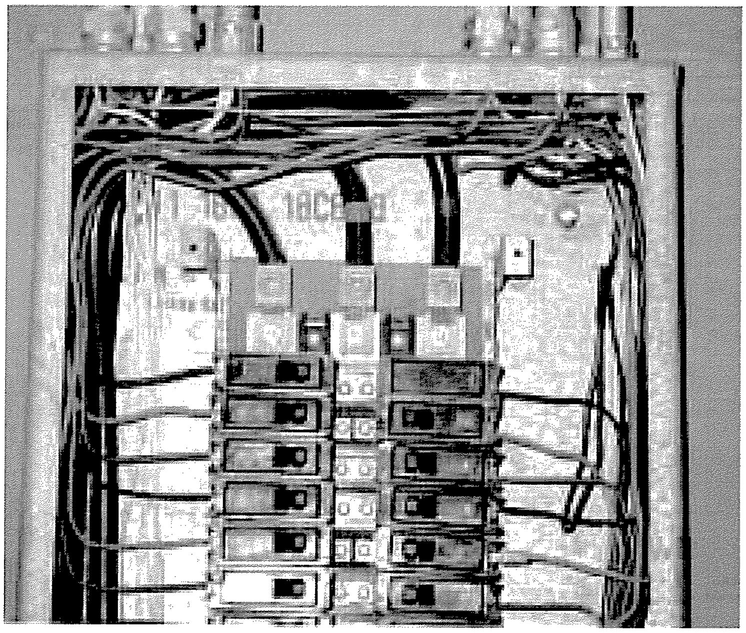


(a)

(b)

FIGURE 9-9 Abnormally high resistance heating in electrical system. (a) Photograph; (b) thermograph.

ing enclosures cannot be done without great care, however, because the thermographer is exposed to the potential for extreme danger, especially from an arc flash explosion. These explosions, which can be triggered simply by opening an enclosure door, can reach temperatures in excess of 15,000°F in less than a half-second.

Every effort should be made to understand and minimize these dangers. NFPA 70-E, which is accepted as law throughout most of the United States, details the steps necessary to protect the thermographer. These include, among others, education and personnel protective equipment (PPE). PPE may include clothing designed to withstand an arc flash, as well as protection for the eyes from the high-energy ultraviolet radiation given off in such an explosion.

Some equipment may be so dangerous to access that other measures are advised. Infrared transparent windows are now being installed in some instances to allow viewing into an enclosure without opening it. Careful placement is required to ensure that all components can be seen. It may also be possible to use equipment that detects airborne ultrasound. Even microarcing in a connection produces a detectable ultrasound signature through a crack or small hole in an enclosure.

Where enclosures cannot be opened easily, such as on an overhead-enclosed bus, the thermal gradient between the problem and the viewed surface is typically very large. A 5°F surface signature on an enclosed bus often indicates that the metal bus bars a few inches away may have already begun to melt! Great care must be used when conducting inspections of unopened enclosures.

For outdoor inspections, wind is a variable that can quickly reduce the value of thermography if it is not used with the greatest of care. Convective cooling by the wind (or inside plants by any forced air currents) will quickly reduce the temperature of a high-resistance connection. What appears to be an insignificant problem during these windy conditions can, in fact, become very significant when the wind speed drops. Many thermographers try to compensate for this by measuring a temperature difference from one phase to another, with the mistaken notion that the effects of the cooling will be neutralized. Such is not the case!

When making delta measurements between like components, one can fail to recognize that the normal phase, operating at only a few degrees above ambient, can never be cooled below ambient temperature. Thus, in the wind, the delta measurement will also seem deceptively small. The results of outdoor inspections when wind speeds are greater than approximately 10 MPH should be viewed only with a great deal of caution. Even "minor" temperature increases may represent extremely serious problems. It is likely that many problems will not even be warm enough to be detectable, much less accurately measured. To be of any value at all, a measurement or estimate of wind speed at the component location must always accompany temperature measurements. The use of Beaufort's Wind Scale, or some other means of estimating local conditions, is recommended.

Two other difficulties crop up during outdoor inspections. The sun can cause heating of any thermally absorbent surface. Dark surfaces in particular can be heated to the point where they are difficult to view with any understanding. Usually, inspecting during the morning hours or on overcast days is sufficient to minimize difficulties. More problematic is using short-wave sensing systems outside in sunshine. Short-wave systems are susceptible to solar "glint," or reflection of the sun's high quantity of short-wave thermal radiation. For extensive outdoor work during sunny periods, long-wave sensing systems will give superior results. Short-wave systems should be used only on a limited basis or, if loads and other conditions allow, on overcast days or at night.

Although many believe otherwise, the job of acquiring reliable thermographic data regarding electrical systems is not easy. Even with good data in hand, too many people use the data incorrectly to prioritize the seriousness of their findings. Temperature is often not a reliable indicator of the severity of a problem. Given the limitations of radiometric measurement on low-emissivity electrical components, the difficulties are further exacerbated.

This reality does not prevent the vast majority of thermographers, or people purchasing thermographic inspections services, from believing that the hotter a finding is, the more serious the problem. Or, more dangerously, they believe that if a finding is not very hot, it is not a problem. Nothing could be less true! The problem shown in Figure 9-10 is an internal fault in a pole-mounted transformer tank; the temperatures seen on the outside of the tank are quite cool compared to the temperature inside at the actual point of high-resistance heating.

The effects of convection on heated surfaces have been previously described. While conducting electrical inspections inside a plant, it is not unusual for warm air to be convected up and over components, causing them to be warmed more than might be expected. High resistance in a loadside (lower) connection of a breaker, for instance, will result in heating, but convection from it may also cause the lineside (upper) connection to appear warm.

When inspecting three-phase electrical systems outside, it is also important to remember that wind (at ambient air temperature) moving over a normal component (also at or near ambient temperature) results in little cooling effect. However, the same wind blowing over a high-resistance, hot connection will dramatically cool it. The result is that when the wind is blowing, the hot problem connection may not be visible or, if it is, it may not appear to be very warm.

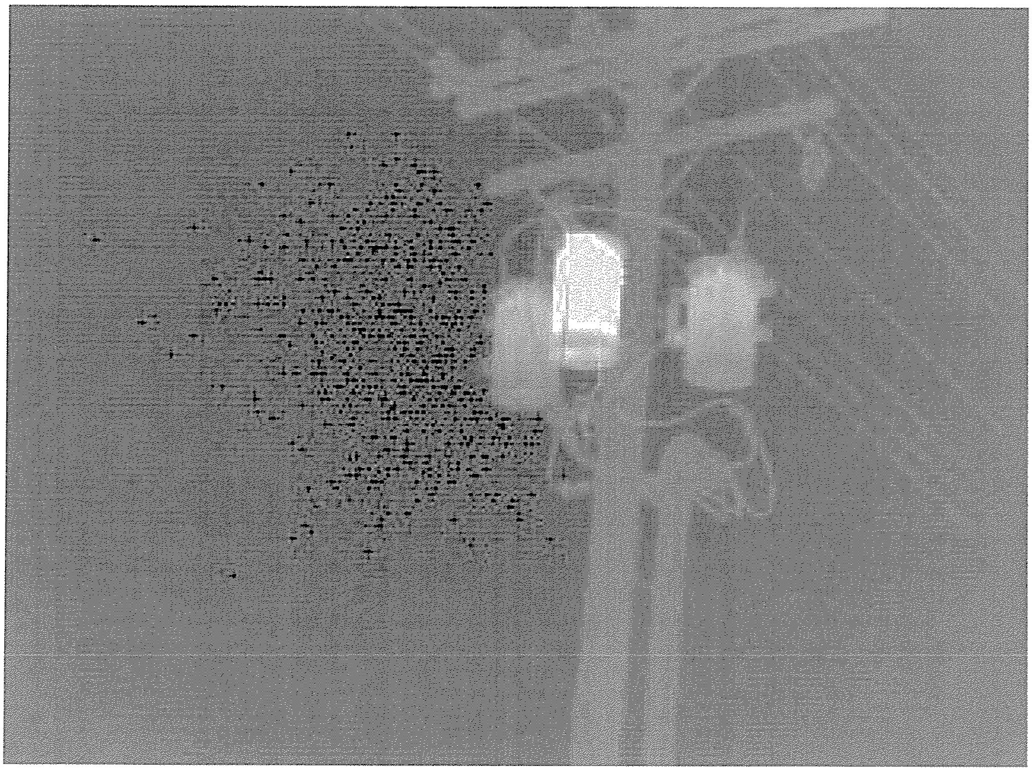


FIGURE 9-10.

The seriousness of many findings will not be made obvious by temperature alone. It must be recognized that any components having low emissivity or a high thermal gradient located inside an enclosure subject to convective cooling, or under light load, will probably not appear very warm. In fact, in most cases, they could be extremely unstable. Further, little is understood about the actual failure mechanisms for the diverse collection of electrical components that can be inspected.

Some generalizations are possible, such as the fact that lower melting points will cause aluminum materials to fail before copper alloys. Spring tension, an essential characteristic of many switch and contact components, fails after the material has been at approximately 200°F for a month. The blocked cooling fins shown in Figure 9-11 also indicate a very serious problem. Insulating oils in transformers break down rapidly when subjected to overheating, and this problem will result in overheating when loads are at peak and ambient temperatures are high.

Rather than basing prioritization strictly on temperature, a more useful approach is to look at all the parameters involved and how they interact with each other. This can be done either with a simple approach or a more complex analysis. On the simple end, a weighted prioritization matrix can be established using any parameters deemed significant. These might include, for instance, safety, loading condition, reliability of the radiometric measurement, and a history of similar components. Certain parameters can be given added value or "weight" as a total score is figured. In Table 9-3, the issue of personnel safety is given a weight of twice the other factors. A simple system like this, if used consistently, can become "smarter" with time if a feedback loop is incorporated. Although this approach is particularly useful for electrical components, it can be used for a myriad of mechanical equipment as well. Other factors, values, and weights can be used, depending on the needs of the thermographer.

A more complex analysis may be required in some instances. This might involve full

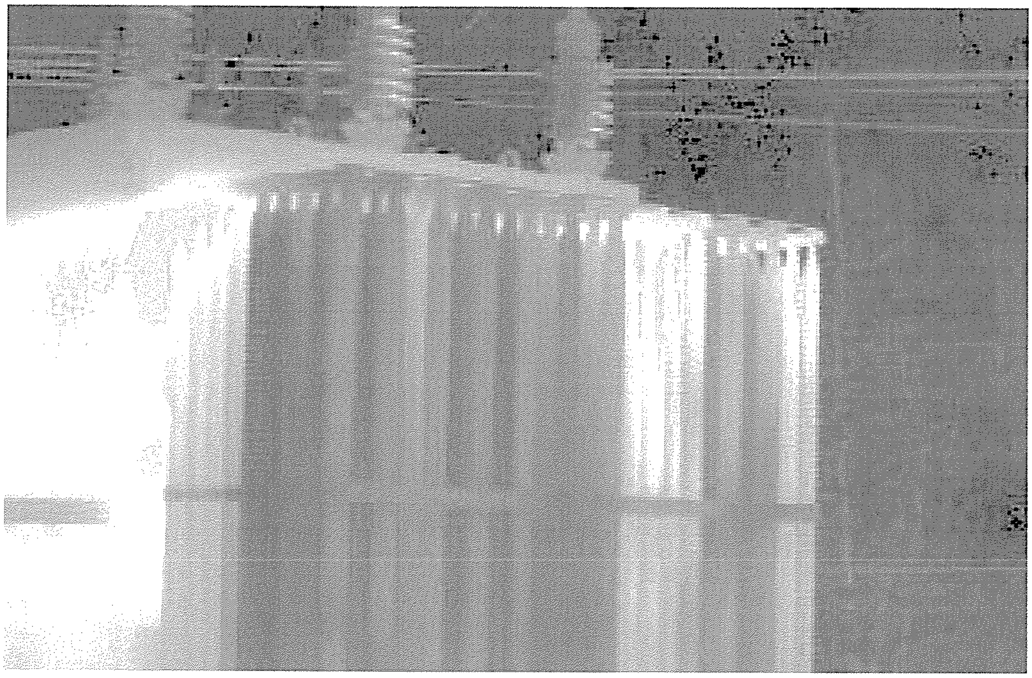


FIGURE 9-11.

TABLE 9-3 Priority of Parameters

	Greater chance →				
	1	2	3	x	=
Will a failure injure people?			*	2	
Is the component critical?					
Will loads increase?					
Will the wind decrease?					
Is the measurement unreliable?					
If it is reliable, is ΔT great?					
				Total	

*Immediate action required.

engineering studies and incorporate data from other sources or test methods. A volatile gas analysis, for instance, provides excellent indicators of various internal faults in oil-filled equipment such as transformers.

Because the consequences of not doing thermal electrical inspections are so great—production outages, decreased product quality, and the potential for injury or death—care should be taken to structure and implement a program that will achieve optimum results. Companies that do this are able to virtually eliminate unscheduled downtime due to electrical failures.

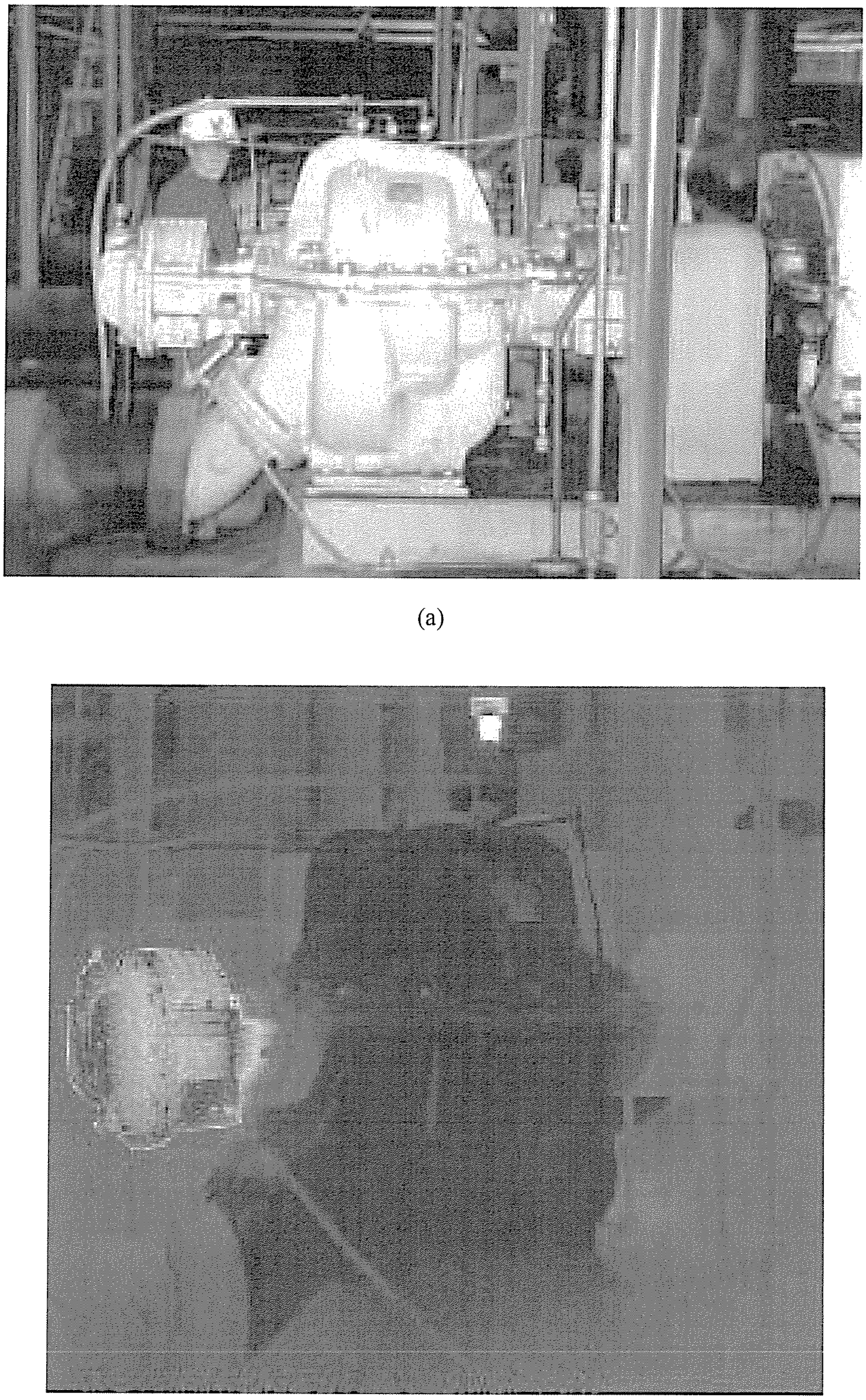
Mechanical Inspections

Mechanical inspections encompass a diverse variety of equipment. The technology has proven to be an invaluable tool for looking at motors, rotating equipment, steam traps, refractory, and tank product levels, among others. Most of these applications are qualitative in nature, often comparing the current thermal image to a previous one and understanding the cause and extent of any changes. In fact, conducting baseline inspections of new or rebuilt equipment has proven to be of particular value. As with electrical equipment, it is beneficial to establish inspection routes and periodic frequencies based on needs and resources.

Approximately 90% of the electricity used in the United States passes through electric motors. Although there are a number of excellent means to monitor the electrical and mechanical condition of motors, infrared has proven particularly useful as a fast screening device. High resistance, abnormal current flow, or excessive friction produces heat. If problems are indicated by one of these abnormal thermal signatures, other testing is often implemented to determine the exact nature of the problem.

Thus, the abnormal heating of a misaligned motor coupling usually precedes a measurable vibration signature. Left unresolved, the problem will be compounded as it wears on the motor bearing itself. Many problems that are related to the motor's electrical system also have characteristic thermal signatures. An internal short caused by a breakdown of insulation on motor windings will result in an increased temperature internally, as well as on the motor casing.

Heating of bearing surfaces caused by abnormal friction can provide an excellent indicator of the location and nature of many problems for all types of rotating equipment. The pump bearing in Figure 9-12 shows a typical pattern of an overheating bearing, in this



(a)

(b)

FIGURE 9-12 Pump. (a) Photograph; (b) thermograph.

case due to lack of lubrication. As often as not, the problem stems from overlubrication rather than lack of it! Especially for low-speed equipment, such as trolleys on overhead conveyors, where vibration signatures may not be reliable, thermography has proved a boon.

Refractory Inspections

In a variety of applications where high-temperature refractory is used, such as in boilers, rotating kilns, and torpedo cars, infrared can be used to monitor outside skin temperatures. With this information, engineers can validate the condition of the insulation or back-calculate the thickness of remaining refractory. It is also possible to identify any hot spots related to refractory failure. Typically, refractory is inspected regularly with a frequency determined by age and the estimated consequence of failure. Figure 9-13 clearly shows a problem with the refractory in this powerhouse boiler, although the root cause will require additional investigation. Rotary kilns benefit from monthly inspections, whereas torpedo cars may require weekly inspections. Because they are under less stress, boilers are often inspected on an annual basis prior to shutdown. All refractory should also receive a baseline inspection at startup so that trends can be established from consequent inspections.

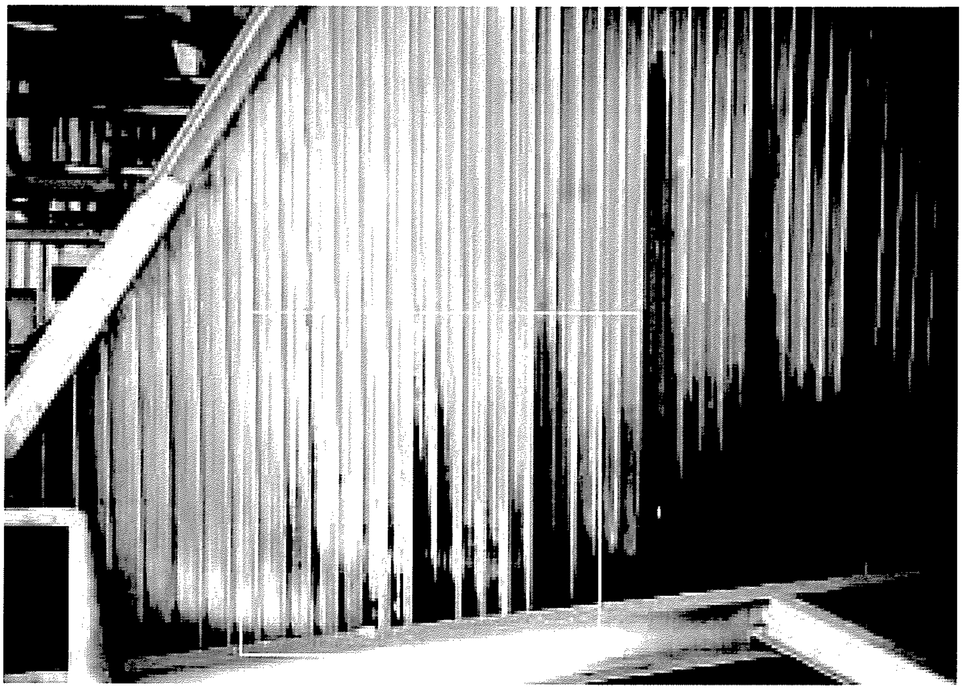
Steam Traps and Lines

Steam traps are highly susceptible to a "stuck open" failure mode, which can often be detected using infrared testing. Although airborne ultrasound is one of the primary methods of investigation, infrared has the advantage of being fast and able to be used even at a distance. A trap that is functioning properly will typically have a detectable temperature difference between the steam and condensate sides. This difference will temporarily disappear as it cycles. If both sides of the trap are warm, particularly if they are at steam temperatures, the indication is good that there has been a failure.

The inspection of steam lines using thermography is also valuable. Where insulation has failed on aboveground lines, a thermal signature is usually a clear indicator of the location of the problem. This is particularly true outdoors where water has saturated the insulation. Because there are more variables, buried underground lines are more difficult to inspect. Using a map of the system, it is possible to walk a steam line with a good handheld infrared system and locate both steam and condensate leaks. Signatures are generally clearer at night, but variations in ground moisture, bury depth, and soil type must be considered.

Heat tracing (both steam and electric) on process lines can also be inspected, except when insulation levels are very high, but this is rarely the case. More problematic is the use of aluminum or stainless steel sheet metal coverings over the insulation. These make inspections practically impossible due to the low emissivity (and consequent high reflectivity) of the coverings.

Many processes depend on maintaining internal temperature at a precise level. Operating temperatures may fall below these thresholds as a consequence of either the insulation or the tracing failing. In the confectionery and petrochemical industries, in particular, this can lead to blockage of a line as the transported product freezes. When blockages do occur, thermography can be used to help locate them while there is still a thermal difference between liquid and solid.



(a)

(b)

FIGURE 9-13 Outside wall of boiler. (a) Photograph; (b) thermograph showing problem with refractory.

Tank Level Verification

One of the most surprising, and usually easy, applications for thermography is locating or confirming product levels in tanks and silos. Although most have some sort of instrumentation, it often does not work or readings must be independently confirmed. As with line blockages, the differing thermal capacities of solids, liquids, and gases mean that they will change temperatures at different rates during a transient heat flow cycle. Gases change most quickly. In fact, in large outdoor tanks the sun can cause a detectable thermal change in a matter of minutes. The levels in the tanks in Figure 9-14 are clearly visible. In the late evening or early morning (before sunrise), the pattern would be reversed but the levels would still be visible.

Solid sediments typically change temperature next, as heat is conducted in or out of the material next to the tank wall. The sludge level in a large tank is evident in Figure 9-15. Next, any floating material, such as waxes, can usually be distinguished from the liquid. The liquid, because it may have a higher thermal capacitance and is also subject to convective heat transfer, typically takes the longest to change temperature. For tanks that are indoors, a normal diurnal swing in ambient air temperature is often enough to reveal the levels. Even in air-conditioned spaces, small ambient fluctuations may be enough. The materials inside many tanks are heated or cooled, and thus provide their own thermodynamic, driving force.

Uninsulated tanks and silos are quick to reveal their levels. Where insulation is present, the image may take longer to appear or may require some enhancement. Levels can be enhanced using simple active techniques like applying heat or by wetting the surface to

FIGURE 9-14.

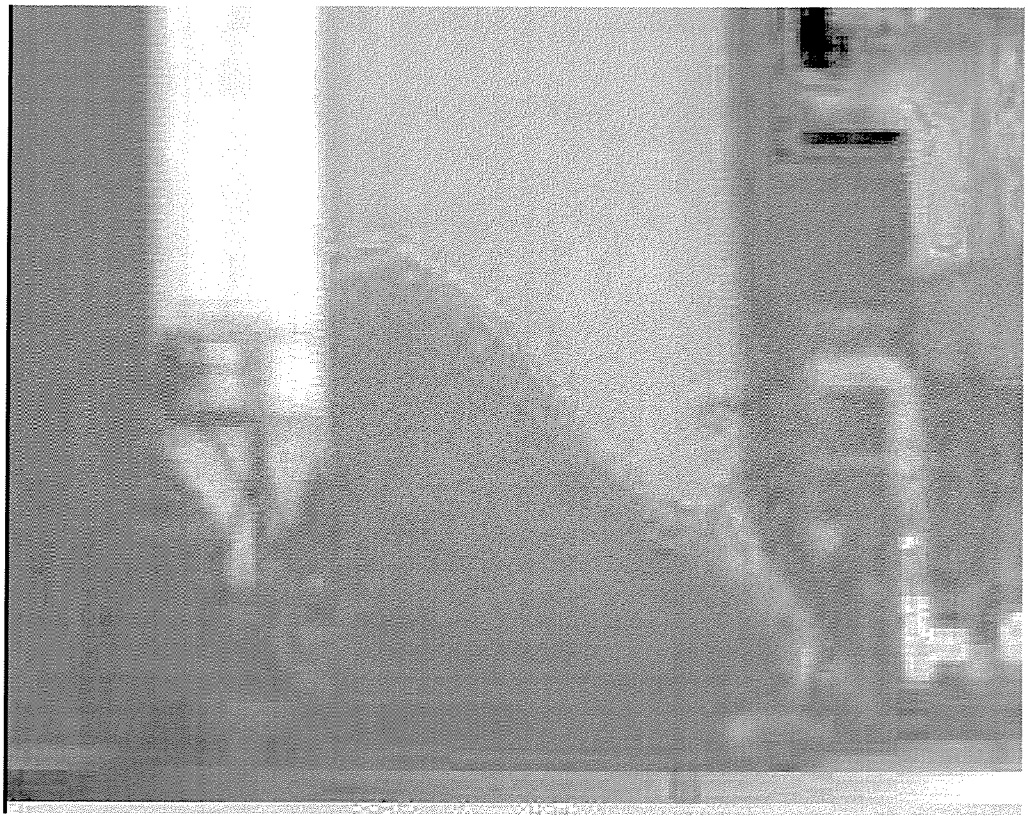


FIGURE 9-15.

induce evaporative cooling. Simply spraying water briefly on a tank is often enough to reveal several of the levels.

Where insulation is covered with an unpainted metal covering, difficulties may arise due to the low emissivity of the surface. Even in this case, however, a high-emissivity vertical stripe, such as paint or a removable tape, can be applied. The levels will be visible on the stripe.

There are numerous other applications for inspecting mechanical equipment thermographically. It is not possible to describe all of them, but it is useful to point out several generalizations. A good baseline inspection is critical. This should be done both at the transition during startup and also during the cool-down period. Be aware that all components of a machine will not go thorough transitional swings at the same rate. Other images should be made when the machine is operating at steady-state temperatures. Again, it is important to understand the impact of variations in conduction and convection and how they affect the surface patterns being seen. Subsequent images taken later on a periodic basis should be compared to this baseline data, noting any changes that may indicate problems. Careful data collection and record keeping is required for these methods to be effective.

Roof Moisture Inspections

The use of infrared roof moisture inspections has grown tremendously over the past decade as a cost-effective maintenance tool. There are literally tens of thousands of acres of flat commercial and industrial roofs throughout the world having a replacement value in the billions of dollars. For a number of reasons related to design, installation, and maintenance, most develop leaks within a year or two. While the damage caused by the actual leak may be substantial, the hidden long-term damage is usually far more costly. From top to bottom, a typical cross section of a flat roof is composed of the membrane, insulation, and a structural deck (see Figure 9-16). Water that enters a roofing system becomes trapped in the roof system, especially in the insulation, resulting in degradation of the system and its premature failure. By locating and replacing the wet roof insulation, subsurface moisture is eliminated, and the life of a roof can be greatly extended beyond the current average. Because water has such a high thermal capacitance, it is slow to change temperature during a transient heat flow cycle. During the daytime, the sun warms a roof. The dry insulation heats faster and to a higher temperature than does the wet insulation. In theory, it would be possible to locate the wet insulation during the daytime, but the sun typically heats the surface of the roof enough to mask these differences. After sunset, however, especially if the night is clear, the roof will begin to cool rapidly. Excessive wind may result in uneven cooling and confusing thermal patterns. At some point in the evening, usually an hour or two after sunset, the dry insulation will become cooler than the wet. It is possible, as this "inspection window" opens, to locate areas of wet insulation by their warmer thermal signature and characteristic patterns. Figure 9-17 shows a typical pattern associated with moisture intrusion into absorbent insulation; water has probably intruded into the system from around the vent pipe seen in the image.

Once patterns are seen, the roof can be inspected quite quickly, marking all wet areas with paint directly on the roof surface. If necessary, the actual presence of moisture in a wet area can be confirmed destructively. It is possible, on a fairly uncluttered roof, to inspect upwards of 500,000 square feet in a night. The inspection window will often remain open long into the night, until it is closed by wind or by the formation of substantial dew.

Typically, radiometric temperatures are not recorded during a roof moisture inspection. A videotape or individual images of all anomalies should be made. Most thermographers work in a black and white or saturation palette with the narrowest of span settings, i.e., high image contrast.

Exactly what pattern will be seen and when depends in large part on conditions and the type of roof insulation. Absorbent insulations, such as fiberglass, wood fiber, and perlite, yield clear signatures. These types of insulation are typically used in built-up roofs. A "board edge pattern," with its characteristic right angles, results because each board of insulation tends to saturate with water before spilling over onto the next one.

On the other hand, nonabsorbent foamboard insulation, which is often used in single-ply roof systems, is extremely difficult to inspect due to the fact that little water is trapped compared to other roof types, although still more than enough to cause degra-

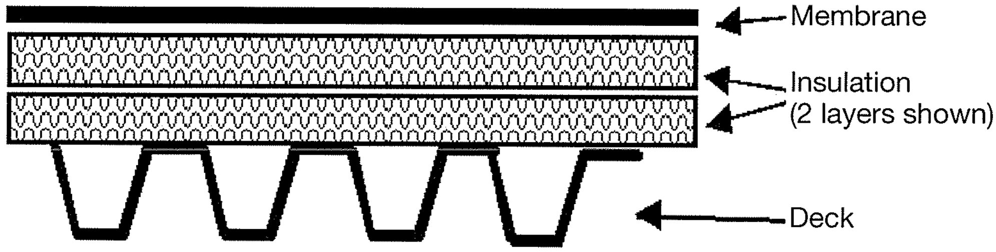


FIGURE 9-16 Cross section of a typical flat commercial roof. Image courtesy Snell Infrared, ©1999.

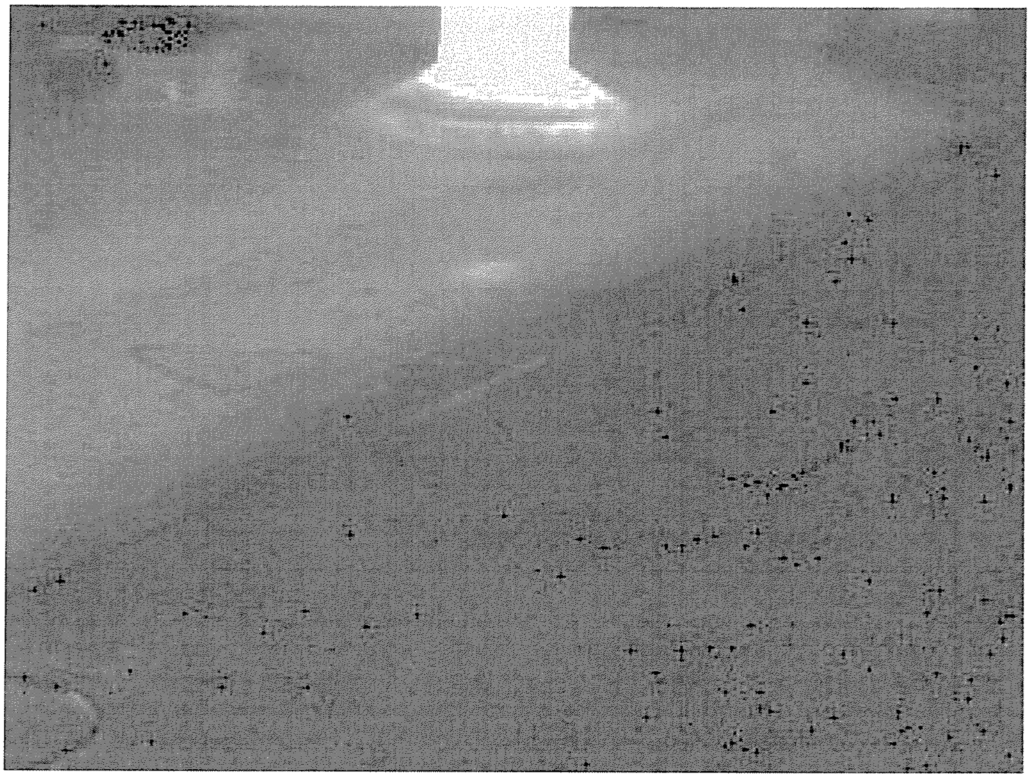


FIGURE 9-17.

dation. The roofing industry recommends installing an absorbent layer of insulation on top of foamboard, but this is often ignored. The unfortunate consequence is that infrared has limited value as an inspection tool on many foamboard roofs. Many single-ply roofs are also ballasted with pavers or a heavy layer of stone. These, too, can render infrared of little or no value. Clearly, the potential for inspection should be considered at the time of design!

Patterns are also influenced by weather. The roof surface must be dry or else evaporative cooling will prevent it from heating up adequately. If heavy cloud cover forms after sunset, the roof will probably not cool quickly enough for the inspection window to open. Wind in excess of approximately 10 MPH will quickly cool a roof and erase all thermal signatures of value. During cold weather, heat transfer from the building through the roof section can produce detectable thermal patterns in the wet insulation, once again resulting in these sections appearing warm. Very good results can usually be achieved with ambient air temperatures as low as approximately 40°F (4.4°C).

Rooftop conditions themselves also help determine patterns. A roof section that is in the shadow of a higher wall, for instance, will not be heated to the same degree as the unshaded areas of the roof. A west-facing wall, on the other hand, will reradiate its energy to the roof long into the night, preventing it from cooling adequately. Extra gravel or flashing material will stay warmer, sometimes masking over the wet insulation beneath. Where the roof has been previously repaired, differences in the type of insulation may cause variations in the thermal signature. Understanding these influences and the result they have on the thermal patterns is relatively easy for a qualified thermographer.

Roofs should be inspected shortly after installation to establish a baseline signature.

Another inspection would be warranted after any potentially damaging incident, such as a heavy hailstorm or hurricane. When leaks occur, as they are bound to, a quick follow-up infrared inspection will help locate the leak and indicate the extent of the wet insulation needing replacement. It is often possible to inspect a well-designed and maintained roof as infrequently as every 3–5 years.

Great care must be used during roof inspections to prevent accidents and unnecessary injuries. Look for safe access to the roof, and notify all local security officials of the inspection. Never work on the roof alone. Thermographers are most vulnerable because the brightness of their instrument displays prevents their eyes from adjusting to the low light conditions found on most roofs. It is critical to become familiar with, and adhere to, any relevant company or government regulations. Especially when people are within ten feet of the roof edge, it is important to be protected from an accidental fall by an appropriate barrier or fall protection device. Falling over the edge is not the only danger. Even stumbling over a small change in elevation can result in serious injury and a damaged infrared instrument.

A walking rooftop inspection is obviously very labor-intensive, relatively slow, and highly weather-dependent. A great deal of information can be obtained very quickly by performing an aerial infrared roof moisture inspection. Using either a helicopter or fixed-wing aircraft, the instrument can be flown at altitudes between 500 and 1500 feet from the roof, depending on local air traffic requirements and the spatial resolution of the test instrument. Obviously it is important to determine what the size of the smallest detectable area must be. If the conditions are right, data for millions of square feet can be acquired in an evening. Of course, bad weather or roof conditions can result in a costly cancellation of the mission.

Great care must be taken to identify the target roofs. A daytime flyover to conduct a visual preinspection is highly recommended. Most professionals videotape their survey and include some type of on-screen geographical positioning information. Once the data has been collected, analysis and reporting will require additional office time.

Although infrared has some limitations as an inspection tool (mainly that its use is weather-dependent), it is fast, thorough, and reliable. Unlike other methods, it also allows for the inspection of every square foot of roof. On roofs with absorbent insulation, the results of an infrared inspection are extremely accurate, measuring areas of wet insulation within several inches.

The potential savings from infrared roof moisture surveys are astounding. It is not unusual to extend the life of a roof by 50% or more. The life cycle cost drops significantly even when the life is increased by a year or two. As waste disposal costs continue to climb, especially for the hazardous materials that many roofs are constructed of, there is a strong incentive to repair and keep a roof in place. Even when the useful life of the membrane has been reached, it may be possible to install a new membrane over the existing insulation, again at great savings.

Building Energy Surveys

During the "energy crisis" of the late 1970s, thermography was used extensively for inspecting buildings. The technology lends itself to checking for both conduction (insulation) and convection (air leakage) problems as well as moisture intrusion and delamination of facades. When inspecting a building, it is vital to understand exactly how it is constructed. This is often not the same as looking at the drawings for the building. In fact, the thermographer's job is often to find performance flaws in a design or discrepancies between the design and its execution. A simple destructive examination often proves a valuable supplement for the thermographer.

Inspections are also simplest if accomplished during steady-state heat flow situations. Generally, a 20°F (11.1°C) temperature difference from inside to outside is needed for conduction problems to express themselves. Heating of the building's surfaces by the sun, however, can result in a reversal of heat flow and/or confusing patterns. These effects can be noticeable for up to 6 hours after the sun has left a building facade. For this reason, it may be difficult to conduct inspections during sunny days in warm or cold weather.

With optimum conditions, however, missing, damaged, or ineffective insulation, as well as the location of framing, becomes obvious. Patterns vary with the type of insulation and the exact conditions. The conductive inspection is best done from inside the building in order to minimize the effects of wind and sun, and because the inside wall is typically better connected thermally to the outside. If possible, an outside inspection is simpler because views of larger building faces can be achieved.

Any conditioned space is influenced by pressure differences caused by natural or forced convection. These result in air movement, which will often leave a characteristic thermal signature. Excessive air leakage can be identified with thermography, even when temperature differences are only a few degrees. During the heating season, signatures will be seen as cold streaks along the interior building surfaces or warm "blooms" on the outside of the building where heated air is exfiltrating. Some air movement may be evident inside the walls, even interior or insulated exterior walls. By artificially inducing a pressure difference on the building using the HVAC system or a device called a blower door fan, air leakage patterns can be enhanced and to some extent quantified.

Although the inspections of residential-scale buildings are quite straightforward, those of large commercial units can be more complicated, although the returns on the investment, which can be huge, usually warrant a thorough inspection. When possible, such buildings should be inspected during construction as each floor is closed in, insulated, and the relevant finish installed. This allows for design or construction problems to be identified and corrected before the entire building is completed and occupied.

Reducing excessive energy consumption is important, but, generally, a well-planned inspection will also increase occupant comfort, which may also lead to reduced energy use. Several case studies have documented not only an overall reduction in energy use, but more importantly, a reduction in peak use or the size of the system required to condition the space. Other issues may be even more important, such as minimizing unwanted moisture condensation and consequent mold blooms, eliminating the undue buildup of ice on the roof, checking air circulation in conditioned spaces, and preventing the plumbing from freezing.

8. ADVANTAGES AND LIMITATIONS

Previous discussion has revealed many of the advantages and limitations of infrared thermography. In some applications, thermography has proven itself as an inspection technique that is highly effective and very easy to use, whereas other applications may require sophisticated analysis.

Probably the two advantages thermography has over many other inspection techniques is that it is fast and it can create a thermal image. For many applications, an experienced and trained thermographer can make a determination of condition almost immediately upon viewing the thermal image with the right equipment, and good thermographers can create an excellent thermal image in seconds.

Today's equipment is extremely capable of doing amazing things. Radiometers are capable of accurate noncontact temperature measurement. Thermal imaging systems can resolve temperature differences of less than 0.18°F (0.1°C). The spatial resolution of the latest imaging systems provides such detail that many thermographers are forgoing capturing a visual image. In-camera processing allows sophisticated field analysis in a package that weighs less than 5 pounds.

As has been seen, thermography is a very versatile inspection method. The applications where thermography is effective are numerous. The aerospace industry is now augmenting, and in some cases supplanting, ultrasonics and radiography for determining the location of subsurface flaws and inclusions in state-of-the-art composites. Using similar techniques, a roofing contractor can locating areas of wet roof insulation for replacement. From identifying production problems in printed circuit boards, to finding loose connections in electrical systems, to the thermal mapping of complex industrial machines, thermography's list of applications is large and diverse. Where heat is a by-product of a process, or where an object undergoes a thermal cycle, thermography may very well have the ability to provide information about the operation and/or the internal integrity of a component.

The limitations of the technology can be summed up rather quickly. Only the surface of an object can be seen thermally. The thermal pattern is the result of either subsurface differential heat transfer or heat reflecting off the surface. As discussed, some material surfaces are so thermally reflective that they require preparation with a high-emissive coating. If the reflective surface cannot be made more emissive, the subsurface condition may not be resolvable, or the internal temperature will have to be increased until the surface temperature exceeds the minimum detectable temperature difference of the thermal imager. The thermal image must be interpreted. This requires knowledge of the application along with training and experience in thermography.

9. GLOSSARY

Absolute temperature scale—Temperature scales that are measured from absolute zero.

Absolute zero—The point on the Kelvin and Rankin temperature scales that indicates zero. Commonly known as the temperature at which no molecular activity occurs.

Background—The radiating objects that are reflected by a surface to the infrared instrument, usually from "behind" the instrument.

Beaufort's Wind Scale—A simple scale developed by a sea captain named Beaufort that allows one to estimate wind speed based on visual indications, such as the characteristics of the waves or leaves on a tree. It is useful to thermographers who need to estimate wind speed at a specific location.

Blackbody—A surface that absorbs and reradiates all energy incident upon it. Perfect blackbodies do not exist, but surfaces that are close to blackbodies do exist and, if traceable to a standard source, can be used to check the calibration of a system.

Boundary layer—A thin layer of fluid that builds up next to a surface during convection. It reduces heat transfer in proportion to its thickness.

British Thermal Unit (Btu)—A unit of energy defined as the amount of heat required to raise the temperature of a pound of water one degree Fahrenheit at sea level (at standard pressure). A Btu is equal to approximately 1055.06 joules

Calorie—Commonly referred to as the amount of heat needed to raise the temperature of one gram of water one degree Celsius. The modern definition is the amount energy equal to about 4.2 joules. Its symbol is "c" or cal.

Cavity radiator——A hole, crack, scratch, or cavity that will have a higher emissivity that the surrounding surface because reflectivity is reduced. A cavity seven times deeper than wide will have an emissivity approaching 0.98.

CCD—Charge coupled device; one of several types of electronic readout devices used in focal plane array systems.

Coefficient of thermal conductivity—See *Thermal Conductivity.*

Conduction—Heat transfer from warmer (more energetic) to cooler (less energetic) areas in a substance due to the interaction of atoms and molecules. This is the only way heat is transferred in solids. Heat transfer by conduction is also present in fluids (liquids and gasses) when atoms or molecules of different energy levels come in contact with each other.

Conductor—Loosely defined as a material that conducts heat well, usually in comparison with materials that don't conduct well (insulators). Most metals are good heat conductors.

Convection—The movement of fluids in response to a temperature difference.

Density—The mass of a substance per unit volume. Units are pounds per cubic foot.

Electromagnetic radiation—Vibrating electrical and magnetic fields in the form of waves that travel at the speed of light.

Electromagnetic spectrum—Electromagnetic radiation at all possible wavelengths from gamma rays to radio waves.

Emissivity—A property of a material that describes its ability to radiate energy by comparing it to a blackbody (a perfect radiator) at the same temperature. Emissivity values range from zero to one.

Film coefficient—See *Boundary layer.*

First law of thermodynamics—Energy in a closed system is constant; it can't be created or destroyed.

Forced convection—Convection caused by wind, fans, pumps, stirring or some other added force.

Foreground—The radiating objects that are "in front of" the camera and the target.

Fourier's law—The rate equation that describes conductive heat transfer, where energy equals thermal conductivity × area × temperature difference.

FOV—Field of view; a measure of the angular view for a given system and lens combination, usually measured in degrees.

Heat—Also known as thermal energy; energy transferred from regions of higher temperature to areas of lower temperature when a material changes temperature.

Heat of fusion—The latent heat released as a material changes from a liquid state to a solid state or absorbed as it changes from solid to liquid.

Insulator, insulation—Loosely defined as a material that restricts the flow of heat, especially in comparison with materials that conduct heat well (conductors).

IFOV—(Instantaneous field of view.) A measure of the smallest area that can be seen by the system at any one instant, i.e., spatial resolution.

$\mathbf{IFOV_{meas.}}$—(Instantaneous field of view—measurement). A measure of the smallest area that can be measured by the system at any one instant. It is a measurement, not a specification of spatial resolution.

InSb—("Ins-bee" or indium antimonide.) A photon detector material with excellent performance in the short-wave band.

Isotherm—A software function that outlines areas of apparent similar temperature or radiosity in the image.

Kilocalories—(One thousand calories.) Commonly used for expressing the energy value of foods. The symbol is Kcal or C.

Kirchhoff's law—For an opaque object, radiant energy absorbed equals radiant energy emitted.

Latent energy—Energy used to make or break the bonds in the phase of a material.

Latent heat of fusion—The energy that is used to create or break the bonds in the solid phase of a material.

Latent heat of vaporization—The energy that is used to create or break the bonds in the gaseous phase of a material.

Long-wave—Radiation with wavelengths between 8–15μm.
Natural convection—Convection occurring only due to changes in fluid density.
Newton's law of cooling—The rate of heat transfer for a cooling object is proportional to the temperature difference between the object and its surroundings.
Opaque—Nontransparent; $T = 0$.
Phase change—The process that matter goes through when it changes from a solid to a liquid to a gas.
Qualitative thermography—Thermal imaging using nonradiometric equipment or images to compare the radiation coming from various targets without making radiometric measurements of temperature.
Quantitative thermography—Thermal imaging using radiometric equipment (radiometers) or radiometric images to make radiometric measurements of the target temperature.
Quasi-steady-state heat flow—A thermal condition that is assumed to be steady-state for the purpose of analysis.
Radiation—The transfer of heat energy by electromagnetic waves or radiation.
Radiosity—All radiation coming from a surface, including that which is emitted, reflected, or transmitted.
Radiometric—An image or system that is calibrated to infer temperature measurements from the detected infrared radiation.
R-value—The measure of a material's thermal resistance. It is defined as the inverse of thermal conductivity.
Resistance—The measure of a material's ability to resist the flow of energy by conduction. Its value is the reciprocal of its conductivity.
Second law of thermodynamics—Heat cannot flow from a cooler object to a warmer one unless additional work or energy is added. Also stated as "heat cannot be totally changed into mechanical work."
Short-wave—Radiation with wavelengths between 2–6 μm.
Slit response function (SRF)—A test used to determine the smallest object that can be seen or measured by a system.
Solar glint—A phenomenon usually associated with short-wave sensing infrared systems whereby reflections of the sun off any shiny surface are very predominant.
Span—The set of temperature values that can be measured within a preset range. Thermal "contrast."
Spatial resolution—A specification, usually in milliradians (mRad), of the smallest size object that can be seen by the system.
Specific heat—The amount of heat required to raise a unit mass of a given substance by a unit temperature.
Spot radiometer—Nonimaging radiometric device that outputs a temperature or other radiometric measurement; also called infrared thermometer.
Spot size—The size of an area that can be measured at a given distance by a radiometric system.
State change—See *Phase change.*
Steady-state heat flow—A hypothetical thermal condition in which temperature difference across a material or system is unchanging.
Stefan–Boltzmann constant—5.7×10^{-8} W/m^2·K^4
Stefan–Boltzmann law—Total energy radiated by a blackbody surface is proportional to its absolute temperature to the fourth power.
Temperature—The relative measure of hotness or coldness of a material or substance.
Thermal background—The radiation sources "behind" the system that are reflected to the detector.

Thermal capacitance—The ability of a material to store thermal energy. It is defined as the amount to heat energy (in joules) required to raise the temperature of one kilogram of material one degree Kelvin. It is arrived at by multiplying a material's specific heat times its density.

Thermal conductivity——The symbol for thermal conductivity is "k." It is the measure of materials' ability to conduct thermal energy. It is defined as the rate at which heat (Watts) flows through a material of unit area and thickness, with a temperature gradient (Kelvin), over a unit of time. In SI units it is $W/m^2 \cdot K$.

Thermal resistance—The inverse of thermal conductivity. It is the measure of a material's ability to resist the flow of thermal energy.

Thermodynamics—The study of energy, how it changes and how it relates to the states of matter.

Thermography—From the root words for "heat pictures."

Thermograph—A visual picture of thermal data; a thermal image.

Thermographer—A person who is qualified to use thermography equipment.

Transient heat flow—A thermal condition in which the heat flow through a material or system is changing over time.

10. BIBLIOGRAPHY AND REFERENCES

1. *Proceedings of Thermosense.* 1980–1999, SPIE, Bellingham, WA.
2. ASTM Standards (misc.), available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959; phone 610-832-9500/ fax 610-832-9555.
3. *ISO 6781 Thermal Insulation, Qualitative Detection of Thermal Irregularities in Building Envelopes, Infrared Method.* American National Standards Institute.
4. *Manual for Thermographic Analysis of Building Enclosures (149-GP-2MP).* Canadian General Standards Board, Ottawa, Canada K1A 1G6.
5. *NFPA 70-B, Recommended Practice for Electrical Equipment Maintenance,* and *NFPA 70E, Standard for Electrical Safety Requirements for Employee Workplaces.* National Fire Protection Association, 1995. (NFPA, PO Box 9101, Quincy, MA 02269; 800-344-3555.)
6. *SNT-TC-1A-1996, Guidelines for the Qualification and Certification of Nondestructive Testing Personnel.* American Society for Nondestructive Testing (ASNT), 1711 Arlingate Lane, P.O. Box 28518, Columbus, OH 43228-0518; 800-222-2768.
7. W. L. Wolfe and G. J. Zissis (Eds.). *The Infrared Handbook,* 1993 Edition, ERIM, Ann Arbor, MI ISBN-0-9603590-1-X
8. D. P. DeWitt and G. D. Nutter. *Theory and Practice of Radiation Thermometry.* Wiley, New York, 1988.
9. F. P. Incropera and D. P. DeWitt. *Fundamentals of Heat and Mass Transfer, 3*rd edition. Wiley, New York, 1990.
10. J. M. Lloyd. *Thermal Imaging Systems.* Plenum Press, New York, 1982.
11. E. C. Guyer (Ed.). *Handbook of Applied Thermal Design.* McGraw-Hill, New York, 1989.
12. R. K. Stanley and P. O. Moore. *Nondestructive Testing Handbook, Volume nine: Special Nondestructive Testing Methods.* ASNT, Columbus, 1995.
13. X. P. V. Maldague. *Nondestructive Evaluation of Materials by Infrared Thermography.* Springer-Verlag, London, 1993.