CHAPTER 9

THERMAL INFRARED TESTING

1. HISTORY AND DEVELOPMENT

Humans have always been able to detect infrared radiation. The nerve endings in human skin can respond to temperature differences of as little as 0.0162°F (0.009°C). Although extremely sensitive, nerve endings are poorly designed for thermal nondestructive evaluation. Even if humans had the thermal capabilities of a pit viper, which can find its warm-blooded prey in the dark, it is most probable that better heat detection tools would still be needed. Thus, as inventive beings, we have turned to mechanical and electronic devices to allow us to become hypersensitive to heat. These devices, some of which can produce thermal images, have proved invaluable for thermal inspection in countless applications.

Sir William Herschel, who in 1800 was experimenting with light, is generally credited with the beginnings of thermography. Using a prism to break sunlight into its various colors, he measured the temperature of each color using a very sensitive mercury thermometer. Much to his surprise, the temperature increased when he moved out beyond red light into an area he came to term the "dark heat." This is the region of the electromagnetic spectrum referred to as infrared and recognized as the electromagnetic radiation that when absorbed causes a material to increase in temperature.

Twenty years later, Seebeck discovered the thermoelectric effect, which quickly lead to the invention of the thermocouple by Nobili in 1829. This simple contact device is based on the premise that there is an emf (electromotive force) or voltage that occurs when two dissimilar metals come in contact, and that this response changes in a predictable manner with a change in temperature. Melloni soon refined the thermocouple into a thermopile (a series arrangement of thermocouples) and focused thermal radiation on it in such a way that he could detect a person 30 feet away. A similar device, called a bolometer, was invented 40 years later. Rather than measuring a voltage difference, a bolometer measured a change in electrical resistance related to temperature. In 1880 Longley and Abbot used a bolometer to detect a cow over 1,000 feet away!

Herschel's son, Sir John, using a device called an evaporograph, produced the first infrared image, crude as it was, in 1840. The thermal image was caused by the differential evaporation of a thin film of oil. The image was viewed by light reflecting off the oil film. During World War I, Case became the first to experiment with photoconducting detectors (thallium sulfide) that produced signals not as a result of being heated, but by their direct interaction with photons. The result was a faster, more sensitive detector. During World War II, the technology began to expand and resulted in a number of military applications and developments. The discovery by German scientists that cooling the detector increased performance was instrumental in the rapid expansion of the infrared technology.

It was not until the 1960s that infrared thermal imaging began to be used for nonmilitary applications. Although systems were cumbersome, slow to acquire data, and had poor resolution, they proved useful for the inspection of electrical systems. Continued advances in the 1970s, again driven mainly by the military, produced the first portable systems usable for thermal nondestructive testing (TNDT).

These systems, utilizing a cooled scanned detector, proved both rugged and reliable. However, the quality of the image, although often adequate, was poor by today's standards. By the end of the decade, infrared was being widely used in mainstream industry, for building inspections, and for a variety of medical applications. It became practical to calibrate systems and produce fully radiometric images, meaning that radiometric temperatures could be measured throughout the image. Adequate detector cooling, which had previously been accomplished through cryogenics—using either compressed or liquefied gases—was now done much more conveniently using thermoelectric coolers. Less expensive tube-based pyroelectric vidicon (PEV) imaging system were also developed and produced. Although not radiometric, PEVs were lightweight, portable and could operate without cooling.

In the late 1980s, a new technology, the focal plane array (FPA), was released from the military into the commercial marketplace. The FPA employs a large array of thermally sensitive semiconductor detectors, similar to those in charge coupled device (CCD) visual cameras. This was a significant improvement over the single-element, scanned detector and the result was a dramatic increase in image quality and spatial resolution. Arrays of 320 × 240 and 256 × 256 elements are now the norm, and for specialized applications, arrays are available with densities up to 1000 × 1000.

Development of the FPA technology has exploded in the last decade. Both long- and short-wave sensing systems are now available in fully radiometric versions, as are systems with data capture rates as high as 500 frames per second and sensitivities of 0.18°F (0.1°C) or less. While the cost of radiometric systems has not dropped significantly, the quality has increased dramatically. The digital storage of data has allowed 12 and 14-bit digital files; the result is access to far more image and radiometric detail than ever imagined. Figure 9-1, taken with a typical FPA system, shows the clarity of detail available and its appeal for specialized work like this biological study of thermoregulation in ravens. (Because this book is printed with black ink only, much of the information conveyed by the original color images has been lost. Interested readers may obtain the original images from the author's website, www. snellinfrared.com.)

Although not radiometric, pyroelectric FPA systems have also been developed that provide excellent imagery at prices below $15,000. Costs have dropped so much that a fixed-lens pyroelectric system is now being installed in some model year 2001, luxury automobiles to enhance the safety of driving at night.

Concurrently, the use of computers and image processing software has grown tremendously. Nearly all systems commercially available today offer software programs that facilitate analysis and report writing. Reports can be stored digitally and sent electronically over the Internet.

With so many advances being made so rapidly, it is difficult to imagine what is next. Certainly, we will see continued development of new detector systems, most notably the quantum well integrated processing (QWIP) systems, with a promise of higher data capture speeds and greater sensitivities. "Tunable" sensors capable of capturing and processing images at several wavelengths will also become commercially available. Probably the greatest area of growth will be in the development of automated systems in which the infrared instrument, combined with a data processing computer, will capture and analyze data and provide control feedback to a process or system being monitored. Systems are already in use for certain processes in the cement, metals, and chemical industries and have significantly reduced failures and costs, while dramatically increasing quality and profits.

As equipment has improved, so has the need to qualify inspection personnel and stan-

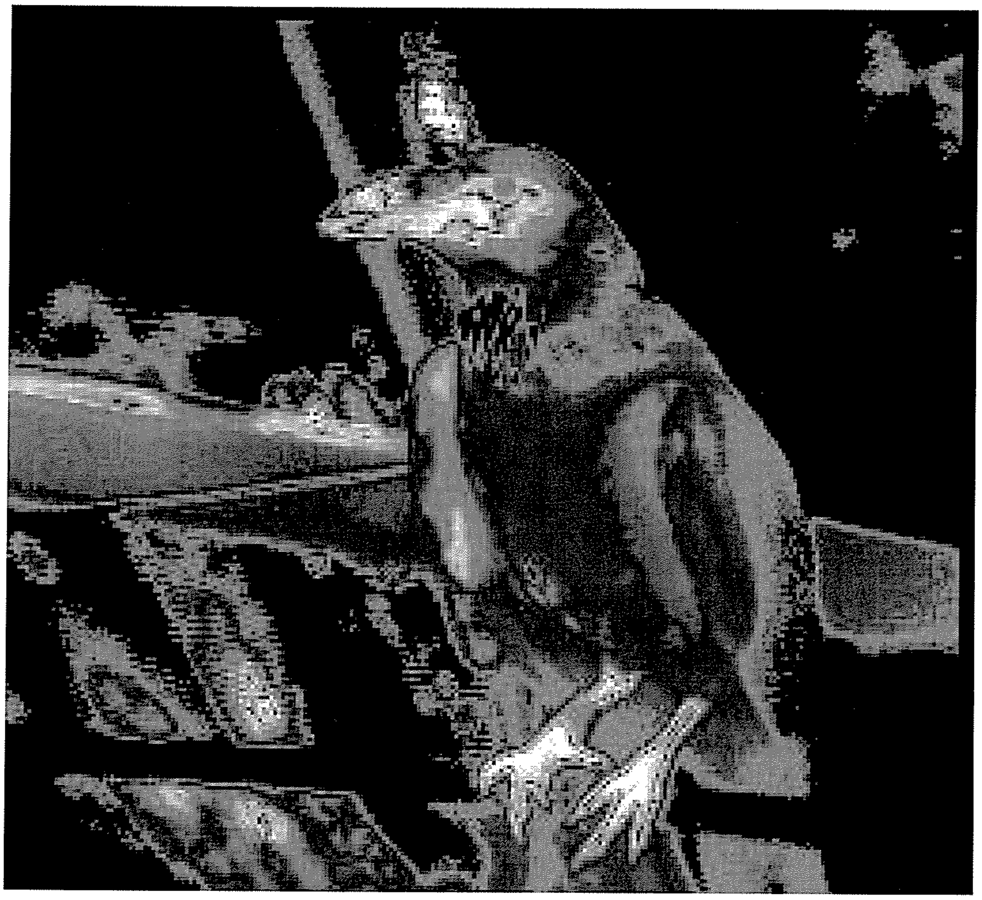


FIGURE 9-1.

dardize inspection methodologies. In the late 1980s, members of the American Society for Nondestructive Testing (ASNT) met to discuss a strategy for having infrared adopted as a standard test method. ASNT, a volunteer professional organization, is responsible for developing personnel qualification programs. Certification, which is conducted by the employer, is based on the practitioner having had the required training and experience, as well as passing written and practical examinations.

In 1992, infrared testing was officially adopted by ASNT and thermographers could for the first time be certified to a widely used, professionally recognized standard. Since that time, a number of large companies in the United States have begun certifying their thermographers in compliance with ASNT recommendations.

The development of inspection standards over the past two decades has also been an interesting process. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) developed a building inspection standard, which was later modified and adopted by the International Standards Organization (ISO). The American Society for Testing and Materials (ASTM) also developed several standards used for determining the performance of infrared systems, as well as standards for roof moisture and bridge deck inspections. Concurrently, a number of relevant ASTM standards were developed for radiation thermometry, which also has application to infrared thermography. The National Fire Protection Association (NFPA) has developed a standard, NFPA 70-B—the maintenance of electrical systems, which incorporates the use of thermography. Even though inspection standards continue to be developed, there are many applications at this time that lack inspection standards. Without standards, inspection results may lack repeatability, which often leads to misleading, perhaps even dangerous, analysis of data.

Access to the technology has become easy as the value of products has improved. Companies investing in developing solid programs, including inspection procedures and qualified personnel, have a distinct advantage due to access to the remarkable long-term benefits provided by infrared.

2. THEORY AND PRINCIPLES

To use today's infrared equipment, it is essential to understand the basics of both heat transfer and radiation physics. As powerful as modern equipment is, for the most part, it still cannot think for itself. Its value, therefore, depends on the thermographer's ability to interpret the data, which requires a practical understanding of the basics.

Thermal Energy

Energy can be changed from one form to another. For instance, a car engine converts the chemical energy of gasoline to thermal energy. That, in turn, produces mechanical energy, as well as electrical energy for lights or ignition, and heat energy for the defroster or air conditioner. During these conversions, although the energy becomes more difficult to harness, none of it is lost. This is the First Law of Thermodynamics. A byproduct of nearly all energy conversions is heat or thermal energy.

When there is a temperature difference between two objects, or when an object is changing temperature, heat energy is transferred from the warmer areas to the cooler areas until thermal equilibrium is reached. This is the Second Law of Thermodynamics. A transfer of heat energy results either in electron transfer or increased atomic or molecular vibration.

Heat energy can be transferred by any of three modes: conduction, convection, or radiation. Heat transfer by conduction occurs primarily in solids, and to some extent in fluids, as warmer molecules transfer their energy directly to cooler, adjacent ones. Convection takes place in fluids and involves the mass movement of molecules. Radiation is the transfer of energy between objects by electromagnetic radiation. Because it needs no transfer medium, it can take place even in a vacuum.

Transfer of heat energy can be described as either steady-state or transient. In the steady-state condition, heat transfer is constant and in the same direction over time. A fully warmed-up machine under constant load transfers heat at a steady-state rate to its surroundings. In reality, there is no such thing as true steady-state heat flow! Although we often ignore them, there are always small transient fluctuations. A more accurate term is quasi-steady-state heat transfer. When heat transfer and temperatures are constantly and significantly changing with time, heat flow is said to be transient. A machine warming up or cooling down is an example. Because thermographers are often concerned with the movement of heat energy, it is vital to understand what type of heat flow is occurring in a given situation.

Heat energy is typically measured in British thermal units (Btu) or calories (c). A Btu is defined as the amount of energy needed to raise the temperature of one pound of water one degree Fahrenheit. A calorie is the amount of heat energy needed to raise the temperature of one gram of water one degree Celsius. One wooden kitchen match, burned entirely, gives off approximately one Btu or 252 calories of heat energy.

The units to describe the energy content of food are also termed “calories.” These calories are actually kilocalories (Kcal or C) and are equal to one thousand calories (c). Various devices, such as a calorimeter or a heat flow meter can measure the flow of heat energy. These devices are not commonly used, except by scientists in research laboratories.

Temperature is a measure of the relative “hotness” of a material compared to some known reference. There are many ways to measure temperature. The most common is to use our sense of touch. We also use comparisons of various material properties, including expansion (liquid and bimetal thermometers), a change in electrical voltage (thermocouple), and a change in electrical resistance (bolometers). Infrared radiometers infer a temperature measurement from detected infrared radiation.

Regardless of how heat energy is transferred, thermographers must understand that materials also change temperatures at different rates due to their thermal capacitance. Some materials, like water, heat up and cool down slowly, while others, like air, change temperature quite rapidly. The thermal capacitance or specific heat of a material describes this rate of change. Without an understanding of these concepts and values, thermographers will not be able to properly interpret their findings, especially with regard to transient heat flow situations. Although potentially confusing, these properties can also be used to our advantage. Finding liquid levels in tanks, for example, is possible because of the differences between the thermal capacitance of the air and the liquid.

Latent Heat

As materials change from one state or phase (solid, liquid or gas) to another, heat energy is released or absorbed. When a solid changes state to a liquid, energy is absorbed in order to break the bonds that hold it as a solid. The same thing is true as a liquid becomes a gas; energy must be added to break the bonds. As gases condense into liquids, and as liquids freeze into solids, the energy used to maintain these high-energy states is no longer needed and is released.

This energy, which can be quite substantial, is called latent energy because it does not result in the material changing temperature. The impact of energy released or absorbed during phase change often affects thermographers. The temperature of a roof surface, for instance, can change very quickly as dew or frost forms, causing problems during a roof moisture survey. A wet surface or a rain-soaked exterior wall will not warm up until it is dry, thus masking any subsurface thermal anomalies. On the positive side, state changes enable thermographers to see thermal phenomena, such as whether or not solvents have been applied evenly to a surface.

Conduction

Conduction is the transfer of thermal energy from one molecule or atom directly to another adjacent molecule or atom with which it is in contact. This contact may be the result of physical bonding, as in solids, or a momentary collision, as in fluids. Fourier’s law describes how much heat is transferred by conduction:

$$Q = \frac{k}{L \times A \times \Delta T}$$

where

Q = heat transferred
k = thermal conductivity
L = thickness of materials
A = area normal to flow
ΔT = temperature difference

The thermal conductivity (k) is the quantity of heat energy that is transferred through one square foot of a material, which is one inch thick, during one hour when there is a one-degree temperature difference across it. The metric equivalent (in watts) is W/(m × °C) and assumes a thickness of one meter.

Materials with high thermal conductivities, such as metals, are efficient conductors of heat energy. We use this characteristic to our advantage by making such things as cooking pans and heat sinks from metal. Differences in conductivity are the basis for many thermographic applications, especially the evaluation of flaws in composite materials or the location of insulation damage.

Materials with low thermal conductivity values, such as wool, fiberglass batting, and expanded plastic foams, do not conduct heat energy very efficiently and are called insulators. Their insulating value is due primarily to the fact that they trap small pockets of air, a highly inefficient conductor.

The term R-value, or thermal resistance, is a measure of the resistance to conductive heat flow. It is defined, as the inverse of conductivity, or $1/k$. R-value is a term that is generally used when describing insulating materials.

The following are the thermal conductivities and R-values of some common materials:

Material	k (Btu × in/ft^2 × hr × °F)*	R (ft^2 × hr × °F/Btu × in)
Extruded polystyrene (1″)	0.20	5.0
Fiberglass batts (1″)	0.32	3.125
Soft wood (average)	1.0	1.0
Brick (average)	10.0	.1
Concrete (average)	13.0	.07
Steel	314.0	.003
Cast iron	331.0	.0036
Copper	2724.0	.00036

*Metric units for k are W/m × °C.

Another important material property is thermal diffusivity. Thermal diffusivity is the rate at which heat energy moves throughout the volume of a material. Diffusivity is determined by the ratio of the material's thermal conductivity to its thermal capacitance. Differences in diffusivity and consequent heat flow are the basis for many active thermography applications in TNDT.

Convection

Heat energy is transferred in fluids, either gases or liquids, by convection. During this process, heat is transferred by conduction from one molecule to another and by the subsequent mixing of molecules.

In natural convection, this mixing or diffusing of molecules is driven by the warmer (less dense) molecules' tendency to rise and be replaced by more dense, cooler molecules.

Cool cream settling to the bottom of a cup of hot tea is a good example of natural convection. Forced convection is the result of fluid movement caused by external forces such as wind or moving air from a fan. Natural convection is quickly overcome by these forces, which dramatically affect the movement of the fluid. Figure 9-2 shows the typical, yet dramatic, pattern associated, in large part, with the cooling effect of convection on a person's nose.

Newton's Law of Cooling describes the relationship between the various factors that influence convection:

$$Q = h \times A \times \Delta T$$

where

Q = heat energy
h = coefficient of convective heat transfer
A = area
ΔT = Temperature difference

The coefficient of convective heat transfer is often determined experimentally or by estimation from other test data for the surfaces and fluids involved. The exact value depends on a variety of factors, of which the most important are velocity, orientation, surface condition, geometry, and fluid viscosity.

Changes in h can be significant due merely to a change in orientation. The topside of a horizontal surface can transfer over 50% more heat by natural convection than the underside of the same surface.

In both natural and forced convection, a thin layer of relatively still fluid molecules

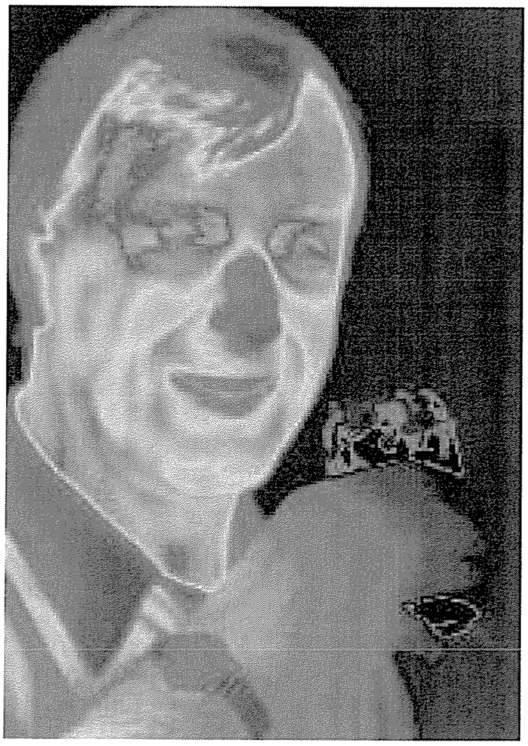


FIGURE 9-2.

adheres to the transfer surface. This boundary layer, or film coefficient, varies in thickness depending on several factors, the most important being the velocity of the fluid moving over the surface. The boundary layer has a measurable thermal resistance to conductive heat transfer. The thicker the layer, the greater the resistance. This, in turn, affects the convective transfer as well. At slow velocities, these boundary layers can build up significantly. At higher velocities, the thickness of this layer and its insulating effect are both diminished.

Why should thermographers be concerned with convection? As forced convection, such as the wind, increases, heat transfer increases and can have a significant impact on the temperature of a heated or cooled surface. Regardless of velocity, this moving air has no affect on ambient surfaces. Thermographers inspect a variety of components where an increase in temperature over ambient is an indication of a potential problem. Forced convection is capable of masking these indications.

Radiation

In addition to heat energy being transferred by conduction and convection it can also be transferred by radiation. Thermal infrared radiation is a form of electromagnetic energy similar to light, radio waves, and x-rays. All forms of electromagnetic radiation travel at the speed of light, 186,000 miles/second (3×10^{-8} meters/second). All forms of electromagnetic radiation travel in a straight line as a waveform; they differ only in their wavelength. Infrared radiation that is detected with thermal imaging systems has wavelengths between approximately 2 and 15 microns (μm). Electromagnetic radiation can also travel through a vacuum, as demonstrated by the sun's warming effect from a distance of over 94 million miles of space.

All objects above absolute zero radiate infrared radiation. The amount and the exact wavelengths radiated depend primarily on the temperature of the object. It is this phenomenon that allows us to see radiant surfaces with infrared sensing cameras.

Due to atmospheric absorption, significant transmission through air occurs in only two "windows" or wavebands: the short (2–6 μm) and long (8–15 μm) wavebands. Both can be used for many thermal applications. With some applications, one waveband may offer a distinct advantage or make certain applications feasible. These situations will be addressed in subsequent sections.

The amount of energy emitted by a surface depends on several factors, as shown by the Stefan–Boltzmann formula:

$$Q = \sigma \times \varepsilon \times T^4 \text{ absolute}$$

where
Q = energy transmitted by radiation
σ = the Stefan–Boltzmann constant (0.1714×10^{-8} Btu/hr $\times$ ft^2 $\times$ R^4)
ε = the emissivity value of the surface
T = the absolute temperature of the surface

When electromagnetic radiation interacts with a surface several events may occur. Thermal radiation may be reflected by the surface, just like light on a mirror. It can be absorbed by the surface, in which case it often causes a change in the temperature of the surface. In some cases, the radiation can also be transmitted through the surface; light passing through a window is a good example. The sum of these three components must equal the total amount of energy involved.

This relationship, known as the conservation of energy, is stated as follows:

$$R + A + T = 1$$

where
R = Reflected energy
A = Absorbed energy
T = Transmitted energy

Radiation is never perfectly transmitted, absorbed, or reflected by a material. Two or three phenomena are occurring at once. For example, one can see through a window (transmission) and also see reflections in the window at the same time. It is also known that glass absorbs a small portion of the radiation because the sun can cause it to heat up. For a typical glass window, 92% of the light radiation is transmitted, 6% is reflected, and 2% is absorbed. One hundred percent of the radiation incident on the glass is accounted for.

Infrared radiation, like light and other forms of electromagnetic radiation, also behaves in this way. When a surface is viewed, not only radiation that has been absorbed may be seen, but also radiation that is being transmitted through the target and/or reflected by it. Neither the transmitted nor reflected radiation provides any information about the temperature of the surface.

The combined radiation reflecting from a surface to the infrared system is called its radiosity. The job of the thermographer is to distinguish the emitted component from the others so that more about the target temperature can be understood.

Only a few materials transmit infrared radiation very efficiently. The lens material of the camera is one. Transmissive materials can be used as thermal windows, allowing viewing into enclosures. The atmosphere is also fairly transparent, at least in two wavebands. In the rest of the thermal spectrum, water vapor and carbon dioxide absorb most thermal radiation. As can be seen from Figure 9-3, radiation is transmitted quite readily in both the short (2–6 μm) and long (8–14 μm) wavebands. Infrared systems have been optimized to one of these bands or the other. Broadband systems are also available and have some response in both wavebands.

A transmission curve for glass would show us that glass is somewhat transparent in the short waveband and opaque in the long waveband. It is surprising to try to look thermally through a window and not be able to see much of anything!

Many thin plastic films are transparent in varying degrees to infrared radiation. A thin plastic bag may be useful as a camera cover in wet weather or dirty environments. Be aware, however, that all thin plastic films are not the same! While they may look similar,

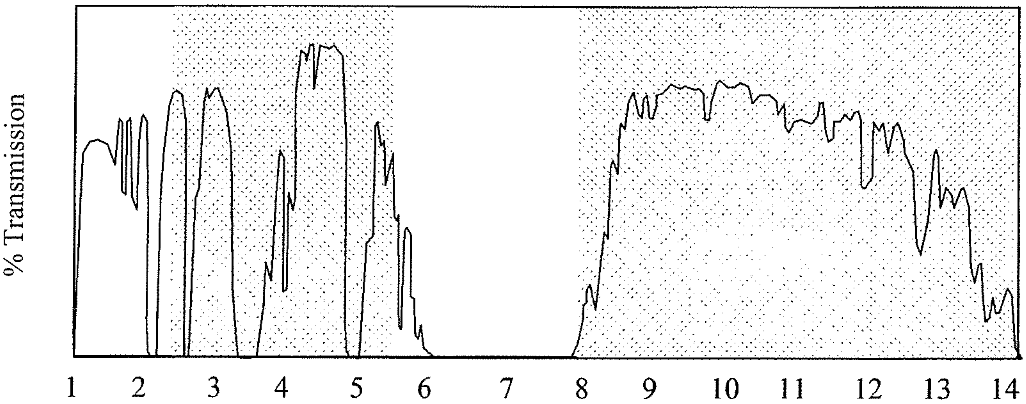


FIGURE 9-3.

it is important to test them for transparency and measure the degree of thermal attenuation. Depending on the exact atomic makeup of the plastic, they may absorb strongly in very narrow, specific wavebands. Therefore, to measure the temperature of a thin plastic film, a filter must be used to limit the radiation to those areas where absorption (and emission) occurs.

The vast majority of materials are *not* transparent. Therefore, they are opaque to infrared radiation. This simplifies the task of looking at them thermally by leaving one less variable to deal with. This means that the only radiation we detect is that which is reflected and absorbed by the surface ($R + A = 1$).

If $R = 1$, the surface would be a perfect reflector. Although there are no such materials, the reflectivity of many polished shiny metals approaches this value. They are like heat mirrors. Kirchhoff's law says that for opaque surfaces the radiant energy that is absorbed must also be reemitted, or $A = E$. By substitution, it is concluded that the energy detected from an opaque surface is either reflected or emitted ($R + E = 1$). Only the emitted energy provides information about the temperature of the surface.

In other words, an efficient reflector is an inefficient emitter, and vice versa. For thermographers, this simple inverse relationship between reflectivity and emissivity forms the basis for interpretation of nearly all of that is seen. Emissive objects reveal a great deal about their temperature. Reflective surfaces do not. In fact, under certain conditions, very reflective surfaces typically hide their true thermal nature by reflecting the background and emitting very little of their own thermal energy.

If $E = 1$, all energy is absorbed and reemitted. Such an object, which exists only in theory, is called a blackbody. Human skin with an emissivity of 0.98, is nearly a perfect blackbody, regardless of skin color.

Emissivity is a characteristic of a material that indicates its relative efficiency in emitting infrared radiation. It is the ratio of thermal energy emitted by a surface to that energy emitted by a blackbody of the same temperature. Emissivity is a value between zero and one. Most nonmetals have emissivities above 0.8. Metals, on the other hand, especially shiny ones, typically have emissivities below 0.2. Materials that are not blackbodies—in other words everything!—are called real bodies. Real bodies always emit less radiation than a blackbody at the same temperature. Exactly how much less depends on their emissivity.

Several factors can affect what the emissivity of a material is. Besides the material type, emissivity can also vary with surface condition, temperature, and wavelength. The emittance of an object can also vary with the angle of view.

It is not difficult to characterize the emissivity of most materials that are not shiny metals. Many of them have already been characterized, and their values can be found in tables such as Table 9-2. These values should be used only as a guide. Because the exact

TABLE 9.2 Emissivity Values*

Human skin	0.98
Black paint (flat)	0.90
White paint (flat)	0.90
Paper	0.90
Lead, oxidized	0.40
Copper, oxidized to black	0.65
Copper, polished	0.15
Aluminum, polished	0.10

*Values will vary with exact surface type and wavelength.

emissivity of a material may vary from these values, skilled thermographers also need to understand how to measure the actual value.

It is interesting to note that cracks, gaps, and holes emit thermal energy at a higher rate than the surfaces around them. The same is true for visible light. The pupil of your eye is black because it is a cavity, and the light that enters it is absorbed by it. When all light is absorbed by a surface, we say it is "black." The emissivity of a cavity will approach 0.98 when it is seven times deeper than it is wide.

From an expanded statement of the Stefan–Boltzmann law, the impact that reflection has on solving the temperature problem for opaque materials can be seen:

$$Q = \sigma \times \varepsilon \times T4 + \boldsymbol{(\sigma \times (1 - \varepsilon) \times T^{4\ \mathrm{background}})}$$

The second part of the equation (in boldface) represents that portion of the radiosity that comes from the reflected energy. When using a radiometric system to make a measurement, it is important to characterize and account for the influence of the reflected background temperature.

Consider these two possible scenarios:

- When the object being viewed is very reflective, the temperature of the reflected background becomes quite significant.
- When the background is at a temperature that is extremely different from the object being viewed, the influence of the background becomes more pronounced.

It becomes clear that repeatable, accurate radiometric measurements can be made only when emissivities are high. This is a fundamental limitation within which all thermographers work. Generally, it is not recommended to make temperature measurements of surfaces with emissivities below approximately 0.50, in other words all shiny metals, except under tightly controlled laboratory conditions. However, with a strong understanding of how heat energy moves in materials and a working knowledge of radiation, the value of infrared thermography as a noncontact temperature measurement tool for nondestructive evaluation is remarkable.

3. EQUIPMENT AND ACCESSORIES

Infrared systems can generally be classified as either thermal imaging systems or point measuring systems. Thermal imaging systems can be further subdivided into quantitative or radiometric (measuring temperatures) and qualitative or nonradiometric systems (thermal images only). Point measuring systems are also often termed "spot" or "point" radiometers and can be either hand-held or fixed mounted.

Qualitative thermal imaging systems are useful when radiometric temperatures are not required. Using these lower-cost instruments, it is possible to make thermal comparisons and thus distinguish thermal anomalies in equipment and materials.

Quantitative thermography involves the use of calibrated instruments. By using correction factors, accurate radiometric temperatures can be determined from the thermal image. Calibration, which is expensive to achieve or maintain, is best made for the specific temperature ranges and accuracy required.

Nonimaging radiometric measuring systems, called point or spot radiometers, are lower-cost instruments, which, although they do not give an image, can be valuable for many types of NDT. For limited areas and pieces of equipment, and when used properly, this equipment can provide accurate, real-time radiometric measurement across a wide range of temperatures. Typically, spot radiometers have emissivity correction capabilities.

Without an image, it can be difficult knowing the exact area the spot radiometer is measuring, possibly resulting in erroneous data. Some models include a laser-aiming device to help aim them. It should be carefully noted, however, that the area being measured is always much larger than the small spot illuminated by the laser. Newer models are available with a projected laser beam that also outlines the exact measurement area, alleviating any misunderstanding.

The waveband response of spot system detectors is typically wide enough to allow them to be filtered to detect narrow wavebands for specialized applications. This is particularly useful for such applications as measuring temperatures of thin plastic films or glass during manufacturing. Spot systems can also be fixed or mounted to constantly monitor process temperatures unattended. The data is typically fed back to a computer or control system. Such thermal data can be correlated not only to temperature, but also thickness, moisture content, material integrity, material type, or parts presence detection. When combined with visual automated systems, a powerful information system is available.

Even though spot radiometers are much less expensive than thermal imaging systems, they should not be thought of as a substitute for an imaging system. Both types of systems have their place in most NDT programs.

A variation of the spot radiometer is the line scanner. It is also very useful for many fixed mounted NDT inspections. This instrument employs a detector or small array of detectors that is then scanned along a line. If the line scanner views a moving object, an image can be created. Line scanners are particularly useful for viewing equipment that is moving at a constant rate because the image is built up one line at a time as the product passes by. Two common applications are viewing the refractory in rotating limekilns or the cross-roll moisture profile on the sheet in a paper machine. Line scanners, which can produce very high-quality images with excellent radiometrics, are less expensive than full imaging systems and lend themselves well to these types of automated inspections.

In the history and development section, it was noted that over the years three main types of infrared imaging systems were developed: scanners or scanning systems, pyroelectric vidicons (PEVs), and focal plane arrays (FPAs). While all three types are still in use today, the overwhelming majority of new equipment sales are the FPA systems.

It is useful to have a general understanding of how imaging systems work. The purpose of the imager is to detect the infrared radiation given off by the object being inspected, commonly called the target. The target's radiosity is focused by the thermally transparent optics onto a detector, which is sensitive to this invisible "heat" radiation. A response from the detector produces a signal, usually a voltage or resistance change, which is read by the electronics of the system and creates a thermal image on a display screen, typically a video viewfinder. In this seemingly simple process, we are able, without contact, to view the thermal image, or thermogram, that corresponds to the thermal energy coming off the surface of the target.

The first infrared imaging systems used a technique called "scanning" to create a full screen image using a single, small detector. A series of rotating or oscillating mirrors or prisms inside the scanner direct the infrared radiation from a small part of the scene being viewed onto the detector. The detector response results in the display of a portion of the field of view. Very quickly, the mirror or prism moves to scan another part of the scene with the resultant display. This process of making a series of single measurements happens thousands of times per second, so that a complete image is built up and viewed in what appears to be "real time," i.e., at 30 frames per second or greater.

For some types of detectors to respond quickly, accurately, and in a repeatable fashion (particularly photon detectors), they must be cooled to extremely low temperatures. Systems with the highest-quality images use liquid nitrogen (LN2) at –320.8°F (–196°C). The nitrogen is simply poured into an insulated container, called a "Dewar," that surrounds the detector. Under normal conditions, the detector will stay cold for between 2–4 hours before it must be refilled. Other cooling systems have employed a cylinder of very high pressure (6000 psi) argon gas as a coolant. As it is slowly released, the gas expands and cools the detector to –292°F (–180°C). Obviously, great care must be used in handling cryogenics. Because of these safety problems and the problems of dealing with cryogenic substances in the field, cryogenically cooled systems are seldom used anymore except in laboratory situations. Several types of noncryogenic cooling schemes have replaced them. While noncryogenic devices require a fair amount of power and have a limited life, their benefits make them much more attractive than cryogenic devices.

Historically, pyroelectric vidicon (PEV) designs have offered a lower-cost alternative to scanners, and many are still in use. While PEVs are not radiometric, they can produce a good quality image. In addition, they do not require cooling. The detector in a PEV system is a monolithic crystal that, when heated by the incoming radiation, changes polarity. An electron-scanning gun, similar to those used in older television cameras, reads this change, which then produces an electronic image of the thermal scene. PEVs are slower than scanners in their response by an order of magnitude. PEVs also need to be constantly moved or "panned," or have their signal chopped. At this time, PEV tubes are no longer being manufactured.

Focal plane array (FPA) systems, which use a matrix of detectors to sense the infrared radiation, have a much higher spatial resolution than scanners or PEV systems. Typical detectors have pixel resolutions of 256 × 256 or 320 × 240. Resolutions of 512 × 512 pixels may soon be the norm. Although early FPA systems had to be cooled and were only sensitive in the short waveband, uncooled, long-wave sensing systems are now available.

There are several types of FPA systems. Short-wave instruments typically use photon detectors. These are cooled detectors, which actually count the number of photons received. Photon detecting systems now have very reliable radiometrics and excellent imagery. Long-wave systems use thermal detectors, which do not have to be cooled, although they must be temperature stabilized. While some are classified as "bolometers" and others "pyroelectric" or "ferroelectric," in all cases, thermal detectors are actually heated up by the incoming radiation. In the former this results in a resistance change, whereas in the latter there is a change in polarization. Very reliable radiometrics and excellent imagery is now possible from bolometers, but pyroelectric systems, while producing good quality images, have proven extremely difficult to be used radiometrically.

Infrared systems vary widely in price. At this time, spot radiometer systems start at under $500. Simple pyroelectric FPA instruments are in the range of $10,000 to $20,000. A complete radiometric system with software and normal lens is typically priced between $45,000 and $55,000. Although specifications and configurations vary, all these systems are designed to be used in typical industrial environments.

Infrared imaging systems are generally made up of several common components, including lens, detector, processing electronics, controls, display, data storage, data processing and report generation software, and filter.

Lens

Lenses serve to focus the incoming infrared radiation on the detector. Some infrared lens materials are actually opaque to visible light. Materials commonly used for lenses are germanium (Ge), silicon (Si), and zinc selenide (ZnSe).

Lenses can be of different focal lengths. A normal lens (with a field of view from 16° to 25°, approximately) is useful for most applications. Where inspection space is limited or a wide view required, the use of a wide-angle lens is recommended. Over longer distances, such as when viewing a disconnect switch in a substation, a telephoto lens may be warranted. Lens selection also impacts spatial and measurement resolution.

Coatings used on some lenses may contain small amounts of radioactive material (thorium). When using the system in a nuclear power plant, make sure to test the system for its baseline characteristics prior to entry.

Detector

The radiation is focused on the detector, where it produces a measurable response. Materials commonly used for detectors are platinum silicide (PtSi), mercury cadmium telluride (HgCdTe), and indium antimonide (InSb).

Processing Electronics

The response from the detector is processed electronically to produce a thermal image, a temperature measurement, or both.

Controls

Various controls on the system allow for adjustments to control the input of infrared radiation or the output of data. These typically include adjustments to range and span, thermal level, polarity, emissivity, and other temperature measurement functions.

Display

The processed data is output to a display, either an electronic viewfinder or a liquid crystal display (LCD) screen. Most instruments can display the thermal image in either grayscale or a color scale. The option of displaying the image in color while working in the field is important. Typically, radiometric systems also feature some very powerful analysis functions in the instrument itself, such as spot or area measurement and isotherm display. Again, these features often make field work simpler and more effective and are generally recommended.

Data Storage

Data is typically stored either as a still digital image or as an analog video image. Digital images are stored on floppy discs or PC cards. Digital voice data can also be stored with an image on some systems as well. PC cards, depending on storage capacity, can hold up to 1000 images with accompanying voice data.

It is also possible to output digital data directly to a computer using an RS-232 port, or to control the camera remotely using the same data port. Most systems also include an output for a standard video signal or an "S-video" signal that can be accepted by any compatible videocassette recorder (VCR), either 8 mm or VHS.

Data Processing and Report Generation Software

Most of the software that is available today is both powerful and very easy to use. Digital images are imported into the computer directly from the PC card and may be displayed in grayscale or with a variety of color palettes. Various color palettes can be selected. Adjustments can be made to all radiometric parameters, such as emissivity, background temperature, span, and level. Analysis functions may include spot, area, isotherms, and line thermal measurement, as well as size measurements. Analysis can extend beyond the image by displaying the numerical data in a spreadsheet or in various standard graphical forms such as a histogram.

When an image has been analyzed and processed, notation labels can be added and the image inserted into a report template. From there, the completed report can be sent to a printer, stored electronically or sent via the Internet.

Filters

Many thermographic applications depend upon the use of specialized filters to obtain a useful image or measurement. Before using filters, it is important to know the exact spectral response of the system as determined by the detector and the lens material. Responses within the long or short wavebands can vary from system to system. It is also important to understand how the selected filter interacts with the detector's response.

There are three generic filter designations:

1. High-pass filters, which allow only shorter wavelengths to pass
2. Low-pass filters, which allow only longer wavelengths to pass
3. Band-pass filters, which allow only a designated band of wavelengths to pass

Among the commonly used infrared filters are:

1. Flame filters. These suppress the peak flame radiation by excluding all radiation except that in the 3.8 μm band (for SW systems) or 10.8 μm band (for LW systems). This enables viewing through flames to hot objects beyond.
2. Sun filters. These suppress the undesirable "glint" affects of solar radiation in SW systems by excluding wavelengths below 3 μm.
3. Glass filters:
    - A. For short-wave systems one type of filter cuts off wavelengths below 4.8 μm. This allows the system to see the surface of the glass rather than through the glass.
    - B. Another glass filter allows a short-wave system to see only through glass by limiting radiation to a 2.35 μm band-pass.
4. Filters for viewing thin plastic films come in various band passes, depending on the exact plastic that is being inspected. Many thin plastic films are very transmissive in both long and short wavelengths. In all cases, the filter limits the radiation detected to that narrow band at which the plastic is opaque (nontransparent). The result is that the surace of the plastic can be seen and measured thermally. For polyethylene, a 3.45 μm band pass filter is used, whereas for polyester a 7.9 μm band-pass filter is used.

To maintain radiometric accuracy, the system must be calibrated for each filter used. Some systems automatically load the correct calibration curves when the filter is installed.

Infrared imaging systems have become much smaller over the past few years. The need to push a cart full of accessory equipment is becoming a thing of the past! With digital data storage densities as high as they are, and with the advent of affordable digital video, data storage is far simpler as well. Several of the instrument manufacturers have developed systems that also allow for bar-code reading. Some systems now allow downloading of images and data from previous inspections onto the imager's PC card, thus allowing for the viewing of archived images in the field.

As with any high-quality measurement tool, it is important to regularly check the calibration of an infrared instrument. It is a good habit to do this before and after each inspection by making a simple check of the temperature of the tear ducts of a person's eyes, which should be between 93–95 °F. For more exacting needs, the use of a calibrated reference blackbody is suggested. This traceable device has a temperature-controllable, high-emissivity target. Set the device for the thermal level at which the work is to be performed, allow it to stabilize, and check the calibration of the infrared instrument. When instruments are out of calibration or in need of a periodic calibration, they should be returned to the manufacturer.

When accurate radiometric measurements are required, additional data may need to be collected at the time the image is captured. Without this data, results may be misinterpreted or incorrect. The following environmental data may be important to collect:

- Ambient air temperature
- Background temperature
- Relative humidity
- Distance to the object being inspected
- Information about wind or other convection
- Impact of the Sun
- Specific operational conditions of the target

In addition, it is necessary to measure or estimate the emissivity of the object. In many instances, especially where safety allows, it may also be important to modify the emissivity of the surface being inspected to make measurements possible.

4. TECHNIQUES

Thermographers have developed a number of very useful techniques for expanding the use of the technology. These techniques can consistently result in higher quality data that is often simpler to gather than in the past. While some development time is often required when applying these techniques, the potential returns usually far outweigh the investment.

Some techniques involve specialized tools or equipment, for instance, lasers used to heat the sample, while others are simply better ways to enhance the flow of heat energy into or out of a sample, such as wetting the surface of a tank to make the level visible.

The basic strategy used in many thermal applications is quite simply termed "comparative thermography." It is no more complex than comparing similar samples or components under similar conditions. When the comparative technique is used appropriately and correctly, the differences between the two (or more) samples will often be indicative of their condition. For this method to be effective, the thermographer must eliminate all but one variable from the comparison. Too often, this simple but essential requirement is not achieved due to the complex circumstances of a test or the poor work habits of the thermographer. As a result, data can be inconclusive or misleading.

As an example, when inspecting three-phase electrical systems, it is very useful to compare the three phases. When the loads are even, which is often the case, all phases will appear thermally similar. However, when the loads are uneven, the phase carrying more load will appear warmer. Unless loads are measured and understood, such a thermogram is without value. Misdiagnosis in such a situation can, at best, result in an embarrassing loss of credibility or, at worst, the loss of valuable equipment.

Prior to inspecting a component or system, it is critical to determine what the normal or desired condition is. What is the "ground truth" or baseline? In some cases it may be easier to determine what the abnormal condition will look like. For flaw detection in aerospace composites, this determination can involve costly theoretical modeling as well as construction and extensive testing of sample test pieces. Understanding a baseline signature may also be simply intuitive. For example, Figure 9-4 shows an outside view of a heated building. The differences in the thermal patterns indicate the location of the framing and cross bracing, the areas that are insulated, and the areas where warm air is exfiltrating along the top of the wall.

In comparative thermography, it is useful to know as much as possible about the sample being tested, such as its construction, basic operations, known failure mechanisms, direction of heat flow, or history. Because this knowledge is often not readily available, the thermographer must become adept at asking clear, simple questions and, even more important, listening carefully to the answers. Many thermographers fail at either one or both of these tasks, and the work quality suffers. Communications skills are as important as technical skills, especially when working with unfamiliar equipment or materials.

A variation of comparative thermography is thermal mapping. Here, temperature distributions over large areas of a sample are compared with other, previously saved images. Baseline thermal mapping is used extensively for inspecting mechanical equipment where the thermal patterns may be complex and the signatures of failure often develop slowly over time. Figure 9-5 shows the degradation over time of a bearing on a motor due

FIGURE 9-4.

FIGURE 9-5.

to misalignment. Again, it is critical to eliminate, or at least understand, all the variables. Because the maintenance of many mechanical systems has a strong time-based component, techniques that trend the changes over time, such as vibration monitoring, are already widely used and accepted. While these thermal mapping techniques can reveal a very accurate and useful temperature trend of past performance, it is important to remember that trending only implies, rather than predicts, the future.

Thermal maps can be made of a material sample and compared to other known references, such as the failure point of a material or the temperature at which contact injury could occur. Thermal mapping has been used with remarkable success in this regard in the automotive industry to validate the temperatures of the sheet metal floor pan. Typically, this temperature data has been gathered via thermocouples, an expensive, time-consuming process that sometimes fails to identify the high-temperature problem areas. Thermal mapping, as can be seen in Figure 9-6, not only verifies that the thermocouple is in the proper location, it also provides a wealth of information about each and every location on the floor pan. These thermal maps can be compared to alarm limits, such as the melting point of the carpet, the ignition temperature of fuel, or the temperature at which a human could be burned.

Thermal mapping has also been used extensively in the electronics industry to look at printed circuit boards (PCBs). Printed circuit boards can be inspected during design, manufacturing, or repair. Typically, the inspection is conducted from the time a cold board is energized until it warms up to steady-state operating temperatures. Image subtraction, another valuable mapping technique, is often used in this application. Specialized image processing software is used to subtract the thermal image of the board being inspected,

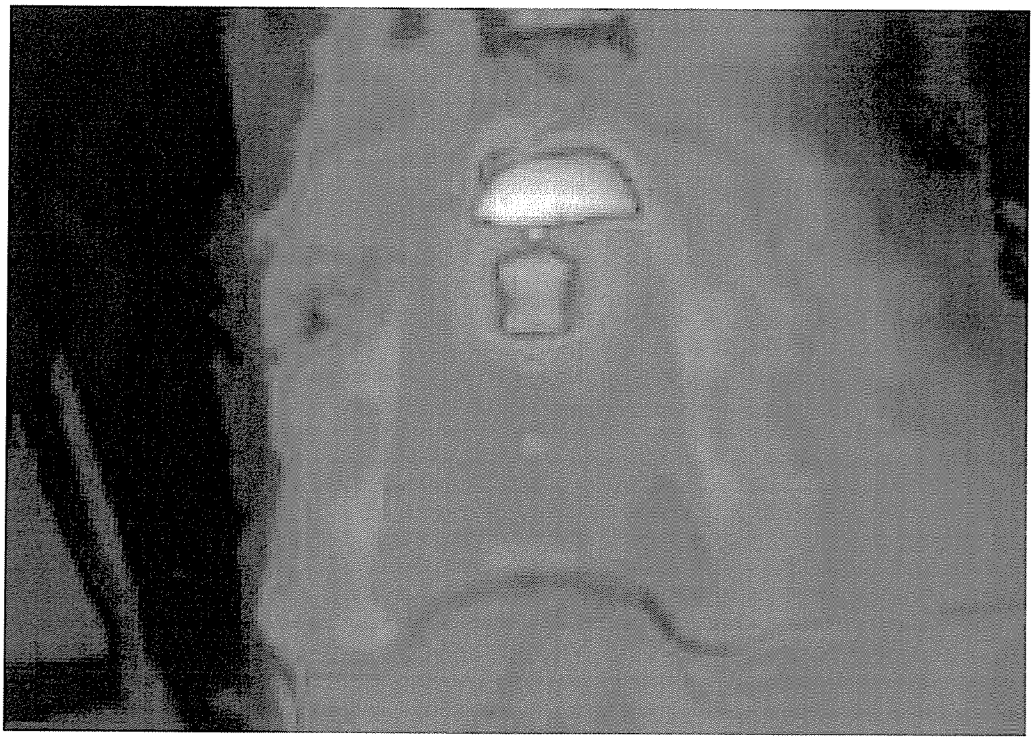


FIGURE 9-6.

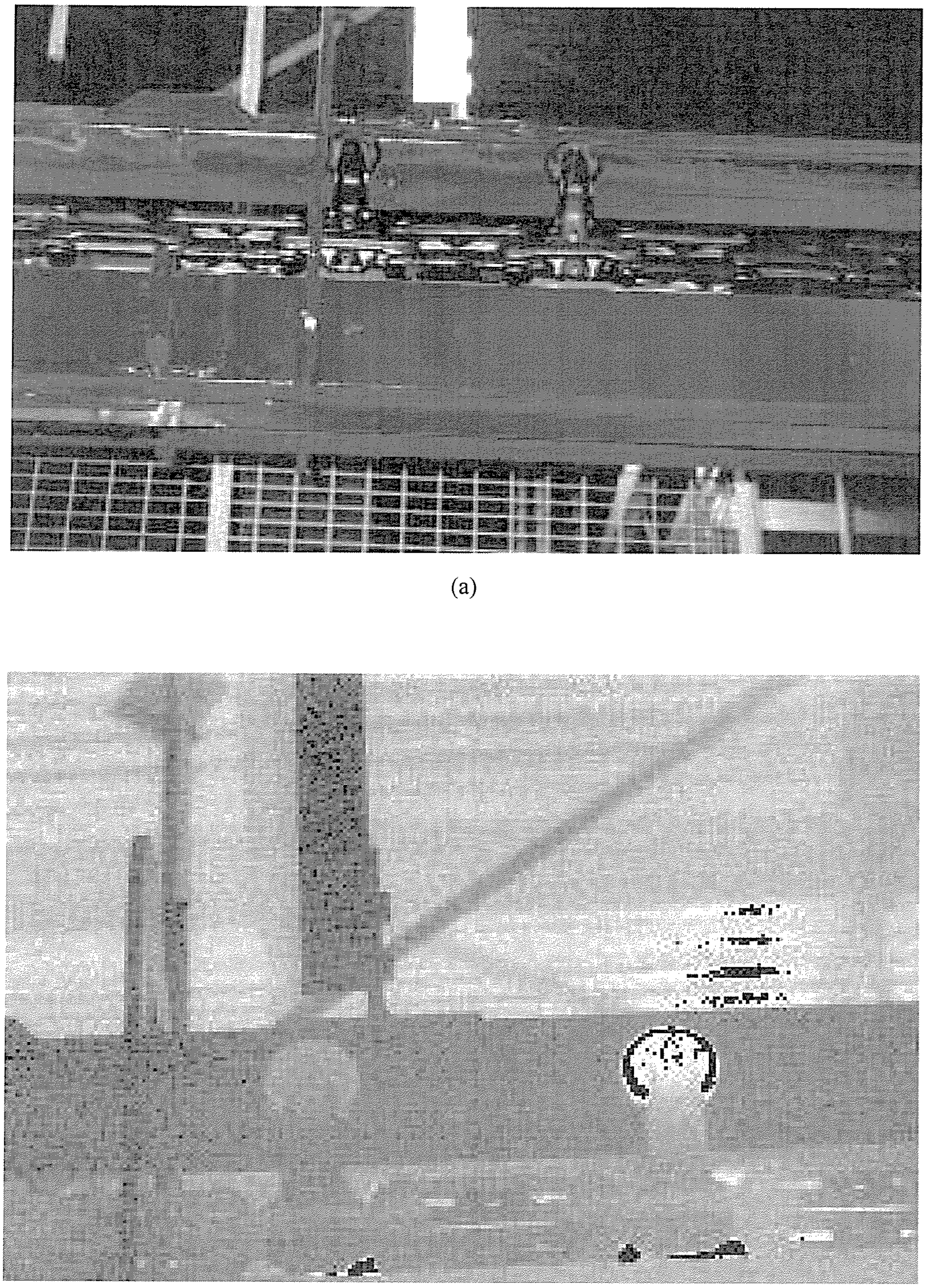
pixel by pixel, from a thermal image of a normal or "golden" board. The difference between the two images represents anomalous components or situations.

Manipulation of images using other software routines provides a wide range of techniques for improving thermal sensitivity, spatial resolution, and image contrast. Standard image manipulation routines, such as multiplication, offsetting, and edge enhancement, can be used to beneficially change the mathematical values of an individual or group of pixels. Some experimentation is required to get the best results, but with practice, remarkable detail can often be revealed in otherwise uncooperative images.

These techniques can also be pushed beyond the pictorial qualities of the image. The numerical values of each of the image pixels can be used in a spreadsheet or histogram function for analysis. Because the human eye is limited in what it can distinguish (approximately 256 shades of gray), these numerical analysis routines allow for a much greater depth of analysis. It is possible to distinguish as many as 70,000 discreet thermal levels with the latest infrared systems.

Image averaging, which can be done in the field "on board" many imaging systems, is a particularly powerful routine used to dramatically increase thermal sensitivity. During this routine, a specified number of images over time are averaged together into one image. Although real-time viewing is sacrificed, it is possible to dramatically reduce noise and note very small temperature differences.

One additional software-based comparative thermography technique utilizes either a saturation palette or isotherm function to highlight alarm limits. Data points that are above or below the set point in the image will automatically be portrayed as a different color; for instance, in Figure 9-7 the system has been adjusted so that anything over a pre-



(a)

(b)

FIGURE 9-7 (a) Photograph of equipment. (b) Thermograph of (a).

defined temperature will show up as red. As such, it is very easy to note for example, any bearings on a fast moving conveyor that are hotter than normal.

Isotherms can be used in a similar manner to highlight areas either above or below an alarm or indicate areas of similar apparent temperature. Isotherms in thermal images are analogous to elevation contours on a geographical map. They are often used to show an area on the side of a boiler, for instance, that corresponds to degraded refractory insulation. If the boiler operating conditions remain the same, during the next inspection these same isotherm settings will reveal any changes in the damaged area. This information allows for the planning of the material and labor that will be necessary during a repair shutdown.

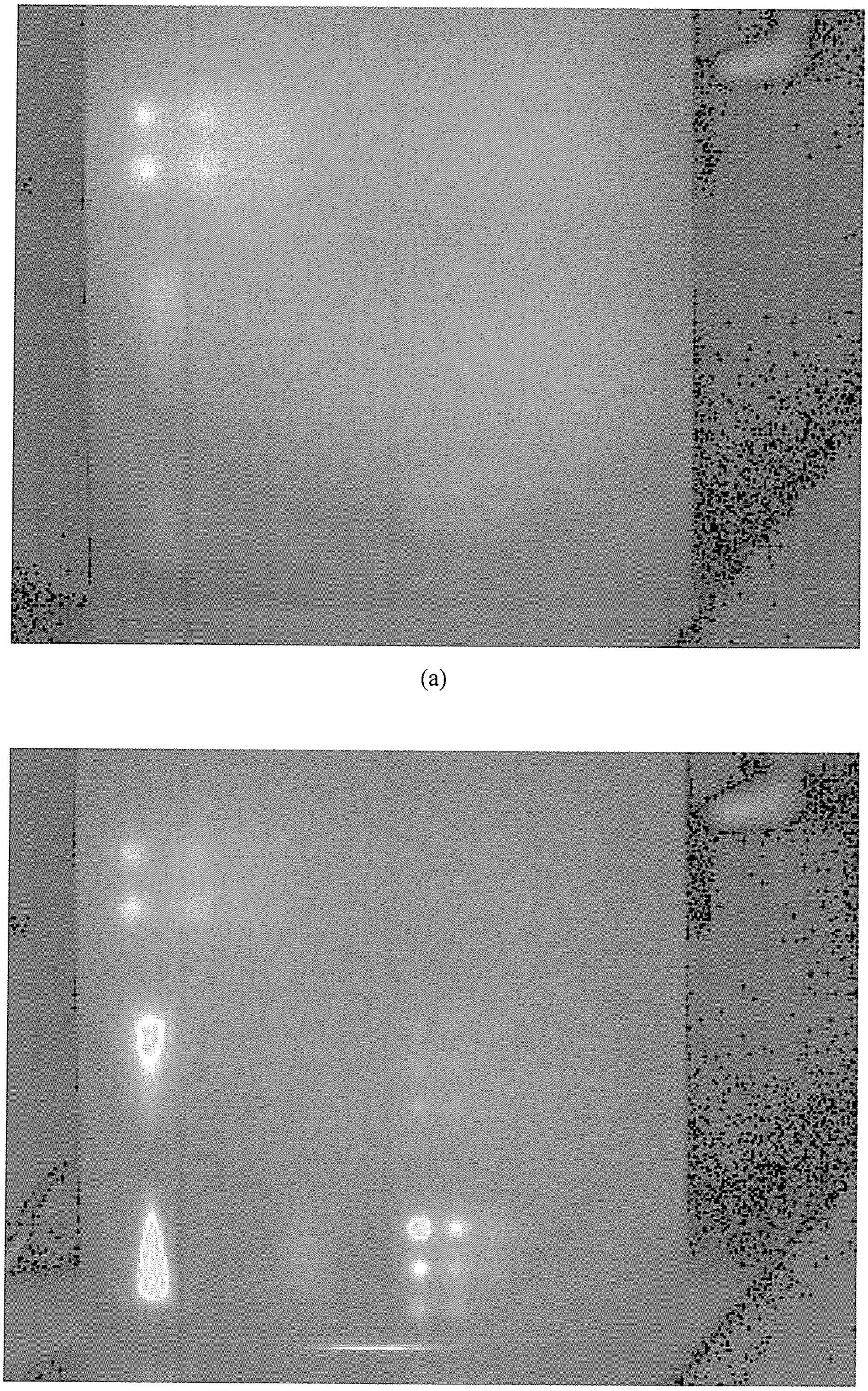
Another interesting variation on comparative thermography techniques is termed "the null method." The temperature of a material (a fiber leaving a spinneret, for example) is viewed against a blackbody surface of the exact same temperature in the foreground. As it becomes thicker or thinner than specifications allow, the fiber changes temperature and becomes visible against the blackbody. Machine logic can be developed to allow the device to control the fiber-making process.

Many techniques used by thermographers depend upon seeing thermal patterns caused by differences in the rates of conduction, heat capacitance, or thermal diffusivity (a combination of the first two properties). The differences between several materials, or between normal and flawed sections within a given material, become thermally obvious when these techniques are employed. For instance, when inspecting a graphite epoxy honeycomb composite, heat energy is injected into the sample using a high-powered flash of light. The surface absorbs much of the light, converting it to heat, which begins to flow into the material. Where the honeycomb is properly bonded, conductivity is high and the heat continues to flow. Around disbonded areas, the flow of heat energy is stalled by microscopic air gaps. Unable to move forward at the same rate as the bonded area, the heat remains in the vicinity of disbond and causes it to heat up. Using these "active" techniques, a disbond will appear warm when viewed from the heated side.

The use of active thermography has grown exponentially in the past decade, especially in the aerospace industry. High-speed data collection and improved spatial resolution enables us to now view the movement of heat energy in and out of a material. This process is sometimes described as a thermal wave, as the conductive heat movement through the material seems to flow in a wave-like fashion as a sequence of images are viewed rapidly. Thus, it is possible to view a sequence of thermal images—snapshots of heat flow in space and time—that show us not only the location of a flaw but its relative size and depth. Typically, the length of time required until a flaw can be observed is a function of the square of the depth of the flaw. This relationship implies that detectable flaws will be relatively shallow and that contrast will weaken at greater depths. Typically, the radius of the smallest detectable flaw will be at least one to two times larger than its depth. Figure 9-8 shows a graphite epoxy composite test panel that contains a number of flat bottom holes of different sizes drilled to various depths.

Inclusions in a composite material will typically have a different thermal capacitance than that of an unflawed sample. They are thus thermally obvious when the sample is made to change temperature. Active thermography techniques are at this time being refined and promise to become more powerful in the near future.

Flash lamps are the prime heating source for these new thermal wave techniques, but many other heat sources are employed in other applications of active thermography. Heat lamps and hot air guns have been used with great success on materials that are not highly diffusive. Microscopic and hairline cracks can be located by injecting heat into the sample across the face of the sample. As it reaches a crack, which has a higher resistance, the flow of heat energy is reduced. Similar results can be gained by subjecting the sample to



(a)

(b)

FIGURE 9-8 (a) Immediately after heat was applied to the surface. (b) 2–3 seconds later, showing heat energy "piling up" over subsurface flaws.

cold; for instance, inserting one end in a cold water bath, which causes heat to flow toward the bath.

On a larger scale, imaging the damage in laminated boat hulls is now common. The hull often consists of inner and outer shells with the space between injected with plastic foam insulation. The insulation bonds to the shells to form a very strong laminate. Unfortunately, impact damage to such structures seriously weakens them but is not readily visible to the eye. If, however, the boat is heated from the inside while in dry dock, the structural anomalies become thermally obvious when viewed from the exterior. Delaminations, which resist the flow of heat energy, will appear cooler, whereas voids, lacking insulation entirely, will usually appear warmer.

The heat of the sun is used as the heat source for many applications including roof moisture inspections, delamination of building facades, fluid levels in outdoor tanks, and the analysis of delaminations in bridge decks and runways. Again, patterns resulting from differential heat flow through the composite allow detection of the defects.

5. VARIABLES

At this time, most applications of infrared thermography require a qualified person to interpret the data. This is largely due to the many variables that are often difficult to understand and sometimes impossible to quantify. For the sake of discussion, in addition to the operator of the instrument, variables can be grouped simply into three categories. These relate to (1) the target, (2) ambient conditions of the system in which the target is operating, and (3) the instrument itself.

Target variables include emissivity, spectral characteristics, temperature, heat transfer relationships in and around the target, thermal capacitance, and diffusivity characteristics. Of these, emissivity is usually the most important. Unless it is very low (below 0.5, approximately), emissivity can be easily characterized and corrected for. As indicated previously, measurements of surfaces with emissivities lower than this are subject to unacceptable error. In an effort to avoid problems regarding absolute measurement of low-emissivity surfaces, many thermographers mistakenly measure the temperature difference between two similar surfaces using an emissivity value of 1.0. The results are nearly always wrong due to the fact that the radiational relationship between compared surfaces is exponential rather than linear.

Some targets, such as glass, thin plastic films, and gases, have transmissivities that vary significantly with wavelength. An understanding of the spectral characteristics of the target, and their relationship to wavelengths detected by the infrared instrument, is thus necessary. The target temperature may also influence emissivity. Polished aluminum, for example, has an emissivity of 0.02 to 0.04 at ambient conditions but at 1000°F (537°C) it is 0.05 to 0.10. The point to remember is to measure or determine emissivity using the conditions which you will encounter at the target.

The target's thermal diffusivity affects how quickly the material changes temperature as well as the shape and intensity of the resulting thermal patterns. Copper has a very high diffusivity, which means that the location of any change in temperature is difficult to pinpoint due to the speed at which heat diffuses through the material.

Among possible variables in ambient conditions are wind speed and direction, solar absorption, radiational cooling, precipitation, surface effects of evaporative cooling, ambient air temperature, background temperature, distance to object, relative humidity, and the presence of emitting/absorbing gases.

The impact of wind-driven convection, in particular, can be profound. Although precise corrections cannot easily be generalized, a commonly used rule of thumb suggests that a 10 MPH wind may reduce the temperature difference (ΔT) from a heated target to an ambient target by approximately one-half; a 15 MPH wind may reduce this ΔT by as much as two-thirds. Be aware that these rules of thumb are based on a very simple analysis; a real life situation will be much more complex and difficult to predict. Temperature data for outdoor electrical inspections are therefore rendered meaningless without local wind speed data.

Precipitation will usually result in evaporative cooling of the surface being inspected, but as freezing occurs—for example, of water absorbed into a masonry surface—latent heat of fusion is released, often with confusing consequences.

Ambient air temperature can add to or subtract from target temperature. An abnormally hot electrical connection, for example, can easily be 100 degrees warmer in the summer than in the winter if no other variables except ambient air temperature change. Especially for low-emissivity targets, a change in the background temperature can be significant. Whenever possible, it is best to have a thermally uniform background free of extremes. If gases with strong spectral emittance/absorptance characteristics, such as CO_2 or water vapor, are present, radiational transfer—and thus radiometric measurements—will be attenuated. Short-wave systems in particular are susceptible to attenuation by the atmosphere and, as a result, correction for relative humidity and distance to object are recommended.

The primary thermal variable relating to the target is whether transient or steady-state heat flow conditions exist. If heat flow is transient, knowing the position in the thermal cycle, as well as the rate of temperature change, is critical to interpreting the thermal image. Regardless of whether the heat flow is steady-state or transient, it is important to know the thermal condition of the target at the time of viewing with respect to the extreme thermal situation that the target may experience. Transfer from a heated building is usually considered steady-state during the late evening and early morning hours, but the effects of the sun can cause heat flow to reverse, even in very cold weather. During these transient situations, thermal patterns can be very confusing. Active thermography—based entirely on variations in transient heat flow—is typically controlled, making its impact much easier to understand.

There are other variables related to the infrared instrument, including the precise waveband detected, thermal sensitivity, detectivity, rate of data acquisition, dynamic range, field of view, spatial and measurement resolution, and system calibration. Short-wave systems are particularly sensitive to problems with solar glint or excessive solar reflection. For extensive outdoor work, long-wave systems are recommended. Long-wave systems, on the other hand, are generally more susceptible to error when used to measure temperatures of very low-emissive surfaces. In general measurements in either waveband produce similar results for temperatures from 14–266°F (–10 to 130°C).

The thermal sensitivity required for some applications is greater than for others. InSb detectors, for example, are favored over less sensitive PtSi detectors for some R&D applications. The detectivity (D^*) of a detector is a measure of its response relative to wavelength. Depending on whether or not this response coincides with the spectral characteristics of the target, one detector may be more or less useful than another. Detectivity also determines in part the rate at which data can be acquired. Most instruments operate at 30 or 60 Hz in order to be compatible with standard video frame rates. Using high-speed computers to store the data, InSb detectors allow for acquisition at rates in excess of 500 Hz over a reduced field of view.

The dynamic range of the acquired data is another important variable. Most of today's focal plane array (FPA) systems can store 12 or 14 bits of data for each image. The result is that a great deal of thermal data is available for analysis beyond the 8 bits that can currently be viewed as an image at any one moment. While it is still possible that data outside these large dynamic ranges may not be acquired, the chances are much less than in the past, when the maximum data acquisition was the 8 bits being viewed.

Using a thermal imager with appropriate resolution is essential. Imagine having to measure a kilometer using a meter stick, or a meter using a car odometer. Each infrared instrument has particular resolution characteristics determined by the detector size and the lens used, and the relationship between the two. On most instruments, the lens can be changed. This results in a change of the field of view (the area viewed by the instrument) as well as a change in spatial and measurement resolution. Spatial resolution—the smallest detail seen—is greater than the measurement resolution, which is the smallest detail that can be measured. It is not uncommon for an inexperienced thermographer to either miss small anomalies or to measure them inaccurately because of a failure to understand resolution. Knowing the specification for the instrument and lens being used, and working within those limits, is critical to accurate work.

Calibration of the instrument is critical to quantitative work. Calibration, usually conducted by the manufacturer, should be for the temperature range in which the instrument will be used. FPA detectors are particularly subject to nonuniform response over the array. Most manufacturers provide for some sort of nonuniformity correction (NUC). The appropriateness of these varies with need.

Where measurement is critical, correction should be at two points in the desired temperature range and should include the lens. Otherwise, a simple one-point correction inside the system is generally adequate. Many instruments make these corrections periodically during normal operations. FPA instruments are also subject to a change in response as the instrument changes temperature. Because they are temperature-stabilized rather than cooled, bolometers, in particular, are susceptible to extreme thermal influences. Where temperature measurement needs are critical, they may need to be allowed to thermally stabilize for up to twenty minutes when ambient conditions change significantly.

Simple field calibration checks are essential for day-to-day accuracy of a thermographer's work. These checks can be as simple as checking the temperature of a human tear duct at instrument startup and shutdown. For more critical work, the inclusion of a thermocoupled surface or a calibrated reference blackbody in the field of view may be warranted. The calibration of an instrument should also be checked against a calibrated reference blackbody on a periodic basis. The exact calibration frequency depends on the requirements of the application. Most manufacturers recommend recalibration on an annual basis. Calibration records should be kept on file.

Of course, the thermographers themselves are probably the greatest variable! Stated simply, the question is "are they qualified?" Qualification is based on appropriate training, experience, and testing. Especially with the industry-wide confusion over the use of the term "certification," variability in personnel qualification is dangerously diverse. Success for many applications also requires the operator to have additional related skills or experience. Regardless of the application, the thermographer must have mastered the basic communications skills of asking questions and listening, without undue "filtering" of the answers.

Today's instruments are so easy to use—literally pressing one button results in a remarkable image—that many operators fail to learn about the many other variables that are not optimized with that single button. Much of thermography is in fact, simply comparative or qualitative work. By comparing the target to another that is similar, it may be possible to minimize or eliminate the effect of one or more of these variables. Clearly, training and experience are fundamental to the process. As an example, it is not uncommon when inspecting a three-phase electrical system to find one phase being warmer than the other two. If the load is balanced, this heating would be considered abnormal, probably associated with an overload condition, an undersized conductor, or possibly heating from a nearby high-resistance connection. But under some conditions, normal loads can also be unbalanced, resulting in an identical thermal pattern. The skill and experience of the thermographer tip the scales in favor of the correct interpretation.

Quantitative thermography requires an even greater understanding of the variables impacting radiometric measurement, as well as a grasp of its limitations. It is vital to determine what margin of error is acceptable before beginning an inspection, and to work carefully to stay within those bounds. Too many thermographers believe that all data output from their instrument is accurate, or that the impact of all variables can be understood and measured. This is simply not true!

Considering the variables that have been discussed, it becomes obvious that there is considerable potential for error in both qualitative and quantitative thermography. Only careful consideration of all variables by a qualified and skilled thermographer can result in good data, and even then it is important to understand—and work within—the margin of error remaining.

6. EVALUATION OF TEST RESULTS AND REPORTING

Much of thermography is still highly dependent on the skill of the thermographer to conduct the inspection correctly, understand the limitations of the test, record all relevant data, and interpret the results properly. As we have seen in the previous section, the number of variables is staggering. Inspection personnel, as a consequence, must be adequately qualified for the task at hand.

It is generally recommended that a Level I qualified thermographer who is working under the supervision of a Level II thermographer collect data. The use of written inspection procedures developed with the support of a Level III thermographer is also critical to success. To write procedures or validate data, it is often necessary to set up other tests. It may be necessary to make emissivity measurements, for instance, of typical components before an inspection methodology can be developed. For NDT of composite materials, it may be necessary to develop costly test pieces to define the limits of detectability.

Procedures should detail the knowledge and skills required to conduct the inspection. As an example, to conduct an electrical inspection, many companies require the thermographer to have a basic working knowledge of electrical systems together with both electrical safety and CPR training. The procedures should also clearly spell out the weather and system conditions necessary for a successful inspection. Any limitations should be clearly spelled out, such as a caution for using short-wave sensing systems outside in the sunshine.

Evaluation of data is also the function of the Level II thermographer. Sometimes additional, supplemental testing using other test methods, as well as specific engineering or Level III support, may be required. On a limited basis, it may be possible for Level I personnel to make "pass/fail" assessments based on clearly written procedures. For instance, when conducting an inspection of boiler refractory, a Level I thermographer can mark refractory as "failed" when the surface temperature exceeds a value set forth in the procedures.

If personnel are qualified and good procedures are followed, evaluation of the data can proceed. A primary challenge is to determine the reliability of measurement, especially for radiometric values. Generally, radiometric measurements are not recommended when emissivity falls below 0.5. Even when qualitatively evaluating low-emissivity materials, one must proceed with caution. System variables, such as load and wind, must also be carefully accounted for, even if it cannot be done precisely.

Even after the data is correctly evaluated, the results must be clearly communicated to others in a report. Part of this process often requires educating the person who is reading the report. If they do not understand the potential problems associated with radiometric temperature measurements or conductive heat flow, for instance, serious misinterpretation of the results is a possibility. Generally, the problem for the thermographer is to have the customer understand the strengths and limitations of the technology or the findings. To what lengths the thermographer should go in the process varies, but is probably directly proportional to his or her investment in having the report make a difference in the inspection process.

Reports can take many forms. As a minimum, the report should include the thermographer's name; the instrument model and serial number(s); and relevant ambient conditions, such as wind speed and direction and ambient temperature. System conditions, such as load, component identification and location information, component emissivity, instrument parameter settings, and, in most instances, a thermal image and matching visual image, should also be included.

These details should be displayed in a way that does not clutter the report, but instead supports the presentation of essential information in an easily understood fashion. The best reports are intuitive in nature with a natural flow of data to support the thermal and visual images.

7. APPLICATIONS

Many of the applications for thermography are not considered mainstream NDE/NDT. Instead, they have come from other areas, such as industrial predictive maintenance and forensic investigation. Regardless of terminology, applications of thermography are nondestructive in nature, allowing the effective evaluation of both materials and systems.

The use of thermography in more traditional NDE/NDT has recently become more widely accepted. Growth has been concentrated in two industries in particular, electronics and aerospace, but new applications are being developed in many other industries as well.

Electronics Industry

In the electronics industry, thermography has become a powerful tool for design and manufacturing of integrated circuit boards (ICBs) as well as, in some cases, their repair. As designers have been pushed to make smaller boards, component density on the boards has increased and so have the problems associated with the heat that they produce. During the design stages, infrared is used to observe the distribution of this heat and its impact on components. The boards are next inspected in situ to evaluate the impact of any further heat flow conditions that might affect their performance.

The emissivities of many of the components on an ICB vary widely, and many are quite low. Two methods have been used successfully to reduce the difficulties of inspection. Boards are first "heat soaked" in an oven. A thermal map of the ICB is created. This map is then compared to the map of the board at operating temperature. The second method involves the application of a relatively high-emissivity, conformal coating to the ICB, thereby allowing direct thermal viewing and analysis.

At the manufacturing stage, infrared can be used to inspect the actual ICB being produced. The board being inspected is energized in a test stand. Its thermal signature is compared to that of a "golden board," meaning an ICB that performs within specifications, both during transient warm-up as well as after it has achieved steady-state operating temperature. Using computerized processing, one image is superimposed on the other, and an image subtraction routine performed. Any anomalous areas are immediately pinpointed. The same technique is used during the repair of more costly boards. The result has been a dramatic reduction in repair costs and an increase in quality assurance.

Aerospace Applications

Nowhere has the use of active thermography grown as it has in the aerospace industry. As more and more composite materials are used, the need to monitor quality of both new and existing stock has also increased. Techniques have evolved that range from simple handheld monitoring to automated inspections using sophisticated computer-based vision systems.

The basic premise of aerospace thermography is that properly laminated or bonded material will have relatively uniform thermal characteristics, including conductivity, capacitance, and diffusivity. Disbonds, delaminations, and inclusions of foreign substances can be located and characterized based on their anomalous thermal signatures. Typically, the component being inspected is heated from one side and viewed from either the same side or the opposite side, depending on the specific requirements. Of paramount importance is that the heat application should be relatively uniform across the area to be inspected. Even heating will promote heat flow through the material, perpendicular to the surface. Active thermography can be accomplished with a variety of heat sources, such as hot air guns, heat lamps, or flash lamps.

Several of today's active systems use a carefully designed system of high-powered xenon flash lamps as a heat source and a computer to capture the thermal data. Flash or thermal wave thermography, as it is often called, is now widely used for production and repair of both commercial and military aerospace components. During flash thermography, the pulse of heat energy is absorbed by the surface of the component. The heat conducts from the surface through the part at a uniform rate until it encounters a discontinuity. Because a delamination or disbond usually has a lower rate of conductivity, the heat over the disbond tends to build up, thus indicating the location, depth, and relative size of the discontinuity.

The wave continues to move into the component, rebounding from discontinuities within the cross section. Data is captured at rates of up to 500 frames per second (60 to 100 frames per second being typical), in order to capture the required detail. Because the entire process takes only a few seconds, the area covered by a single flash pulse—approximately four square feet—can be inspected in a very short time.

While much of this work is still being performed by technicians, new techniques are evolving quickly to utilize robots that can move the flash in a preprogrammed route over the entire aerospace structure. The data is then processed and analyzed by the computer system. Of course, considerable experimentation is required to set up such an operation, but, especially for manufacturing of new components, these automated systems hold great promise.

Also being inspected is moisture intrusion into honeycomb structures. Successful inspections have been conducted right after an aircraft has landed. Because water has a high thermal capacitance, it remains cool (from the high altitude) long after the rest of the plane has reached ambient conditions. Active thermography can also be used to locate moisture. The area of the material with no water intrusion heats evenly, whereas the areas with water appear cooler due to the high thermal capacitance of the water.

Electrical Inspections

Thermography is most widely used for inspecting the integrity of electrical systems. It has the distinct advantages of being fast and noncontact. While heat is not a perfect indicator of all problems in electrical systems, heat produced by abnormally high electrical resistance often precedes electrical failures. Much of electrical thermography work is qualitative, comparing the thermal signature of the similar components. This is quite simple with three-phase electrical systems—the heart of all utility, commercial, and industrial installations—where the phases should almost always appear similar. One or more components at a different temperature (usually warmer) suggest a problem is at hand.

The technique for inspecting electrical systems is quite straightforward. The component is viewed directly while energized. Particular attention is paid to any connection or point of electrical contact. These areas are most susceptible to high resistance and associated heat-related failure. It is possible to inspect a good-sized power substation, containing thousands of points of contact—each a potential problem—in less than an hour. Figure 9-9 shows a classic pattern associated with a loose or corroded connection point. Electrical current imbalances among phases are also readily seen. Often, these are considered normal, such as in a lighting circuit, while in other parts of the electrical system they can result in very costly failures, such as when a phase imbalance is caused by an internal fault in a large motor.

Although the application is straightforward and widely used, it is often used ineffectively. A good electrical systems thermographer must contend with several problems related to the component, the infrared instrument, and the interpretation of the data. Many electrical components have extremely low emissivities, resulting in the inability to accurately measure temperatures. Low emissivity also means that components must be very hot before they radiate enough energy to even be detected. Often, by the time you see a high resistance problem, some damage has already been done. Although it can represent a significant investment, more and more plants are placing high-emissivity targets on these critical components in order to increase the probability of early fault detection and improve the reliability of measurement.

Some thermographers advocate measuring nearby surfaces that have higher emissivities—the electrical insulation, for instance. While this can be useful, care must be taken. Most components have such a high thermal conductivity and diffusivity that a large thermal gradient can exist even over a small distance. This means that the measured temperatures may be much less than those at the site where high-resistance heating is occurring.

Temperature also varies widely as the electrical load on the system changes. The heat output from a high-resistance connection is predictable and can be correlated with changing loads; unfortunately, the temperature change of the connection is much less predictable. All that can be known is that as load increases, the temperature of a connection will increase at a rate that is greater than linear and less than exponential. The National Fire Protection Association (NFPA) standard *70-B, Maintenance of Electrical Systems,* recommends inspections be done with a 40% minimum load and, when possible, at the highest normal load. Even seemingly insignificant problems should be noted when inspecting systems that are temporarily under a light load.

Too many thermographers still try to inspect electrical equipment without opening the enclosures to directly view the components. Except where extenuating circumstances make a direct view impossible or dangerous, components must be viewed directly. Open-