LBNL-46590

Infrared Thermographic Systems

A Review of IR Imagers and Their Use

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July 27, 2001

Manuscript for eventual publication as a chapter in the

The Encyclopedia of Imaging Science and Technology

Joseph P. Hornak, Editor-in-Chief, John Wiley and Sons.

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INTRODUCTION

Infrared (IR) thermographic systems, or IR imagers, provide images that represent surface temperatures, or *thermograms*, by measuring the magnitude of infrared radiation emanating from the surface of an object. Because IR imagers see the radiation naturally emitted by objects, imaging may be performed in the absence of any additional light source. Modern IR imagers resolve surface temperature differences of 0.1ºC or less. With this high sensitivity, they can evaluate subtle thermal phenomena, which are only revealed in the form of slight temperature gradients. Some applications that employ IR thermography include: inspections for predictive maintenance, non-destructive evaluation of thermal and mechanical properties, building science, military reconnaissance and weapons guidance, and medical imaging.

Infrared thermography can be used as both a qualitative and a quantitative tool. Some applications do not require obtaining exact surface temperatures. In such cases, it is sufficient to acquire *thermal signatures*, characteristic patterns of relative temperatures of phenomena or objects. This method of qualitative visual inspection is expedient for collecting a large number of detailed data and conveying them in a fashion that can be easily interpreted. In contrast, accurate quantitative thermography demands a more rigorous procedure to extract valid temperature maps from raw thermal images. However, the extra effort can produce large arrays of high-resolution temperature data, which are unrivaled by contact thermal measurement techniques, such as using thermocouple wires.

A skilled operator of an IR thermographic system, or *thermographer*, must be conscious of the possibility that reflected or transmitted, rather than emitted, IR radiation may be emanating from an object. These additional sources manifest themselves as signals that appear to be, but are not actually, based exclusively on the temperature of the spot being imaged.

To understand the challenges and possibilities of IR thermography, it is first necessary to review the principles of physics on which it relies.

THEORY OF OPERATION

The fundamental principles that make IR thermal imaging possible begin with the observation that all objects emit a distribution of electromagnetic radiation that is uniquely related to the object temperature. Temperature is a measure of the internal energy within an object, a macroscopic average of the kinetic energy (the energy of motion) of the atoms or molecules of which the object is composed. Electromagnetic radiation arises from the oscillation of electrostatically charged particles, such as the charged particles found within an atom, the electron and the proton. Electromagnetic radiation propagates by means of the interaction between oscillating electric and magnetic fields and can sustain itself in the absence of any conveying media. The wavelength, the distance between successive peaks in the oscillations of the electric and magnetic field, can vary over a wide range representing a diverse range of phenomena including radio transmissions, microwaves, infrared (IR), visible and ultraviolet (UV)

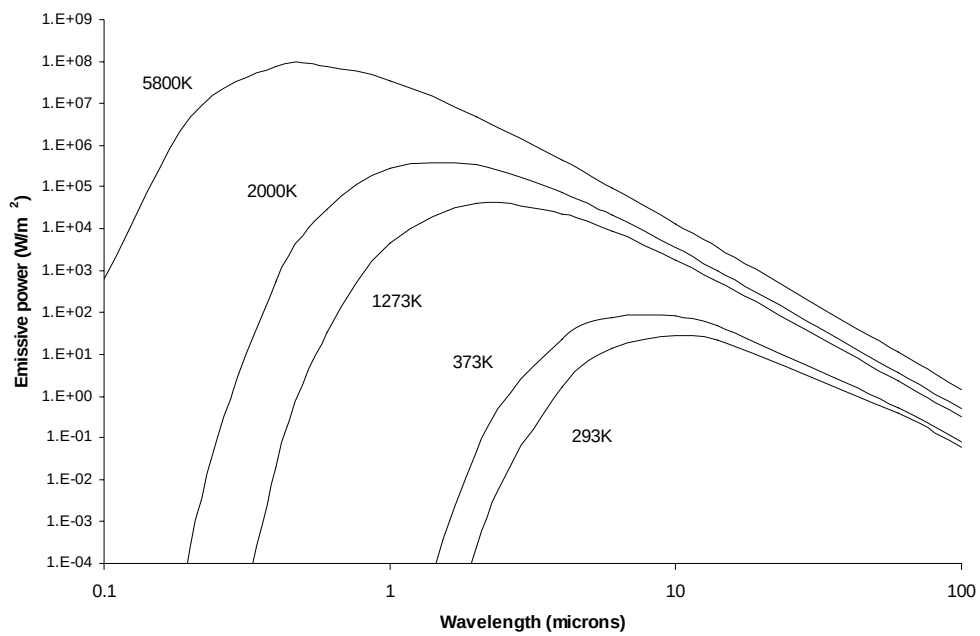
light, x-rays and gamma rays. The IR portion of the electromagnetic spectrum, which is of primary in interest to thermographers, includes wavelengths from about 1 to 100 μm.

The interaction of materials with radiation of different wavelengths is extremely varied. Electromagnetic radiation may be absorbed, reflected, or transmitted by a material, depending on the material properties with respect to the wavelength in question. The IR band of radiation is considered "thermal" in nature, mostly because it contains the wavelengths of radiation emitted by objects of ordinary temperatures. However, if it weren't for the high absorption of IR by most objects, it would not be nearly as important to heat transfer. For example, human skin absorbs well in the IR; for this reason we perceive IR radiation as heat more readily than we perceive radiation of other wavelengths, such as x-rays, which are mostly transmitted. Visible radiation is also considered thermally important, because visibly dark objects absorb it well, and because it is a substantial component of the radiation emitted by the sun.

An object with a single temperature does not simply emit a single wavelength of electromagnetic radiation. Because temperature is a macroscopic average of molecular scale oscillations, there is, in fact, a distribution of molecular kinetic energies underlying a single temperature. Correspondingly, there is a distribution of wavelengths and intensities of electromagnetic radiation emitted by an object of a single temperature, as a result of the varied oscillation rates of the charged particles within. Using a theoretical, idealized emitter termed a *blackbody,* Planck first derived a mathematical expression for the emissive power of radiation as a function of wavelength and temperature, hence, it is

known as the Planck distribution. Qualitatively, at low temperatures, the shape of the distribution is broad, without a well-defined peak. At higher temperatures the distribution is narrower, and the peak is very well defined. Figure 1 shows Planck distributions, or blackbody curves, for objects at 5800K (temperature of the sun), 2000K, 1273K (1000°C), 373K (100°C), 293K (20°C - room temperature).

Fig. 1 Blackbody Emissive Power vs. Wavelength



It can also be seen in Figure 1 that the wavelength emitted with the most intensity, or peak wavelength, is also a function of temperature. The Wien displacement law expresses this relationship of temperature, ***T*** (in Kelvin) to the peak wavelength, λ_{peak}, of radiation emitted by a body:

$$\lambda_{Peak} = \frac{2897.8}{T} \qquad (1)$$

Using this expression, it is clear that most commonly encountered temperatures correspond to radiation in the IR band (1 to 100 μm). For example, an object with a temperature of 300 K (room temperature) corresponds to about 10 μm. In contrast, the surface of the sun is 5800 K, hence, the peak wavelength of solar emission is in the visible portion of the spectrum (about 0.5 μm). Because most terrestrial temperatures yield emission in the IR band, it is important to recognize that, in IR imaging, unlike in common experience with visible imaging, almost every object in the field of view is a source, not just a reflector of a source.

Integrating the Planck distribution over all wavelengths for a given temperature yields the blackbody emissive power, $\boldsymbol{E_b}$. Equation 2 is a simple expression for $\boldsymbol{E_b}$ called the Stefan-Boltzmann law ($\boldsymbol{\sigma}$ is the Stefan-Boltzmann constant, 5.67 x 10^{-8} W/m^2-K^4).

$$E_b = \sigma T^4 \tag{2}$$

This relationship is at the core of IR thermography because it is the emissive power that an IR imager physically measures, while temperature is the parameter of interest. Furthermore, the success of IR thermography is highly dependent on the fortuitous fourth power relationship, so that emissive power is a very strong function of temperature. The large response makes it possible to achieve excellent temperature resolution.

Because it is derived from Planck's distribution, the Stefan-Boltzmann law is limited to describing an idealized blackbody emitter. In reality, no body emits exactly as much power as a blackbody. The ratio of power actually emitted by a given body to that of the

power emitted by a blackbody at the same temperature is referred to as the *emissivity*, and is represented by a non-dimensional number between zero and one. Emissivity is a wavelength, temperature and incidence angle dependent property specific to each material. The term *emittance*, or **e**, is more useful to the thermographer because it is used to describe the emissivity of object in aggregate, over a range of wavelengths, temperatures and incident angles. Usually this simplified quantity is only valid over a limited range of these parameters, within which the variation in emmisivity with respect to each parameter is not highly significant. A surface that meets the criteria of nearly constant emmisivity with respect to wavelength and incidence angle within a certain regime is termed a *gray surface* and can be characterized with a single emittance for simplified calculations. Published values of emittance should only be used when the wavelength, temperature and angular parameters are in close agreement with those concerning the IR imaging arrangement at hand. Surface emittance needs to be well understood for successful operation of IR thermographic systems. Introducing emittance into Equation 2 yields Equation 3, the Stephan-Boltzmann law modified with emittance, ***e***:

$$E = e\sigma T^4 \qquad (3)$$

Thermal radiation is largely a surface phenomenon, because most materials are not transparent to IR. As a result, it is the material properties of the surface of an object that determine emittance. Polished metals have low emittance, but a thin layer of paint can transform them to high emittance. For materials that are opaque to IR radiation,

emittance can be considered the complement of reflectance (the amount of incident radiation that is reflected by a surface), expressed by 1-e. It is important to realize that because no real surface has an emittance e=1, the radiation that is viewed as coming from an object is always a combination of emitted and reflected radiation, termed *radiosity*, and it contains information regarding both the temperature of the object and its surroundings. Special techniques described within this chapter are necessary to distinguish the two components and obtain accurate surface temperatures for the object of interest. When imaging outdoors, it should be taken into account that the sun is a significant source of IR radiation, particularly in the shorter wavelengths of the IR band.

TYPES OF IMAGING SYSTEMS

General Characteristics

Infrared thermographic systems are essentially imaging IR radiometers. Often they provide IR images continuously, in real time, similar to the "TV" image provided by conventional video cameras. The imager itself contains, at a minimum, a detector and an image formation component. Complete thermographic systems also integrate an image processing and display system. An IR imager is often called *radiometric* when it is designed for measuring temperatures. Non-radiometric IR imagers are used in applications which do not require measuring quantitative temperatures differences, but rather are satisfied by a qualitative image display. For example, this type of imager is used for night vision and surveillance. Non-radiometric imagers do not need extensive calibration, thermal stability, or image processing capabilities, making them less expensive.

The two basic types of IR imagers are focal plane arrays (FPA) and scanners. There are also two categories of detector technologies used in these systems: photon absorbers and photon detectors. They are summarized in Table 1.

Table 1. Summary of Specifications of Various Types of IR Imaging Systems

IR imager system types	Resolutions available (pixels)	Response ranges (μm)	NETD (Noise Equivalent Temperature Difference) (mK)	Typical Uses
FPA, Indium Gallium Arsenide (InGaAs)	320 x 256, 640 x 512	0.9 to 1.68	N/A	IR Laser/LED development, High temperatures
FPA, Indium Antimonide (InSb)	320 x 256, 640 x 512	1.0 to 5.4 3 to 5	25	General, Military imaging, Fast
FPA, Microbolometer (absorber)	160 x 128, 320 x 240	8 to 14	100	General, Predictive Maintenance, Fire Fighting
FPA, Quantum Well Infrared Photodetectors (QWIP).	320 x 256, 640 x 512	Narrow band within 8 to 10	30	R&D, Laboratory
Scanner, Mercury	Variable,	8 to 14,	50	R&D, Laboratory

Cadmium Telluride (HgCdTe or MCT)	173 x 240, 1024 x 600,	3 to 5

System Selection

The choice of an imaging system for a particular application depends on a number of variables including the temperatures of the specimens to be measured, the amount of money available to purchase thermographic equipment, the necessary measurement accuracy, the ease of use, and the appropriate wavelength for the application. Table 1 lists typical applications for the various types of IR imagers. Shorter wavelength IR imagers are also referred to as near-IR imagers, because the wavelengths are near the visible range (1 to ~8 μm). IR imagers with sensitivity in the longer wavelengths (~8 to 14 μm) of the IR band are typically called long-wave imagers. Near-IR imagers work well for high temperature subjects, but there is almost always enough thermal radiation for high temperature objects to be imaged with long-wave imagers, as well. Near-IR imagers are often used to image lasers, such as in the development of LIDAR systems. Long-wave IR imagers experience fewer problems when making measurements in the presence of sunlight, because the solar spectrum peaks in the visible, and has very little power at longer IR wavelengths. More materials are transparent to near-IR than to long-wave IR. In order to measure the surface temperature of an object, it is important to choose a detector that utilizes wavelengths to which the object of interest is opaque. A common material that is transparent to near-IR, yet opaque to long-wave IR is conventional glass.

IR imagers with large array sizes tend to be more expensive to produce largely because of their increased complexity and the challenge of making large arrays without excessive numbers of non-operational pixels. For many applications, it will be important to consider the imager's instantaneous field of view (IFOV) measured in milliradians; a combination of array size and optical arrangement, that determines the physical dimensions represented by any one pixel, for a given distance from the imager. Special optics are available to allow IR imaging on the micron length scale, however, most IR imagers have a wide field of view, resulting in pixels with physical dimensions on the order of millimeters, for object distances in meters.

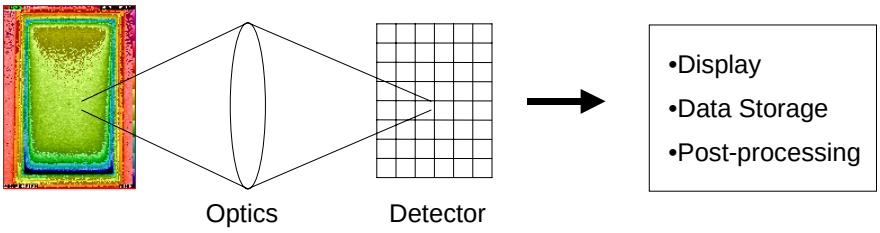
Some detectors require cooling to low temperatures with liquid nitrogen or a closed-cycle Stirling cooler. The need for cooling can add inconvenience, expense, and start-up delay, depending on the cooling method used. Stirling coolers are expensive and require several minutes of operation before the imager can be used. Liquid nitrogen cooling is inexpensive, however it can be inconvenient for field use where it may not be readily available. There are also detector technologies that do not require cooling.

Focal Plane Arrays

Focal plane array (FPA) imagers are the most common types of systems today. They are analogous to the CCD arrays found in hand-held video cameras but are sensitive to IR, rather than visible radiation. In an FPA, each pixel that makes up an IR image is measured with an individual detector. The detectors are arranged in a flat, two-

dimensional array. One-dimensional arrays are also used, providing line imaging. The array is placed in the focal plane of the optical system (lens) of the imager, as diagrammed in Figure 2. Typically, array size does not exceed 1024 by 1024 pixels. However, larger arrays are produced on a custom basis for specialized uses, such as astronomical imaging.

Fig. 2 **Focal Plane Array Detectors**



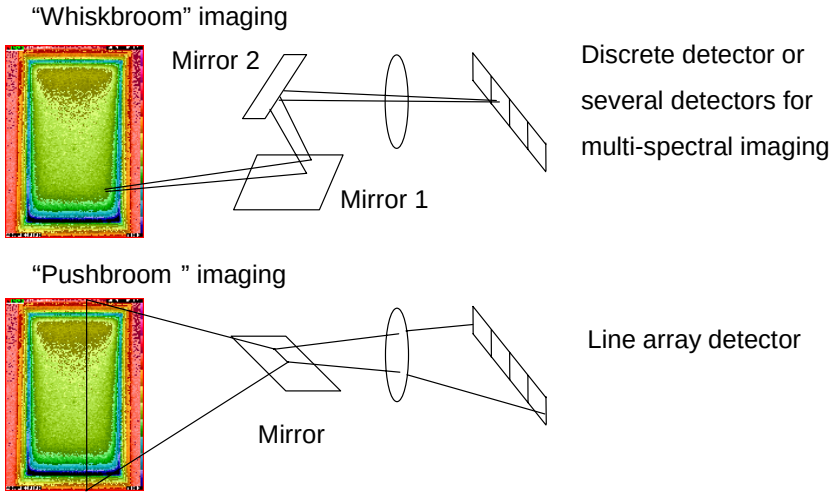
Operability describes the percentage of functional pixels in an array. Most fabrication processes yield operability greater than 99%. Still, most arrays inevitably contain bad pixels. Software usually masks this defect by interpolating missing data from neighboring pixels. In contrast to scanners, FPA imagers are more mechanically robust and provide an improved depth of field and field of view, as a result of a simple optical design. FPAs do not have any moving parts, other than a simple focus adjustment.

Scanners

In a scanning imaging system, one or several detectors are combined with a single or multiple-axis mirror system. Images are acquired sequentially by combining individual

measurements. Scanning mirror imagers were used before large FPAs became readily available in the 3-12 μm range. Multiple detector units are used in multi-spectral imaging systems; each detector records a certain band of the spectrum. Old Landsat satellites are equipped with multi-spectral scanning systems. Figure 3 diagrams two scanning designs. So-called *whisk broom* scanning uses a two-axis mirror system. Single point measurements are combined into a line; many lines then compose the final image. Interlaced whisk broom scanning acquires every other line initially, and then fills in the remaining lines in a second pass. Non-interlaced whisk broom scanning acquires all lines sequentially. Older IR scanners are usually of the whisk broom type. *Push broom* scanning acquires an entire line at once with a linear array detector. A single-axis mirror configuration scans perpendicularly to the linear array to compose the image. Some systems can be set to different scanning speeds; 60 and 30 Hz frame rates are common.

Fig. 3 Scanning System Configurations



Scanning systems have the advantage of being able to acquire image arrays of any size. Often the manufacturer fixes the image array size; however there are also systems that

dynamically configure the scanning head to acquire the desired image array. Mercury Cadmium Telluride detectors are the most frequently used single-element detectors in handheld scanning systems, although any detector with a sufficiently fast dynamic response could be used.

Scanners are delicate mechanical instruments that will not always tolerate vibration or high instrument acceleration. Another disadvantage is that the dynamic response of the detector limits the maximum gradient obtainable in an image at a given scanning speed. As a result, the frame rates are relatively low compared FPAs. Also, the acquisition time delay across the image may pose a problem when it is capturing rapid transient events.

Photon Absorbers

A microbolometer is an example of a photon absorber. The absorber is made of a passive energy absorbing material that is simply warmed by the IR radiation. Incoming thermal radiation results in an increase in absorber temperature that is proportional to the radiosity of the surface being imaged. The detector temperature is then determined by measuring a temperature dependent material property such as electrical resistance. The absorber has to be thermally decoupled from the substrate and the environment for maximum performance. Absorbing materials perform well over a large range of the spectrum. Microbolometer arrays are temperature stabilized, but do not need to be cooled to cryogenic temperatures, as is necessary for some photon detectors discussed in the following section.

The pixels are typically 30 by 30 μm and are micro-machined in monolithic wafers that also incorporate signal acquisition and processing. The individual pixels are suspended and electrically connected by two arms. Heat exchange through gas convection is suppressed by packing the array in a hard vacuum housing. The broad-band absorption intrinsic to the detector is thus limited to 6 to 14 μm by the transmission of the vacuum housing window. This technology will likely see further development in the near future that will increase sensitivity (NETD below 50 mK).

Photon Detectors

Photon detectors are active elements. A photon striking the detector triggers a free charge, which is collected and amplified by an electronic circuit. Detectors and read-out circuits are constructed on different substrates and are electrically connected into a hybrid assembly by Indium bump bonding. A variety of detector materials are used today, each with a specific spectral range and specialized application. Some detectors require cryogenic cooling to reduce the dark current (the amount of current passed by the detector, in the absence of any photon signal) to acceptable levels. The following are the most commonly used detectors (summarized in Table 2).

Table 2. Focal Plane Array (FPA) Devices

Detector Material	Wavelength[μm]	FPA Size	Sensing	Operability	Cooling
InGaAs	0.9-1.6	320 x 240	Detection	> 99%	Uncooled
InSb	3.0 – 5.0	1024 x 1024	Detection	> 99%	Cooled 70K
QWIP (GaAs/AlGaAs)	8.0 – 9.0	512 x 512	Detection	> 99%	Cooled <70K
Microbolometer	7.5-13.5 (limited by optics)	320 x 240	Absorption	Typical of Si process	Uncooled
HgCdTe	1.0 – 20.0 (Limited by optics)	1024x1024	Detection	85 - 95%	Cooled 60 - 160K

Indium Gallium Arsenide (InGaAs)

Indium Gallium Arsenide detectors work best mounted on a lattice-matched substrate. Unfortunately, this arrangement also limits the spectral response to 0.9-1.6 μm, making this detector material unsuitable for room temperature applications. However, InGaAs is well suited for measuring temperatures above 500°C. Uncooled FPA and linear arrays are produced in large quantities and many size variations. This is the detector of choice for military applications such as heat-seeking missiles. InGaAs arrays employed in general purpose IR imagers are commonly 320 by 240 pixels in dimension.

Indium Antimonide (InSb)

Indium Antimonide detectors are functional in the 3-5 μm range, so they are useful in room temperature IR imagers. Glass and certain plastics are partially transparent in this

range of the spectrum and need to be painted or covered with an opaque adhesive tape in order for accurate radiometric data to be collected. Some materials exhibit a larger reflectivity in this spectral range compared to the 8-12 μm range, so distinguishing emitted radiation from reflected background radiation may prove more challenging. Arrays up to 1024 by 1024 pixels and NETD as low as 10mK have been demonstrated with InSb. These large arrays are not commonly produced and are primarily used in observatory telescopes. InSb detectors are known for rapid acquisition, with frame rates up to 80Hz. Cryogenic cooling is required to minimize the dark current.

Quantum Well Infrared Photodetectors (QWIP)

QWIP arrays were developed in the mid 1990s. Only in recent years have QWIP detectors become commercially available in mass-produced, handheld IR imagers. Enormous advances in crystal growth technology and processing techniques made it possible to produce uniform large arrays. Quantum well detectors are characterized by a sharp spectral absorption line. The well is tuned in depth and width, so it can only hold an electron in the ground or first excited state. A photon whose energy is equal to the difference between the energy level of the ground state and the first excited state will promote a ground state electron to the first excited state. An externally applied voltage then sweeps the excited electron out, resulting in a photo current. The spectral response can be set during fabrication by adjusting the well width and depth. QWIP arrays can typically have their absorption line anywhere in the 8-10 μm range, which is the ideal range for observing room temperature objects. Sterling coolers are used to reduce the

temperature of these detectors to 70K. Quantum wells are made of layers of Aluminum-Gallium-Arsenic and Gallium-Arsenic.

Mercury Cadmium Telluride (HgCdTe or MCT)

Mercury Cadmium Telluride is sensitive to wide range of wavelengths (1 to 20 μm), which allows making detectors for highly varied applications. Large arrays up to 2000 by 2000 pixels are produced in very small numbers for astronomy applications. Unfortunately, technical difficulties prevent such large arrays from being commercialized in small handheld IR imagers. The fabrication process requires very toxic substances and poses an environmental problem. In addition, the detector arrays are currently produced with a poor operability of 85 to 95%. Cooling to between 60 and 160K is required, depending on the selected bandwidth. MCT is commonly employed as a single-element detector in scanning systems.

Data Acquisition/Image Processing

Collecting image data is an important part of operating a real-time imager. The data are commonly recorded for later analysis, assembly into reports, etc. Continuous video signals may be recorded on tape or with the aid of a computerized video digitizer. In steady-state thermal situations a single IR image would be generated by averaging a number of frames over a period of time. Transient thermal situations are usually recorded continually, and a series of images are stored over time.

The resolution of acquired data is typically expressed in number of bits. An 8-bit system will distinguish 256 different levels of temperature or radiosity; a 12-bit system distinguishes 4096 levels.

GOOD PRACTICE/SYSTEM OPERATION GUIDANCE

Emittance and Background

The key to using an IR thermographic system well is to combine skilled operation of the imaging system with a good understanding of how IR radiation interacts with the object(s) being imaged and consideration of the movement of heat energy in and around the object(s) by all modes of heat transfer (conduction, convection and radiation). Emittance and its relation to reflected IR radiation from the background were discussed briefly in the theory section of this article. However, this topic deserves a more thorough treatment, because understanding how to interpret these effects is essential to successful thermography. Variations in surface emittance can cause large changes in the appearance of an IR image, so the thermographer must know the emittances of the various objects in the image in order to distinguish genuine temperature differences from those resulting from non-uniform emittance. Emittance describes the capability of a surface to emit IR radiation; it is a non-dimensional value ranging from zero to one: zero for no emission and complete reflection, one for complete emission and no reflection. As long as the surface is opaque to radiation of the band of wavelengths measured by the imager's detector then reflectance and emittance are complementary and added together equal one. Some published sources of emittance values may not be appropriate for IR thermography.

Accurate IR thermography results are best achieved by establishing emittances through testing, as described later in this article in the *Emittance Measurement* section under *Scientific Temperature Mapping*.

Because no real object has an emittance of one, background thermal radiation arriving at a surface from the surroundings is in part reflected and becomes a component of the apparent radiation emanating from the surface. The complete background thermal scene is the combination of the geometry or orientation of surfaces (including the sky) that are in view of the object being imaged and their effective temperatures. The sky has a very cold effective temperature that is hard to quantify, and it is heavily dependant on cloud cover and the moisture content of the air. IR thermography measurements should therefore be made indoors, if possible, or the sky should be screened with large cloth backdrops. A thermographer should not merely consider the emittance and temperature of objects in the direct field of view, but also be aware of the entire background thermal scene. What IR radiation is arriving at the surfaces being imaged? Is an observed hot spot real or a reflection from a nearby object? IR radiation generated by emission gets reflected and re-reflected and may eventually emanate from all directions with varying magnitudes that are dependent on the temperatures, geometries, and emittances of the walls, floors, lights, windows, open sky, trees, and everything else that surrounds the objects or phenomena being imaged.

Specimen Considerations

For a specimen to be imaged, a thermographer should consider the physical properties of emittance, reflectance, and transmittance/absorption coefficients, especially over the wavelengths detected by the IR imager. Reflectance and emittance are closely related and mathematically complementary, in the case of no transmission. In IR imaging, high emittance is preferable. In this case, most of the apparent radiation is actually due to emission from the object of interest. Low-emittance (low-e) surfaces are problematic because the reflection of background radiation can be a more significant portion of the apparent radiation than the emitted signal of interest. Table 3 lists some emittance values for various materials. These measurements were made by the authors using the procedures described in the *Emittance Measurement* section found later in this article.

Table 3. Emittance Values for IR Temperature Measurements with 8 to 12 μm Mercury/Cadmium/Telluride Detector

Material	Emittance
Glass	0.86
Wood	0.90
Vinyl tape	0.90
Paper	0.90
Gold	0.02
Shiny aluminum	0.04
Common paint	0.90

Most common materials have an emittance of e=0.9, which means that roughly 10 percent of the IR radiation incident from surrounding objects will be reflected and 90 percent of the theoretical blackbody radiation will be emitted. These surfaces work well for IR imaging. For surfaces with lower emittances, particularly below e=0.5, precautions are in order. A surface with very low emittance, such as a shiny metal surface, will reflect much more IR radiation than it emits, and the IR imager will observe a collection of reflections from the surfaces surrounding the specimen rather than information regarding the specimen itself. This phenomenon may be used to the thermographer's advantage when analyzing the background thermal scene, and as a means to document reference positions by use of small highly reflective location markers. However, when the task at

hand is to collect temperature data from an object that has low emittance, the surface needs to be modified by applying a thin layer of a higher-emittance material to the surface. An opaque adhesive tape or paint can be applied to the surface to raise its emittance. One quick way to check surface properties is to manipulate the background thermal scene. For example, a thermographer may introduce a background object with a temperature significantly different than ambient (e.g. the thermographer's hand, a butane lighter, or an ice-cube). Moving the background object laterally near the specimen and observing any corresponding movement or changes in the IR image can identify highly reflective surfaces. It is important to recognize that reflections off a specimen can be both specular and diffuse. A diffuse reflection is angularly independent and blurs out non-uniformities in the background thermal scene. Specular reflections are angularly dependant and preserve the image of thermal non-uniformities in the background. It is more difficult to evaluate the emittance of a specular surface by visual inspection. For example, window glass is specular and, despite its high emittance (e=0.86), it can show clear imaged reflections because of the high sensitivity of IR imagers. The distinction becomes one of magnitude. If a specular surface is also low-e, the reflections appearing as movement in the image will be more intense than for that of a higher emittance surface.

A roll of paper/masking tape (e=0.90) is a valuable asset to a thermographer faced with a specimen of unknown surface properties. A quick check for problematic low-emittance or transmittance can be performed by applying tape to the specimen and then imaging the

specimen. The thermographer will know the specimen has an emittance different than 0.9 (or that the specimen exhibits measurable transmittance) if the piece of tape is apparent in the image. The tape should be in good thermal contact with the specimen and should not appreciably alter the true temperature. For example, if the background thermal scene has an effective temperature colder than the specimen and the region with tape shows as warmer, then it is very likely that the surface has low emittance and will need to be modified by painting or being more completely covered with tape.

Painting low-e surfaces is a good idea if it is feasible. An even, opaque coating of paint is often the best solution for imaging low-e, varying emittance, specular, or transmitting surfaces when a clean, accurate image or an accurate temperature measurement is desired. Water-based, temporary paint (e=0.9) applied as a spray is useful and relatively easy to clean up and remove. Repeat the tests described above for determining whether a surface is low-e or specular in order to be sure that the paint is applied sufficiently thick; a coating that is too thin will not raise the emittance completely or uniformly. Location markers can be applied to a specimen for later use in identifying geometry and spatial locations in the thermogram. Small strips of aluminum adhesive tape are examples of low-e surfaces that can be used as location markers in an IR image, if the background is at a different temperature than the specimen.

Altering the emittance of surfaces for the purpose of IR imaging will also alter the heat transfer situation. This can lead to significant changes in the real surface temperatures of a test subject whose surface has been painted, especially when the radiative heat transfer

dominates convection and conduction. A thermographer should be careful to report any modifications made for imaging purposes so that the results can be interpreted properly. Repeat some measurements with and without paint to clarify the effect of modifying the surface emittance. The usefulness of good quality IR data often offsets the drawback of needing to extrapolate from measured results to account for altering the radiation heat transfer situation. If altering emittance is not possible and high quality data are required for a varied surface (such as a semiconductor), it is possible to use additional procedures to obtain a pixel-by-pixel emittance map to use for correcting an image if the subject can be fixed in place, made isothermal, and controlled to have two temperatures that differ from the background (1).

Thermal setup

As a thermographer develops facility in accounting for emittance, reflection, and transmission, the potential for collecting misleading IR images decreases. The challenge is then to do a good job of interpreting the heat transfer phenomena that are revealed in the information contained in the image. Because an IR imager displays surface temperatures, and temperature differences drive heat flow, thermograms can also be used to visualize where energy is flowing as it moves from hot to cold. Consideration of heat transfer is important both when designing an experiment that will use IR imaging and when interpreting thermal patterns in the image. IR images can reveal temperature differences in a specimen; when there is a temperature difference, heat energy is moving. If a thermographer wants to image something based on observing temperature

differences, then he or she will likely need to make heat energy move as part of that effort.

In any IR imaging setup, there are two possible heat transfer situations, steady-state and transient. In steady-state heat transfer, temperatures and heat flows in any one place are constant over time. In transient heat transfer, temperatures and rates of heat flow change over time. Steady-state heat transfer is dependent on varying thermal conductance, while transient heat flow is also dependent on the varying thermal capacity of materials. Often the objects being imaged will determine which situation is used because of a pre-existing condition such as internal heat generation, a fabrication process, or other normally occurring temperature difference. Most objects that consume energy are likely to be imaged during actual or simulated operation.

However, a thermographer is frequently faced with an energetically passive situation where heat flow must be induced in order to gather the desired information. The same physical phenomenon that IR imagers rely on, thermal radiation, is an important vehicle for heat transfer; conduction and convection being the other two. A thermographer can use thermal radiation as a method of heating a surface in an imaging setup. Lamps can provide a convenient source of thermal radiation when a thermographer needs to add heat to a system. Non-destructive testing efforts often make use of high-powered flash lamps to generate an abrupt pulse of radiant thermal energy that quickly heats a surface in transient studies. Other techniques for generating a heat flow include mounting

specimens between warm and cold environmental chambers, attaching resistive contact heaters, blowing hot or cold air on the specimen, scanning lasers, etc.

Features of the material being imaged can be observed based on the propagation of the heat into the material, indicated by the temperatures as they evolve over time. To test the effectiveness of a fluid-based cooling circuit in a heat exchanger using thermal imaging, both the heat load and the cooling mechanism should be activated. Often, establishing a known, repeatable heat-flow situation is the most challenging aspect of performing an IR imaging measurement. Creativity and attention to all aspects of the thermal scene are necessary to design and conduct an IR imaging effort that gathers valid and revealing data.

An IR imager can also be used to gather information based on varying transmission/absorption of IR by a material. For example, a gas may absorb IR differently than air, so it can be detected or quantified using an IR imager. For accurate surface temperature mapping, transmission of IR by the object of interest is a liability, but there are applications where IR transmission can be beneficial. A material may be slightly transparent in the IR (but not in the visible band), so an IR imager would be useful for tasks such as aligning components. Spectral filters can be used to control the wavelengths monitored during transmission/absorption measurements.

System Operation

It is impractical to try to describe the operation of all the different IR imagers available. However, some important aspects of operation are relevant to most systems. The magnitude of the temperature in a thermogram is represented by a color or gray scale. For visual interpretation, it is not necessary to exceed 256 (8-bit) possible display colors, and gray scale images often need only 16 (4-bit) shades of gray. The span adjustment of an imaging system will allow the user to manipulate the maximum displayable temperature difference by assigning a different temperature increment to each color step (determining the width of the scale in temperature units). The center temperature adjustment provides a means for shifting the absolute temperature of the middle of the scale.

Random noise is inherent to IR detectors; it can be mitigated by averaging many frames together, pixel by pixel. The standard error of the average of N "identical" measurements with random noise is the standard deviation of those measurements divided by the square root of N. Because the standard deviation of most imagers is small, it is not usually necessary to average more than 15-50 frames before the random error is reduced to be a much smaller component of the total error than the systematic error involved in using the instrument. Most commercial thermographic systems provide a means to average frames to remove random noise.

IR image data are essentially two-dimensional numerical arrays often with 12-bit resolution (4096 temperature steps). Colors are assigned to levels, but there is no such

thing as true color as in visible imaging. Black and white thermal images are better for indicating the form of objects, while color IR images are better for indicating temperature magnitudes and differences. Figure 4 shows the same IR image data in both color and black and white. The image is of an architectural model of a city that is being artificially heated by halogen lights.

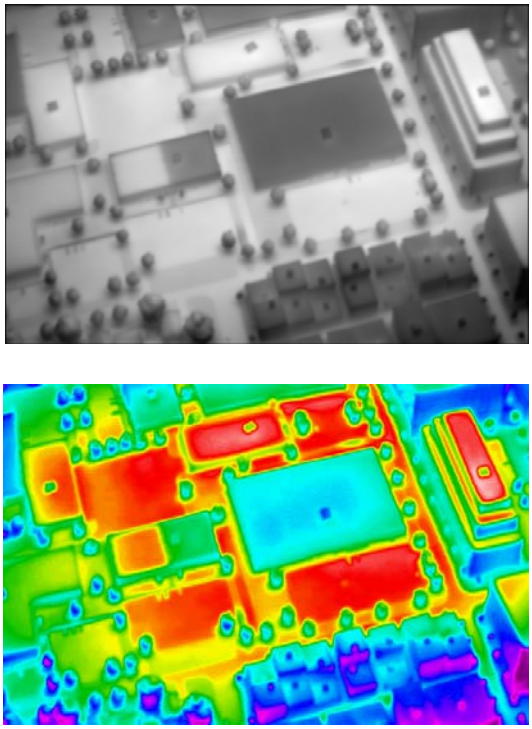


Figure 4 Black and White vs. Color Image Display

Imaging Procedures

IR imagers need to be focused. The best focus will show the steepest gradients at edges that have abrupt changes in temperature. If there is a region on the object with sharp thermal contrast this is relatively straightforward, but if the object is isothermal, then focussing can be a challenge. One focussing technique is to apply a piece of low-e tape,

such as aluminum, and focus on the contrast created by the tape. The tape can then be removed and the focus maintained.

The background thermal scene should be assessed early in the arrangement of an IR imaging experiment. For this purpose an IR mirror is indispensable. Use a material with a front surface that is highly reflective in the IR. Typical glass mirrors are inappropriate because they usually have a glass front surface and the reflective metal is behind the glass. A long-wave IR imager will image the surface temperatures of the glass more than reflecting the background, since glass has a relatively high emittance. A piece of metalized polyester film is a good choice for a background mirror. It can be placed on, or in front of the specimen to be measured, and allows imaging the background radiation which is incident on and hence may be reflected from the specimen. It is desirable to establish a thermal background that is as uniform as possible. Non-uniformities in the background can manifest themselves as non-uniformities in the specimen being measured. A back-drop such as a sheet of foam or heavy cloth can provide a uniform background. IR mirrors are usually specular, this is useful for identifying thermal patterns in the background, but unless the mirror is very large, or the background radiation very uniform, it may be difficult to collect a good average background temperature to use in surface temperature corrections. Diffuse reflecting mirrors, special highly reflective but convoluted surfaces, are available to provide thermal background information which represents more of an average background temperature as incident on the location of the mirror. This can be convenient for determining a single value for background temperature, when it is not possible to attain good background uniformity.

THERMOGRAPHIC INSPECTION

Thermographic inspection primarily evaluates images for qualitative thermal signatures (rather than absolute temperature levels) to discern the presence and proximity of a feature of interest or defect. The status-of-operation or maintenance condition of a piece of equipment may also be discerned. Thermographic inspections can be used in industry, medicine, and aerospace to reveal malfunction, leaks, material loss, delamination, contamination, friction, pain, and tumors, etc. It is important to recognize that there is a distinction between radiometric imaging for absolute temperature accuracy, and thermal imaging for relative temperature information or thermal signatures.

Radiometric Imaging

In radiometric imaging, IR imagers are used as non-contact temperature sensors. The objective of the imaging is to monitor, check, or compare an object's surface temperatures or temperature differences. Most IR imagers sold today are radiometric instruments. Although the imaging interface of a radiometric thermographic system will provide quantitative temperatures, it is imperative to recognize that these temperatures are only accurate when sufficient attention is given to the imaging setup, calibration, surface emittance, and background radiation (see *Scientific Temperature Mapping*). Examples requiring this approach are process temperature monitoring in activities such as baking, or the evaluation of the heat dissipation behavior of a prototype electronic circuit.

Thermal Imaging

Most routine inspections only require simple thermal imaging, without consideration for the parameters necessary to achieve accurate absolute temperatures. There are many applications where the temperature difference of the thermal signature is large enough to be distinct despite less than ideal imaging conditions. Also, given the basic criteria of high, uniform specimen emittance and a uniform thermal background, the relative temperatures displayed by the imager will be reasonably accurate. Qualitative visual inspection is usually sufficient to resolve the thermal signatures in basic thermal imaging applications, and numerical data collection and post processing is not necessary. Typically, thermal imaging inspections focus on surface temperature differences; however, a surface contamination might be revealed by an altered local surface emittance. Differences in surface emittance of the imaged object can be determined only if the energy levels of object and background are different and background radiation is uniform.

Predictive Maintenance

Historically, most IR thermographic systems have been marketed and sold for predictive maintenance activities using largely qualitative thermal imaging. Commercial training and certification is available (Snell Infrared and Academy of Infrared Thermography). The most common application is monitoring the condition of electrical power distribution systems and infrastructure. Figure 5 shows an IR image of a circuit breaker panel with an overloaded circuit and the heat generation at the electrical contact resistance where a wire

is attached to a circuit breaker. In this electrical example, the heat of electrical I^2R losses generates the observed thermal signature. However, any phenomenon with an impact on heat flow is likely to be detectable. Bad bearings in a conveyer system will develop heat from additional mechanical friction. A fluid leak might lead to localized cooling from evaporation. And, missing or bad thermal insulation will cause an increase in heat flux. All of these heat flow phenomenon can be imaged with IR thermography.

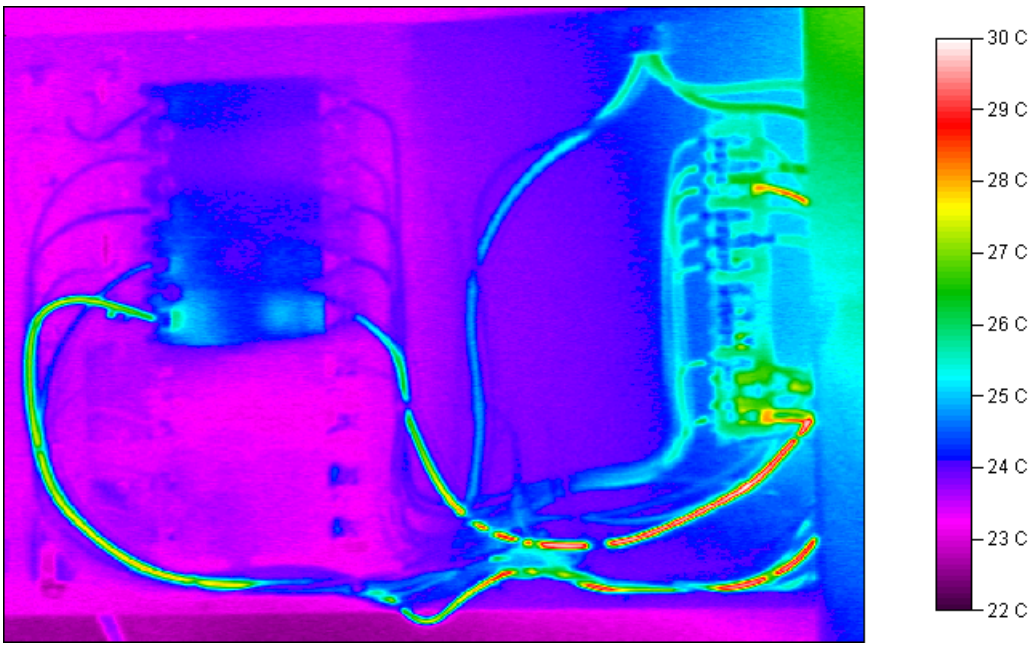


Figure 5 IR Image of Circuit Breaker Panel, One Circuit is Nearly Overloaded

Non-Destructive Evaluation (NDE)

Fast Transient NDE

Fast transient thermal imaging is based on the time-evolution of surface temperatures on test specimen during heating or cooling. Variations in temperature depend on the heat

flow through the object; heat flow is sensitive to cracks, delaminations, voids, and changes in material properties. In a typical setup, flash equipment is used to generate a heat pulse, and the surface temperature of the test specimen is monitored with an IR imager. The pulse duration and the total energy delivered over the length of the pulse depend on the material properties and the nature of the defect to be detected. A series of approximately 10 to 30 frames is recorded with frame rates up to 80 Hz with scanners or 1 kHz with FPA imagers. In the absence of thermal pulse equipment and a high speed imager, transient NDE can be successfully performed on some specimens, particularly those with low thermal conductivity. Figure 6 shows several frames taken at 10 second intervals after a steady IR heat source was applied to the back side of a composite truck bed panel. The well bonded portions warm faster on the opposite, imaged side. An image sequence like this can already be very informative when visually inspected by a technician experienced in interpreting thermograms. However, image post-processing can greatly enhance images and reveal features that are hidden in the unprocessed image. Post-processing includes averaging of image sequences, coloration with different palettes, image subtraction and edge enhancement. Complex processing is possible, including Fourier transformation of time sequence images and tomography, if sufficient computer power is available to perform these tasks. Tomography analysis translates the time image sequence into a three-dimensional object sequence; defects can then be located in depth as well as in the image plane even though data are collected only at the surface (2).

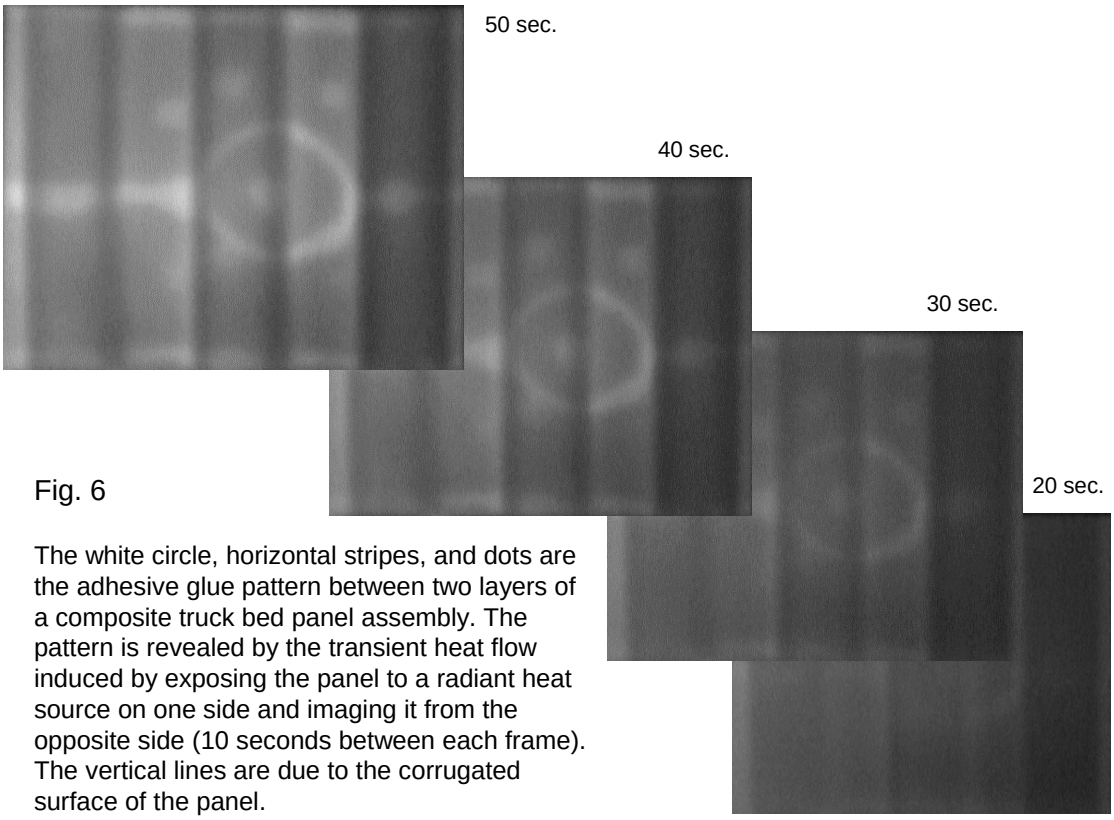


Fig. 6

The white circle, horizontal stripes, and dots are the adhesive glue pattern between two layers of a composite truck bed panel assembly. The pattern is revealed by the transient heat flow induced by exposing the panel to a radiant heat source on one side and imaging it from the opposite side (10 seconds between each frame). The vertical lines are due to the corrugated surface of the panel.

Steady-state NDE

Fast transient thermography can provide a more robust non-destructive evaluation technique than steady-state thermography, but its use has been limited because it requires expensive thermal-pulse equipment and storage of a large number of data for each specimen. Steady-state IR thermography, by contrast, is much less expensive, requiring minimal equipment and data storage. Near steady-state thermography could be used for NDE during production phases where temperature cycles have been applied to parts, for example the cool-down period after paint baking, adhesive curing, or injection molding of plastic parts. The required temperature difference between the part to be evaluated and the environment depends on the material, geometry, and size of the part; the size and

nature of the defects being sought; and the minimum resolvable temperature difference of the IR imager being used. This difference can be as small as a few degrees Celsius.

Defects in the sample are more blurred in the steady-state condition than in a transient image, as can be seen in figure 7; a pattern bonded composite truck bed panel. The blurring is caused by the thermal conduction of the sample. However, image-processing algorithms based on convolution of data with a kernel function can improve image definition (3).

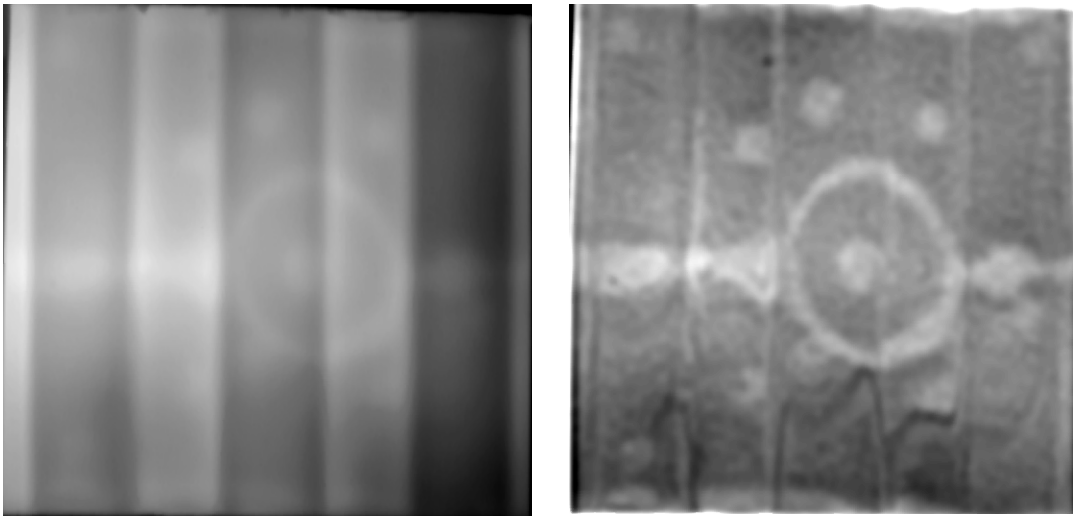


Fig. 7 IR thermogram of composite truck bed panel after reaching steady state with a radiant heat source. Gradients are not as sharp as in fast transient thermography when imaging materials with high thermal conductivity. Post processing can improve image quality as shown in the image to the right.

Prior to post-processing of the images, it is necessary to remove random and digital noise from the data. A filtering technique based on convolution of the data with a kernel function can be used for this purpose (3). The filtered data are calculated from the inverse

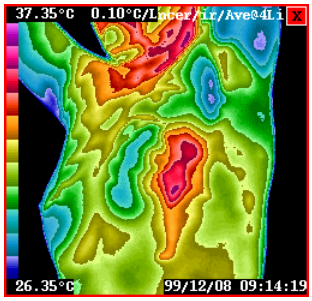
Fourier transformation of the product of the discrete Fourier transforms of the thermographic data and a kernel function. In the nomenclature of signal processing, the kernel function is a low-pass or band-pass filter. The kernel function is adjusted to provide the level of detail necessary for further image analysis, e.g. temperature gradients or heat flow in a joint of the specimen. The final image may not represent valid temperatures, but will likely reveal features of interest more prominently.

Medical Imaging: Breast Cancer

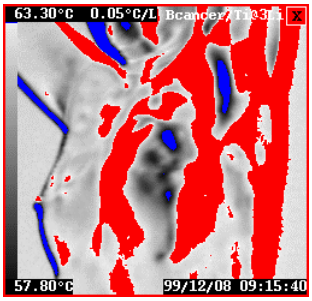
IR imaging of the exterior of the human body is straightforward and completely harmless. Pain management doctors have long made use of thermography to assess inflammation and other conditions. Breast cancer is a widespread problem that can be mitigated by successful early detection. IR thermography offers a completely harmless method of imaging tissue that can resolve subtle changes in blood vessel temperature and configuration associated with the early stages of cancer development. Evidence suggests that thermal imaging can detect the beginning stages of cancerous cell growth, up to 2 years earlier than would be detectable by other methods. The detection rate of the IR method is 87%, while traditional mammography is 67% (4). Because they test for different indicators, they are actually quite complementary, and used together attain detection rates of 95% (4). IR imaging is particularly well suited to early detection in young women whose higher hormone levels support fast cell growth, since the IR method relies upon indicators that are much more pronounced under these circumstances. It is also valuable to have reference images starting as early as possible, because an individual's thermal signatures are quite consistent over time, and any variations are likely to be indicators of increased breast cancer risk. First, the thermal image is

analyzed for asymmetric temperature signatures between the left and right breast. Warm spots are usually an indication that the person is at risk. By exposing the patient to a thermal stress (a cold room) the response of their body's sympathetic nervous system can be evaluated. The sympathetic nervous system is responsible for adjusting the blood flow near the skin surface when stimulated by external environmental conditions. Disfunction in the sympathetic nervous system is associated with nerve damage in the region of tumor development. Localized regions of different skin surface temperatures under conditions of environmental thermal stress thus suggest cancer development. Sophisticated image processing can be performed to enhance the patient's blood vessels in the image. Often tumors cause a change in the blood vessel density and orientation (or vascular pattern). More vessels become apparent and the vessels are oriented in a circular manner, however fibro-cystic cell growth can cause similar patterns and does not pose a threat to the person's health. Usually the tumor is located in the center of that circular pattern, and is the cause of the altered blood vessels. Figure 8 shows a raw thermographic image, a sympathetic disfunction processed image, and a vascular map processed image. IR thermography as a breast cancer screening is a new and very promising field, as it provides early detection, and imaging can be performed as often as desired without the additional health concerns associated with the ionizing radiation of mammography.

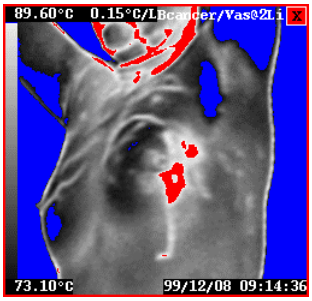
Fig. 8



The raw IR image taken as a medical breast cancer screening, can provide an initial indication of an abnormality by displaying temperature asymmetry from left to right such as the hot spot on the left breast of the patient above.



Processed images provide more positive identification by focusing on medically pertinent parameters. This image has been taken with the patient in a cold room and processed to reveal the response of the sympathetic nervous system to the thermal stress as manifested in the near skin surface blood flow. The region identified in the raw image continues to show abnormality.



This image has been processed into a vascular map showing the density and configuration of blood vessels by spatial high pass filtering. Areas of tumor development often exhibit dense circularly oriented blood vessels. This signature is also present on the left breast and is a strong indication of cancerous cell growth

SCIENTIFIC TEMPERATURE MAPPING

Temperatures are a common parameter of interest to measure. Accurate temperatures are typically acquired using contact probes, such as thermocouples and thermistors. These methods are highly reliable and accurate; however, it is difficult to make large numbers of simultaneous measurements and the presence of a contact probe can also interfere with the heat flows that establish the temperature of interest. The two-dimensional array of temperatures provided by IR thermography is unparalleled for its non-invasive acquisition of many high-resolution temperatures. However, it takes extra effort to raise basic thermography to a level where it can be relied upon for repeatable quantitative scientific measurements. Rigorous attention must be given to the measurement of emittance and background radiation as well as to the collection of so-called meta-data

parameters (e.g. the environmental conditions at the time of the test) to ensure accurate results.

External Temperature Referencing

Each thermal image is composed so that a reference emitter with multiple targets for calibrating the IR data is included in the view. The addition of external referencing targets allows absolute accuracy of temperature measurements. The reference emitter should be situated near the specimen being measured, within the field of view of the IR imager and should be kept reasonably in focus while the imager is focused on the specimen. Commercial reference emitters are available; they consist of a thermoelectric heat pump device on a plate of highly conductive metal. The metal plate is painted to provide a well-characterized surface emittance, and the temperature of the plate is stabilized with a sophisticated closed-loop controller. If a temperature-stable circulating water bath is available, a reference emitter can also be fabricated by providing channels for fluid flow in a highly conductive metal plate. To measure an accurate absolute temperature, it is desirable to have a bore in the reference emitter plate that can be used to accommodate a platinum resistance thermometer (PRT) probe contact thermometer. Two IR mirrors should also be mounted on the reference emitter to quantify background thermal radiation. One mirror is aluminized polyester film, and the other is gold-coated aluminum with a surface shaped to provide diffuse reflection.

View Arrangement

In contrast to flat or convex surfaces, concave or self-viewing surfaces are more complex to image and require additional steps to gather background radiation levels and discern accurate temperatures. After obtaining a first set of uncorrected IR data for the specimen, data are gathered for the effective temperature of the reflected background at each location by temporarily applying background mirrors (aluminized polyester film) to the specimen in multiple stages. Thus, for the case of an interior corner (e.g. the sill of a window frame), three sets of images would be collected: the unmodified surface, the background levels for vertical surfaces, and the background levels for horizontal surfaces. This technique allows for temperature corrections in only the area where the mirror is applied, so it is difficult to image an entire object in this way. However, this procedure can be useful for extracting accurate linear temperature profiles in complex areas of interest. It is necessary to keep in mind that the addition of the low-e mirror alters the thermal environment that determines the background, so it is important to keep the mirrors as small as possible.

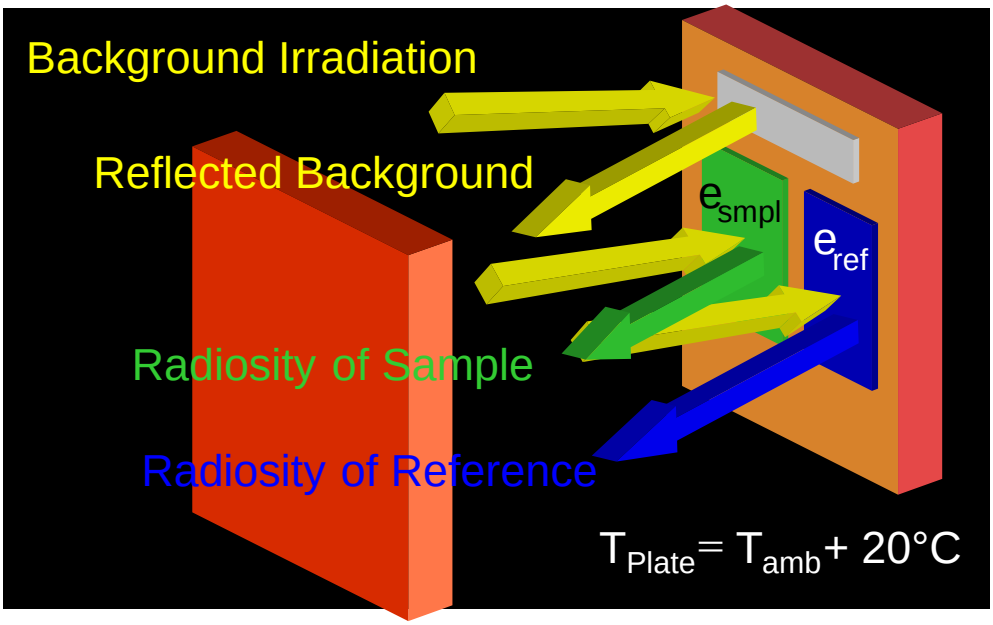
Emittance Measurement

Emittance describes the ability of a body to emit radiation. It is necessary to determine the appropriate emittance value for each surface on a specimen with respect to wavelength band of the IR imager being used and the temperature range on the object. Emittance is a basic material property; however, the appropriate emittance value to use for quantitative IR thermography is scaled by the wavelength-dependant response of the detector used in the radiometer and the temperature range of the object being imaged.

Therefore, the emittance values used in thermography may differ from literature values and may also vary among different types of detectors. The IR thermographer should use values for emittance of the various materials on a specimen's surface that have been first measured in a separate experiment, which compares the specimen's emittance to the emittance of a known material. An experiment of this type is diagrammed in Figure 9. Thin specimens of both the known material and the unknown sample material are mounted in good thermal contact to an isothermal, temperature-controlled plate and brought to the same surface temperature. Paper masking tape (e=0.9) makes a good reference. The temperature is set to at least 20°C above or below the background temperature to insure high contrast between the radiosity from the specimens and the radiation from the background. The IR imager is set to emittance 1.0 to turn off any background radiation compensation. Both specimens are imaged simultaneously. Readings are averaged over both time and space for the equivalent blackbody temperature of the unknown sample, $\mathbf{T_{e=1,smpl}}$, and the equivalent blackbody temperature of the known reference material, $\mathbf{T_{e=1,ref}}$. Background radiation equivalent blackbody temperature, $\mathbf{T_{back}}$, is quantified using a background mirror. Care is taken to provide a very uniform background, which is verified by imaging the background mirror. The emittance of the sample material, $\mathbf{e_{smpl}}$, is then calculated from the emittance of the known material, $\mathbf{e_{ref}}$, using Equation 4. Temperatures are Kelvin. Several measurements are made and then averaged.

$$e_{smpl} = \frac{\left(T^4_{e=1,smpl} - T^4_{back}\right)}{\left(T^4_{e=1,ref} - T^4_{back}\right)} e_{ref} \qquad (4)$$

Fig. 9 **Emittance Measuring**



Infrared Temperature Calculations

In order to obtain quantitative surface temperatures, raw thermographic data may need to be extracted from the imaging system and processed in a separate mathematical program. The image-processing component of the imaging system is used to extract data from the thermal image and export them in appropriate arrays of text values to be synchronized with spatial coordinates. The result for temperature at each data point should be calculated with the correct emittance and a location-specific background level. The calculated IR temperature for the reference emitter may be compared to direct contact measurements, and deviations may be used to scale the rest of the IR data. Separate data sets may be merged together to combine data from different views.

Equation 5 shows an expression for calculating a surface temperature, $\mathbf{T_{IR}}$, from the total thermal radiation represented by the variable $\mathbf{T_{e=1}}$, the emittance of the surface, $\mathbf{e_{surf}}$, and the background radiation level represented by the variable $\mathbf{T_{back}}$. $\mathbf{T_{e=1}}$ is an equivalent blackbody temperature for the surface being measured. $\mathbf{T_{back}}$ is the equivalent blackbody temperature for the background thermal radiation level as measured at each location with the aid of an applied mirror. Values for both $\mathbf{T_{e=1}}$ and $\mathbf{T_{back}}$ are obtained from the thermographic system by setting emissivity to unity. Conversely, setting emittance to less than one should cause the IR image-processing component of the imaging system to process the image data using the calculation in Equation 5. The thermographer should consider performing this calculation him or herself, using varying values for $\mathbf{T_{back}}$ and $\mathbf{e_{surf}}$.

$$T_{IR} = \left(\frac{(T_{e=1}^4 - (1 - e_{surf})T_{back}^4)}{e_{surf}} \right)^{1/4} \tag{5}$$

Equation 5 is used to determine both the apparent reference emitter temperature, $\mathbf{T_{IR,Ref}}$, (as measured by IR imaging) and the apparent sample surface temperature, $\mathbf{T_{IR,smpl}}$. The difference between $\mathbf{T_{IR,Ref}}$ and the direct contact measured value, $\mathbf{T_{DC,Ref}}$, may be applied to correct $\mathbf{T_{IR,smpl}}$ and to arrive at the final IR surface temperature result, **T**, as shown in Equation 6. This correction should be made for each temperature datum and for each IR image, to produce arrays of temperature values.

$$T = T_{IR,smpl} - (T_{IR,Ref} - T_{DC,Ref}) \tag{6}$$

Final data sets merge spatial location coordinates with temperature values. The real distances between location markers on the specimen are measured, and a coordinate system is used to create temperature/location data pairs. The temperatures may be

distributed linearly. Temperature data are then made a function of spatial coordinates, mapped to the appropriate coordinate system.

Infrared Temperature Uncertainty

The thermographer will want to estimate the uncertainty in temperature data. A previous publication by the authors discusses in detail the origin of the following equations used to propagate uncertainty (5). Errors in $\mathbf{e_{surf}}$ should be treated as a source of undefinable systematic uncertainty, $\delta\mathbf{e_{surf}}$, and may be analyzed by propagating uncertainty in Equation 4. Errors in $\mathbf{T_{e=1}}$ and $\mathbf{T_{back}}$ lead to random uncertainties, $\delta\mathbf{T_{e=1}}$ and $\delta\mathbf{T_{back}}$. $\delta\mathbf{T_{e=1}}$ and $\delta\mathbf{T_{back}}$ are usually closely related to equipment specification for Noise Equivalent Temperature Difference (NETD). To analyze error propagation in Equation 5, the sum of the squares of partial differentials of Equation 5 are calculated with respect to variables $T_{e=1}$, T_{back}, and e_{surf}, which leads to one possible solution, shown in Equation 7. The uncertainty in T_{IR}, $\delta\mathbf{T_{IR}}$, is then calculated using Equation 7.

$$\delta T_{IR} = \frac{1}{4}\left(\frac{T_{e=1}^4}{e_{surf}} + T_{back}^4 - \frac{T_{back}^4}{e_{surf}}\right)^{-\left(\frac{3}{4}\right)} \left(\sqrt{\left(4\frac{\delta T_{e=1}}{e_{surf}} T_{e=1}^3\right)^2 + \left(4T_{back}^3 \delta T_{back} - 4\frac{\delta T_{back}}{e_{surf}} T_{back}^3\right)^2 + \left(\frac{\delta e_{surf}}{e_{surf}^2} T_{back}^4 - \frac{\delta e_{surf}}{e_{surf}^2} T_{e=1}^4\right)^2}\right) \quad (7)$$

The total uncertainty in the measured surface temperature, $\delta\mathbf{T}$, is obtained from Equation 8. Values for both $\delta\mathbf{T_{IR,smpl}}$ and $\delta\mathbf{T_{IR,Ref}}$ are obtained using Equation 7. The uncertainty in the direct contact measurement of the reference emitter surface temperature, $\delta\mathbf{T_{DC,Ref}}$, is determined from the overall system accuracy of the direct contact sensor combined with any errors associated with adjustments that correct for gradients in the surface material. The uncertainty arising from variations across the field of view, $\delta\mathbf{T_{FOV}}$, is

determined from the magnitude of deviations in heavily averaged data for an isothermal plate that fills the section of the field of view being used. The uncertainty arising from non-linear performance or calibration of the imager, $\delta \mathbf{T_{Lin}}$, is determined by evaluating $\mathbf{T_{IR}}$ for a temperature controlled and separately measured target for a range of temperatures and evaluating how deviations change over that range.

$$\delta T = \delta T_{IR,smpl} + \delta T_{IR,Ref} + \delta T_{DC,Ref} + \delta T_{FOV} + \delta T_{Lin} \qquad (8)$$

Window Thermal Testing Example

An example of IR imaging science producing a temperature map is drawn from the authors' work in building sciences (6, 7). Figure 10 shows two IR images of the sill region of a window. The window was conditioned in laboratory chambers to simulate a long, cold winter night. Building scientists would like to know the exact distribution of surface temperatures on the window for the purpose of checking computer simulations. The upper image in Figure 10 shows the window with an external reference emitter on the left side. Location markers are visible that delineate spatial features in the IR image. The lower image shows the same specimen but with IR mirrors mounted on it for gathering data on the effective temperature of the background. The final temperature data, shown in Figure 11, were obtained using Equations 5 and 6.

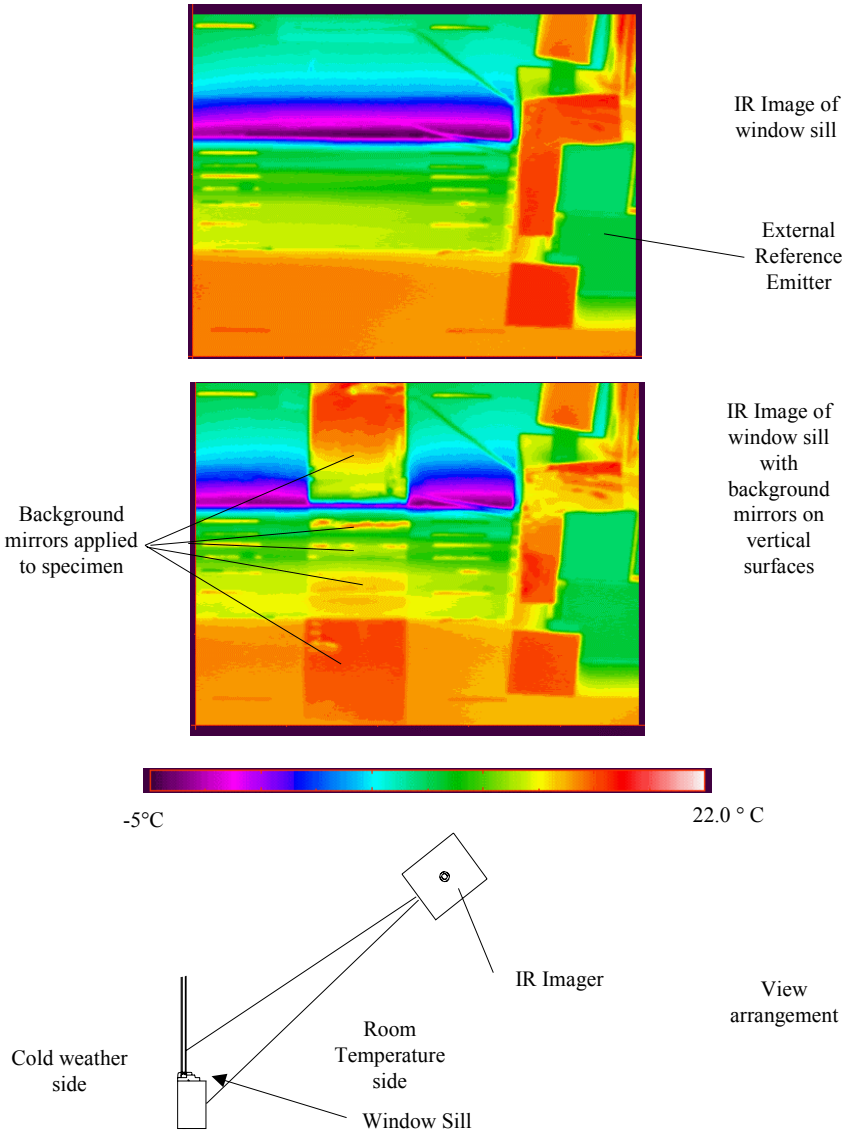
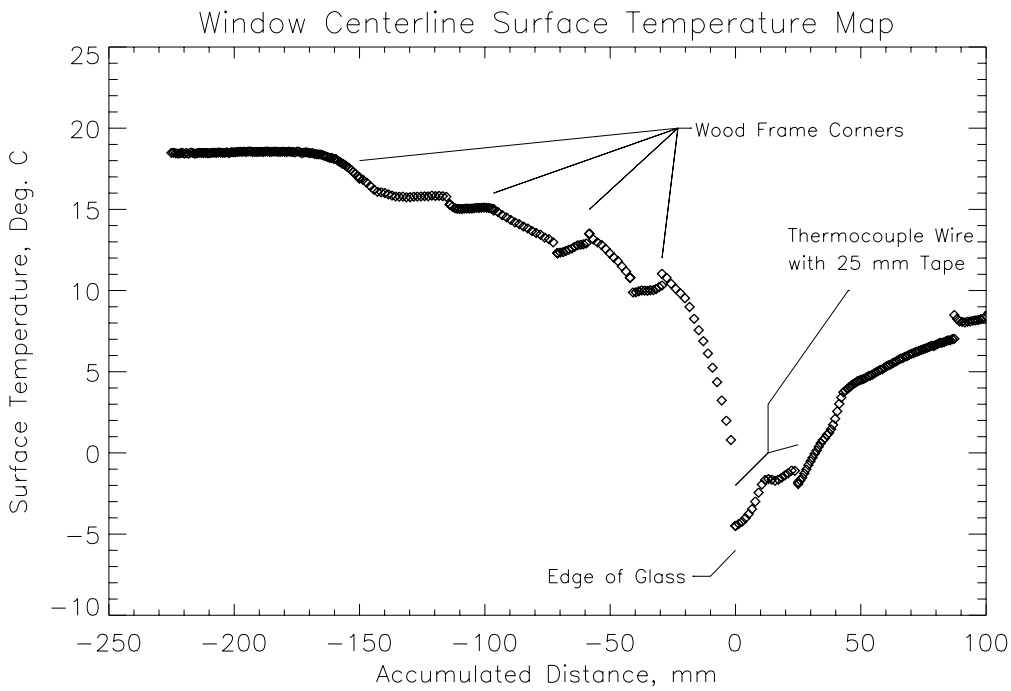


Figure 10 IR Images Used in Mapping Temperature of Self-Viewing Surface



CONCLUSION

This article provides a summary of infrared thermographic systems. The theory of operation, which is based on measuring blackbody thermal radiation, and the fourth power temperature dependence of emitted IR energy, demonstrates the strong signal inherent to this sensing technology and hence, the high temperature resolution that is achievable. There are various types of IR imaging systems. All of them generate images that represent the surface temperatures of an object, but they can be comprised of a variety of detector materials, each with unique spectral-physical properties, which makes it important to select the proper detector technology for a particular application. There are two major families of optical design, focal plane array imagers and motorized scanning

mirror based imagers. For successful IR imaging, it is essential to be aware of the surface property emittance. Knowledge of surface emittance, in the spectral band of the imager being used, allows the thermographer to distinguish the emitted portion of the measured radiation from the reflected portion. The thermal setup and environment also require special considerations for successful thermography. The thermographer often manipulates the overall heat transfer situation that leads to the temperature differences imaged on the specimen of interest in order to produce the most accurate and informative thermal data. Scientific temperature mapping is a methodology that improves upon the absolute accuracy of quantitative thermography. The procedures employed include external referencing targets and background mirrors. Typical applications of IR imaging include: thermographic inspection for predictive maintenance, medical imaging, non-destructive materials testing, and building component testing.

The future of IR imaging will likely see many more applications emerge, as this powerful technology becomes more accessible with less expensive and more compact equipment. New detector types such as microbolometers, QWIPS or direct sensing optical systems (change of refraction due to temperature) will become more prominent. IR imagers will be substantially smaller and more portable with reduced power requirements, as a result of compact focal plane array optics and not being burdened by providing cryogenic cooling for sensors. Increasing computing power will make image analysis and processing possible for online usage. Image resolution of focal plane arrays is expected to rise. Mega-pixel arrays will likely be available for thermal imaging. Faster image acquisition speeds will open a new world of diagnostic possibilities for very fast thermal

phenomena such as combustion or blasting technology. The various detection mechanisms may make IR imagers even more specialized for their intended application. Selecting the appropriate technology for the job will continue to be important. For instance, an imager with a very high frame rate may lack the ability to make absolute temperature measurements as accurately as an imager designed for slower phenomenon, where absolute accuracy is most crucial. Overall, there is much to be learned by "seeing" temperatures with an IR imager, and this capability is likely to grow more powerful, and become more accessible, in the future.

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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