PDHonline Course E407 (3 PDH)

Introduction to Infrared Inspections

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Course Description

This course consists of a primer in the subject of infrared thermography and infrared cameras. It begins with a discussion of heat transfer. Emphasis is placed on the complex subject of thermal radiation. It progresses to an examination of infrared cameras, and provides an overview of applications for infrared thermography.

This course will take about 3 hours for study and quiz-taking. The student will acquire three (3) continuing education credits upon successful completion of this course.

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1. What Is Thermography?

The author is unaware of any standard definition of thermography. A suggested definition is: *the study of apparent temperature patterns of physical objects and buildings*. A *thermographer* is a person who is trained and experienced in *thermography*.

All objects on Earth emit invisible heat radiation. This radiation occurs in the form of infrared radiation, or **IR**. Laboratory instruments to detect IR were developed in the 19th century. A first generation of commercially useful IR cameras was developed about 1960. For decades, though, IR cameras were expensive, large, difficult to use, and limited in usefulness. Fortunately, in the early 1990s, technological advances led to the development of much more compact and powerful IR cameras. Progress in microelectronics and material science now allows manufacturers of IR cameras to pack more capability into devices which are easier than ever to use. Each of the thousands of detectors in a camera consists of a microbolometer. A microbolometer is a sensor whose electrical characteristics change in response to exposure to IR. The current generation of “long-wave” IR cameras uses Focal Plane Array, or FPA, technology.

Infrared radiation will be explained in greater detail later in this course.

Objects or buildings will radiate different amounts of radiation depending upon how hot or cold they are. So, infrared cameras can be used to take “thermal pictures.” A thermal picture will be shown on the view screen of an infrared camera. Software provided by manufacturers of IR cameras can then be used to convert invisible thermal pictures into colored or grayscaled images that can be easily printed out and presented in reports. The printed images show patterns of temperatures that people can understand and use.

Thermography allows hot areas or hot spots, or cold areas or cold spots to be detected. It is also a non-contact technology, which reveals an overall picture that would otherwise have to be obtained by thousands of temperature sensors.

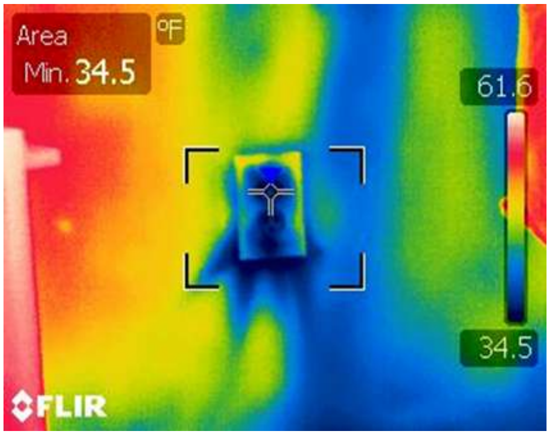
2. Uses and Benefits of Thermography

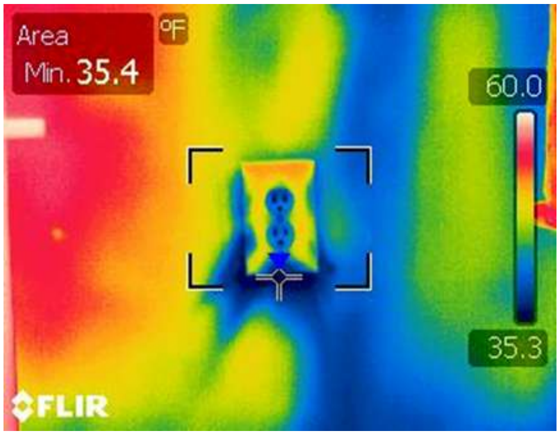
All businesses, and indeed, all organizations, need to maintain their equipment, assets and buildings in good working condition. Equipment failures can result in lost production, downtime and inefficient use of personnel, delays in filling orders, and physical damage, including damage that can cause injuries and even deaths. Governmental organizations, and schools and universities also need to keep their building systems, and supporting facilities and equipment up and running. A common factor is that all plant equipment, all building systems, and all buildings are prone to failures and wear that can impair an organization’s ability to function normally. Yet organizations are often kept running by equipment which is expensive to buy, and, in event of failure, costly to replace. Similarly, the flat roofs which are typical of buildings with large floor space are prone to water leakage due to a variety of factors. The breach of a roof’s water impermeability can have costly consequences.

Infrared cameras are very useful because they detect patterns of temperatures of surveyed objects. And because IR cameras are non-contact devices, they can detect these patterns at a distance from the object(s) in view. Entities which are hotter than most objects in an IR camera's field of view will be apparent in a captured infrared image. Conversely, images which are abnormally cold will also be evident. The differences in temperatures allow conclusions to be drawn about defects and shortcomings. For example, electric wire terminals which are too hot due to loose connections can be spotted from a safe distance. Or, the pattern detected by an IR image of a home's walls could be indicative of the partial failure of a home's insulation due to water infiltration.

IR cameras are currently being used for a wide range of applications. The most common application is inspection of electrical equipment. They are also used for sensing areas of abnormal heat movement of the walls of buildings and homes; inspection of mechanical equipment in factories, distribution centers and buildings; finding missing or compromised segments of refractories and insulation for furnaces and boilers; and detecting areas of water infiltration through a flat roof. The U.S. military routinely uses infrared cameras.

Decades of experience have shown that intelligent use of infrared cameras can save organizations a lot of money.





The two thermal images above of an electrical outlet demonstrate the ability of an infrared camera to capture patterns of temperature. They also illustrate how insulation can lessen heat loss. The warmest parts of the image are about 60°F and shown in red; the coldest part are about 35°F and shown in dark blue. Markers appear at the coldest spots. The images show an outlet mounted on the outside wall of a home. In the first image, there is no insulation behind the electrical outlet. In the second image, a foam insulating piece inserted behind the outlet's faceplate reduces heat loss from inside to outside. Notice how cold blue areas are reduced at the outlet in the second image.

3. Conservation of Energy and Thermal Equilibrium

The first law of thermodynamics states that energy can neither be created nor destroyed, but is always conserved, even though energy appear in different forms, such as kinetic energy, voltage or heat. Energy is also conserved even when it is converted from one form to another, for example, from the mechanical energy of a power station's turbine to electric power.

Here's one example of conservation of energy: A roof which is cold at 6 a.m. is gradually heated by the sun after sunrise. Some of the impinging solar radiation heats up the roof, and some of it reflects back into the sky or towards other buildings. As the roof warms some of its energy is transferred to air in the attic roof; some to the roof's rafters; and some to outdoor air. Energy transfer processes are going on continuously.

A concept of importance to thermographers (users of IR cameras) is *thermal equilibrium*. When a thermal equilibrium is achieved, the temperatures of objects are reasonably stable. Thermographers should always strive to do their inspections during times when objects are neither heating up nor cooling off rapidly. This is because the closer the objects in view of an IR cameras are to thermal equilibrium, the more certain a thermographer can be that the temperatures of the objects are *not* due to a circumstance which will change quickly.

In reality, there is no such thing as perfect thermal equilibrium, because objects never achieve complete temperature stability outside of a controlled laboratory setting. In practice, though, engineers, technicians and electricians will be able to assume temperature equilibrium prevails during infrared inspections as long as they avoid situations where the upsetting influence of factors like strong winds or bright sunlight occur. Thermal equilibrium, or temperature stability, is assumed during the discussion of radiation heat transfer.

4. Specific Heat and Changes of State

Thermographers benefit by knowing about the importance of a substance's specific heat. They also are helped by knowing how changes in state of water from liquid to vapor, or ice to liquid can affect their work.

The *specific heat* of a substance is a measure of how much energy is required to raise a unit mass by one degree. Metric units for specific heat are kilojoules per kilogram-degree C.

Table 1 below lists the specific heats for a variety of substances. It also lists the energy required to change 1 cubic centimeter (cc) of the substance by 1°C.

TABLE 1
SPECIFIC HEATS

Material	Specific Heat	Specific heat per unit volume
	Kilojoules[1] per kilogram - °C	Joules per cc - °C
Air (at 0°C)	1.005	.001
Aluminum (pure)	0.896	2.425
Building brick (common)	0.84	1.344
Concrete, Stone 1-2-4 mix	0.88	1.848
Copper (pure)	0.383	3.429
Fiber, insulating board	0.048	.001
Steel, 1.5% carbon	0.486	3.768
Water (saturated, at 0°C)	4.225	4.225
Wood (maple or oak)	0.166	0.090

Table 1 shows that water has a specific heat over 4 times larger than that of air. By analyzing data in the right column, one can see that it takes more than 4,000 times as much energy to raise the temperature of one cc of water by 1°C as it does to raise one cc of air 1°C.

The specific heats of substances are important because they are indicative of how much energy they can store and how readily their temperatures change. Specific heat is like inertia. A heavily loaded truck will not accelerate as fast as a lightly loaded truck, but once it is up to highway speed, it has a lot of inertia. Similarly, substances with high specific heats like water or brick are generally slow to heat and slow to cool. Wetted substances also will generally not change temperature quickly. Conversely, the temperatures of a substance like fiber insulating board experiences temperatures changes with less heat input or heat loss, per unit mass.

Changes of state from solid to liquid (or the reverse, solidification), and from liquid to vapor (or the reverse, condensation) involve significant inputs (or releases) of energy. The following energies are required to change the state of water:

ENERGIES ASSOCIATED WITH WATER	
Melting (at standard atmospheric pressure) (Heat of Fusion)	334 kilojoules per kilogram (kJ/kg) (79.7 calories/ gram)[1]
Temperature rise from 0°C to 100°C	418 kJ/kg (99.8 calories/ gram)
Boiling (at standard atmospheric pressure) (Heat of Vaporization)	2,257 kJ/kg (538.7 calories/ gram)

[1] A calorie is the amount of heat required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C at atmospheric pressure.

Occasionally a change of state of water will impact a thermographer's thermal survey. For example, insulation in a home' s wall may be wet due to the condensation of water vapor passed through a tear in a vapor barrier. The chances of spotting the wet insulation with an IR camera are better in winter than in summer, because in warm weather, the water may have evaporated.

5. The Three Modes of Heat Transfer

IR cameras are thermal radiation detectors. Yet radiation is just one of the three modes of heat transfer, and it's crucial for thermographers to understand all three modes. Radiation will be discussed last and get the most attention.

Conduction

Conduction is the movement of heat through solid bodies. The *thermal conductivities* of materials are of interest to thermographers. Objects with high thermal conductivities will heat up and cool down faster than those with low thermal conductivities. They will also carry heat to and from other objects more readily. *Thermal conductivity* is represented by the letter *k*. Table 2 below lists the thermal conductivities of some substances:

TABLE 2 – THERMAL CONDUCTIVITIES

Substance	k (Watts/ meter - °C)
Air (at 0°C)	0.0224
Aluminum (pure)	204
Building brick (common)	0.69
Concrete, Stone 1-2-4 mix	1.37
Copper (pure)	386
Fiber, insulating board	0.048
Steel, 1.5% carbon	36
Water (saturated, 0°C)	0.566
Wood (maple or oak)	0.166

Table 2 shows there's a lot of variation in thermal conductivity among substances. Copper has the highest, and air the lowest, among listed substances. Fiber insulating board has a very low thermal conductivity.

Thermal conductivity and electrical conductivity are closely related. Both properties are due to a substance's abundance or lack of "unbound" electrons. Materials like copper that have an abundance of unbound electrons allow for the ready transmission of heat and electrical current. Steel has fewer unbound electrons than copper. The material structures of insulators have electrons which are tightly bound to the nucleus of their atoms. Insulators don't heat up easily. In general, metals have more unbound electrons than other substances.

Convection

Convection is heat transfer involving a fluid. A fluid can be either a liquid, like water; or a gas, like air.

Convective heat transfer is frequently "forced". The operation of a car's radiator offers one example of forced convection. A car's water pump forces radiator fluid through cavities of the car's engine, where it picks up excess heat generated by combustion in the engine. The water pump circulates radiator fluid to the radiator. As the car is driven down the road, air impacting on the radiator cools the radiator fluid (and heats the air.) If the car is moving slowly in stop-and-go traffic on a hot day, the radiator fan may kick on and off to provide forced air cooling not delivered by movement of the car. In contrast, "natural convection" happens when air and other fluids move due to density differences, as occurs outside during storms as heated warm air expands upwards, and cooler, denser air sinks towards the ground.

For thermographers, though, convective heat transfer will usually involve the transfer of heat from an object to the atmosphere, or, less often, from an object to water or another liquid.

When the need arises to express a rate of convective heat transfer numerically, the units used are always associated with an object's surface area. Equation 1 below is typical:

$$\mathbf{q = h * A * \Delta T} \qquad \textbf{(Eq. 1)}$$

The various terms in Equation 1 have the following units:

q: Watts (or BTUs/ hour)
h: Watts/ $(\text{meter})^2$ * °C (or BTUs/ hour * $(\text{ft})^2$ * °F)
A: $(\text{meter})^2$ (or $(\text{ft})^2$)
ΔT: °C (or °F)

In Equation 1, *h* is the *coefficient of convective heat transfer*. Thermographers shouldn't need to know rates of convective heat transfer. Engineers sometime use convective heat transfer coefficients determined through testing to analyze the performance of heat exchangers. Thermographers can get by with an understanding how *h* in Equation 1 will vary in different circumstances. Convective heat loss from the transformer's cooling fins, and the coefficient *h*, will be larger if there is a wind blowing than if no there's no wind at all.

Here's an example of the differences between and interactions of convective and conductive heat transfer: A pizza topped with cheese is removed from an oven. The cheese topping cools off faster than the crust due to convective heat transfer to the air. Air bubbles between the topping and crust insulate the topping from the crust somewhat, and hasten the cooling of the topping. However, the crust has more thermal inertia, and a minute after removing the pizza from the owner, a person might burn their mouth on crust but not the topping. The cheese topping has a high coefficient of convective heat transfer.

Radiation

Heat transfer by radiation is a much more complicated, and less intuitive, subject than conductive and convective heat transfer. The following treatment of this subject will begin with a discussion of some fundamental physical laws about energy and the electromagnetic spectrum.

Physicists have determined that energy is emitted from atoms in the form of entities which have no mass called *photons*. Photons travel at the speed of light in a vacuum. All photons have both a frequency "f" and a wavelength "λ", and are inversely related by the speed of light "c" as shown in Equation 2 below:

$$f = c/\lambda \qquad \text{(Eq. 2)}$$

In Equation 2:

f = cycles/ second;
c = $3.00 * 10^8$ meters/ second (the speed of light);
λ = meters/ cycle

The electromagnetic spectrum summarizes all forms of energy by wavelength and frequency. For convenience, exponents of 10 are used because the numbers which characterize the electromagnetic spectrum are both very small (e.g., 10^{-12}, a thousandth of a billion) and very large (e.g., a thousand billion, 10^{12}). Table 3 below has an approximate breakdown of the electromagnetic spectrum. "Approximate" is stressed because there is no exact breakdown of the divisions of the electromagnetic spectrum, and there is some overlap between some adjacent bands.

TABLE 3 – THE ELECTROMAGNETIC SPECTRUM

Classification	Wavelength range (meters)	Frequency range (cycles/ second)
Gamma rays	$(4.0 * 10^{-14})$ to $(6.0 * 10^{-10})$	$(5.0 * 10^{17})$ to $(7.5 * 10^{21})$
X rays	$(3.0 * 10^{-11})$ to $(1.0 * 10^{-8})$	$(3.0 * 10^{16})$ to $(1.0 * 10^{19})$
Ultraviolet radiation (UV)	$(1.0 * 10^{-8})$ to $(4.0 * 10^{-7})$	$(7.5 * 10^{14})$ to $(3.0 * 10^{16})$
Visible light	$(3.8 * 10^{-7})$ to $(7.6 * 10^{-7})$	$(3.9 * 10^{14})$ to $(7.8 * 10^{14})$
Infrared radiation (IR)	$(1.1 * 10^{-3})$ to $(3.8 * 10^{-7})$	$(7.9 * 10^{14})$ to $(2.7 * 10^{15})$
Microwave	$(1.1 * 10^{-3})$ to $(1.1 * 10^{-1})$	$(2.7 * 10^{9})$ to $(2.7 * 10^{11})$
Radio Waves	$(1.0 * 10^{5})$ to $(3.0 * 10^{-1})$	$(3.0 * 10^{3})$ to $(1.0 * 10^{9})$

The energy of a photon *E*, and its wavelength λ, is related in Equation 3 below as follows, by a number h which is known as Planck's constant:

$$E = (h * c)/ \lambda \qquad \textbf{(Eq. 3)}$$

In Equation 3:

E = energy (joules)
$h = 6.63 * 10^{-34}$ joules-seconds (Planck's constant)
$c = 3.00 * 10^{8}$ meters/ second (the speed of light);
λ = meters

Note: In Equation 3, h (Planck's constant) should not be confused with the coefficient of convective heat transfer h in Equation 1 (page 8).

The reader will note from Equation 3 that the energy of a photon is inversely proportional to its wavelength (and directly proportional to its frequency.) So, X rays, for example, are more energetic than ultraviolet radiation because X rays have shorter wavelengths than ultraviolet rays. Likewise, ultraviolet radiation has more energy than visible light, and both ultraviolet radiation and visible light photons have more energy than infrared radiation (IR) photons.

The sun is the main source of energy affecting the Earth. Solar energy which reaches the earth's surface consists of ultraviolet radiation, visible light, and infrared radiation of mostly short wavelengths.

Thermal radiation is self-emitted by objects within a range of about 2 – 14 microns.
At this stage the discussion of radiation emissions becomes more complex. By 1900, physicists had conceived an idealized object called a *blackbody*. A *blackbody* is an object which absorbs all thermal radiation energy impinging on its surfaces.

In reality there is no such thing as a blackbody, as all objects reflect some radiation. It's possible to construct devices which approximate blackbodies very closely, but that topic is not discussed further here. However, a blackbody is a very useful concept for many purposes.

Equation 4 below is the *Stefan-Boltzmann equation*, and it relates the power per square meter, E_b, emitted by a blackbody of uniform temperature, to its absolute temperature T, through the Stefan-Boltzmann constant σ:

$$E_b = \sigma * T^4 \qquad \textbf{(Eq. 4)}$$

In Equation 4, each individual term is detailed as follows:

E_b = Watts/ (meter)^2
σ: $5.669 * 10^{-8}$ Watts/ (meter)^2 * °K^4
T: °K (absolute temperature)

The temperature T of a blackbody in the Stefan-Boltzmann equation is always an absolute temperature. The Kelvin temperature scale is similar to the Celsius scale. Temperatures in the Kelvin scale start at 0°K at absolute zero, where there is no energy and no molecular motion. The freezing point of water at atmospheric pressure corresponds to 273.15°K and 0°C. The boiling point of water at atmospheric pressure corresponds to 373.15°K and 100°C.

It's possible to express the Stefan-Boltzmann equation in terms in English units using, for example, the Rankine scale, wherein 0°R is absolute zero, 491.67°R (32°F) is the freezing point of water and 671.69°R (212°F) is the boiling point of water. But thermographers won't be performing such calculations, so that subject will not be discussed further.

The most important fact to note about the Stefan-Boltzmann equation (Equation 4) is that the emissive power of a blackbody is proportional to the *fourth* power of the emitting object's absolute temperature. So, *the energy emitted by a blackbody increases a lot as its temperature rises*.

A blackbody will emit radiation of differing wavelengths depending upon its temperature. There is some complex physics involving integral calculus underlying this statement, and for simplicity it won't be repeated. Two points are stressed, and Figure 1 on the next page, which shows "bell curves" for blackbodies of differing temperatures, graphically explains these points.

First is that blackbodies of differing temperatures will have differing wavelengths at which there is a peak intensity of radiation emission. Second is that the higher a blackbody's temperature is, the more the wavelength bands of peak emissive power will shift to shorter and higher-energy wavelength bands.

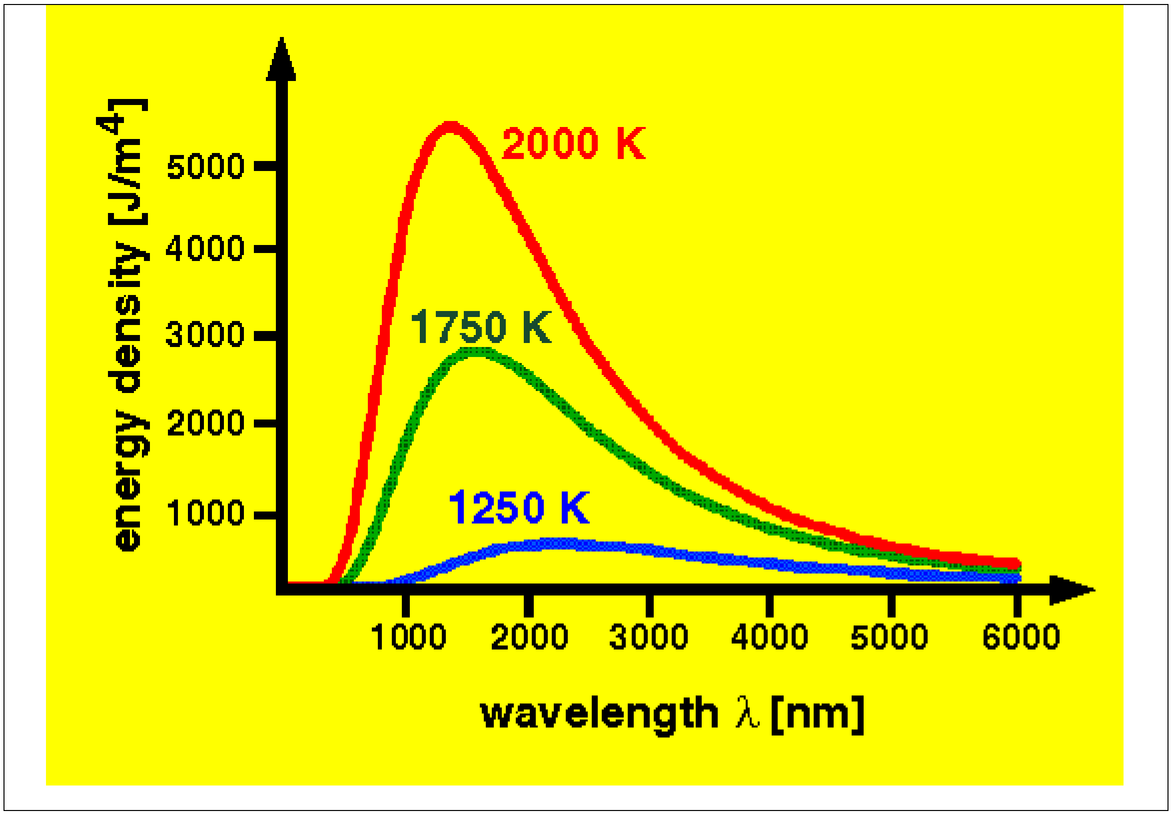


FIGURE 1[2]

6. Absorption, Reflection, and Transmission of Radiation

As mentioned previously, blackbodies – entities that absorb all radiation falling on them – are theoretical rather than real. In reality, thermal radiation impinging on the surfaces of real object will be *absorbed*, *reflected*, or *transmitted*.

If thermal radiation is *absorbed*, it acts to increase the object's temperature. *Reflected* thermal radiation will "bounce off" an object's surface either to other objects, or to the sky without heating the object. *Transmitted* radiation is passed through the objects. Most – but not all - objects in view of infrared cameras are *opaque*, meaning that they will not allow the passage of thermal radiation. Glass and some plastics are noteworthy exceptions.

Glass will allow passage of light and mid-wave IR but will block passage of long-wave IR. This helps explain why greenhouses are useful for growing plants. Mid-wave and short-wave IR are discussed later in Section 10.

7. Thermal Radiation, Emissivity and Thermal Equilibrium

The fact that all impinging thermal radiation is either absorbed, reflected or transmitted is a consequence of the first law of thermodynamics, which says that energy is always conserved.

Reflected Energy + Absorbed Energy + Transmitted Energy = 100%

For convenience, one can refer to Reflected Energy as "ρ", Absorbed Energy as "α", and Transmitted Energy as "Ƭ". Using this shorthand, the preceding equation simplifies to:

$$\rho + \alpha + \tau = 100\%$$

Most objects of interest to thermographers are opaque, so there is no transmission of impinging thermal energy through them. In these cases, the preceding equation simplifies to:

$$\rho + \alpha = 100\%$$

The preceding discussions have referred to impingement of thermal radiation on objects. In reality, *most objects of interest are raised to their temperature by heat from an interior source*, for example, by the electric current flowing through a wire, or a home's heating system. So the thermal radiation sensed by infrared cameras mostly comes from energy sources within the objects viewed, and the reflected portion of radiation sensed is much less than the emitted energy. This explains why infrared cameras are so useful – they can be used to make conclusions about objects based on temperature patterns.

If an object is opaque – and most objects are – than all of the energy coming from the object will consist of absorbed energy and reflected energy. So for opaque objects:

$$\rho = 100\% - \alpha$$

The *emissivity*, Ɛ, of an object is an index – an average number - of how much impinging thermal energy is absorbed by the object relative to 100%. An object that absorbs 90% of all impinging thermal radiation will have an emissivity of 0.9. A blackbody – a perfectly absorptive entity - has an emissivity of 1.0.

So, opaque objects with an emissivity of 0.9 will have a reflectivity of 0.1.

Section 4 of this text mentioned thermal equilibrium. It can be shown that *for objects in thermal equilibrium – that is, for objects with a stable temperature – that a material's emissivity, Ɛ, is equal to its absorptivity,* α[3]. Mathematically, this is expressed below in Equation 5:

$$\varepsilon = \alpha \qquad \textbf{(Eq. 5)}$$

Section 4 also mentioned that perfect temperature equilibrium is difficult to achieve. Fortunately, over short periods of time, the temperatures of most objects are quite stable, and Ɛ and α will be nearly identical even when temperatures are changing. So, *the emissivity Ɛ of an object is a property that thermographers can use with confidence*.

Applying the Stefan Boltzmann equation (Equation 4), the total radiation E emitted by an object (per square meter) becomes a function of the object's temperature T, the object's emissivity Ɛ, and the temperatures of background radiation sources with temperatures T_{b1}, T_{b2}, through T_{bN} which are emitting impinging energy.

$$E = \sigma * ((\varepsilon * T^4) + (1-\varepsilon) * (T_{b1}^4 + T_{b2}^4 + \ldots + T_{bN}^4)) \qquad \text{(Eq. 6a)}$$

Infrared cameras only have the capability to assume there is one background radiation source affecting the object of interest. This is acceptable because the percent of reflected energy received by an infrared camera from an object is usually much lower than the percent of emitted energy (most objects have an emissivity which is relatively high.) It's also true partly because temperature of the background source is usually significantly lower than the object's temperature. Equation 6a thus simplifies to Equation 6b:

$$\mathbf{E = (\sigma * ((\varepsilon * T^4) + (1-\varepsilon) * (T_b^4))} \qquad \textbf{(Eq. 6b)}$$

8. Real Bodies, Grey Bodies and Emissivity

Section 8 mentioned that an object's emissivity, Ɛ, is an index of its heat radiance. Emissivity is discussed in greater detail here.

Emissivity is an average number. It is calculated based on observations made in laboratory tests. When researchers measure emissivity, they look to see how absorptive it is over a particular range of wavelengths. The emissivity of a substance in what one source calls "the mid-wave region" (of infrared radiation) – from 2.5 to 6 microns[4] – will likely be different than it is in the "long-wave region" – from 8 to 15 microns. A substance may not absorb any thermal radiation in the bandwidth from 8.18 to 8.21 microns – but it might experience high absorptivity (and emissivity) in the bandwidth from 8.21 to 8.48 microns. (Wavelengths were chosen at random to illustrate a point).

The actual absorptivity and emissivity of a substance will vary a lot from one wavelength to another. This is characteristic of any substance – of any *real body*. But for convenience, engineers and scientists assume that substances are *grey bodies*. *Grey bodies* are idealized substances whose emissivity, Ɛ, is the same for all wavelengths in a certain range. The result is a useful, average value for emissivity. For example, one source reports that the emissivity of 3M Type 88 Black Vinyl Electrical Tape is 0.96 over the range 8 to 14 microns[5]. This is an average number.

Thermographers and engineers assume that objects are grey bodies with fixed emissivity settings. Thermographers should always use infrared cameras with adjustable emissivity settings for professional work.

TABLE 4 - EMISSIVITIES

Material	Emissivity
Aluminum (roofing material)	0.216
Copper (polished, 212 °F)	0.023
Duct Tape, Gray	0.84
3M Type 88 Black Vinyl Electrical Tape	0.96
Human Skin	0.98
Paint (oil based, average of 16 colors)	0.94
Water	0.95 – 0.963
Wood (pine, 4 different samples)	0.81 – 0.89

Table 4 above lists the emissivities of some materials. Much more comprehensive lists of emissivity settings are available from some manufacturers of infrared cameras.

By now, readers should have an appreciation of just how complicated heat transfer can be. Heat transfer is always going on through the three modes of conduction, convection and radiation. Also, objects are always emitting radiation towards other objects, and have radiation emitted by other objects impinging on them. Fortunately, thermographers don't need to calculate these effects. The beauty of infrared cameras is that one can use them to detect the temperature patterns of objects without physical contact, and often at considerable distances, too.

It was mentioned previously that the radiation emissions of blackbodies increase a lot with increasing temperatures. Equation 6b shows that the same is true of real bodies and real bodies.

9. Solar Radiation, the Atmosphere and Water Vapor

Solar radiation impinging on earth is heavily filtered by the atmosphere. Ozone in the upper atmosphere, for example, prevents most ultraviolet (UV) radiation from reaching earth's surface and bodies of water. Various gases in the atmosphere also react to the radiation bombardment. Water vapor in the form of clouds reflects a lot of sunlight back into space. Water vapor also absorbs a lot of the incoming radiation – not only light, but UV, and short-wave & mid-wave infrared radiation, too. Radiation reaching earth's surface consists of light, UV and IR.

Thermal energy always moves from hot objects to cooler objects. Objects on earth are warmed by solar radiation. As they cool, they emit radiation with lower energy states and longer wavelengths than the incoming radiation. So, radiation of various wavelengths reaching earth is radiated back into the atmosphere and space mostly in the form of long-wave IR.

The different gases in Earth's gases absorb radiation emitted by the earth to varied extents. But the concentration of most of these gases is predictably constant. The big exception is water vapor; its concentration varies a lot. As this affects thermographers, it means that the IR emitted by objects will be reduced in intensity before it reaches an IR camera, because water vapor absorbs some of that radiation. It also means that there will be more atmospheric absorption of IR on a humid day than a dry day. Likewise, more absorption of IR will occur as the distance between the user's infrared camera, and the surveyed objects increases. For the sake of accuracy, buyers of infrared cameras might want to make sure the camera they buy has an adjustment for the air's relative humidity, even if it costs more money.

Commercially available infrared cameras are subdivided between mid-wave and long-wave IR. Table 5 lists applicable ranges for mid-wave and long-wave infrared radiation.

TABLE 5

Infrared Radiation (IR) Classifications	Range
Mid-Wave	2.5 – 6.0 microns
Long-Wave	8.0 – 15.0 microns

These subdivisions are not precise. However, they align quite well with available products. Long-wave cameras are more common, and less expensive, than mid-wave cameras.

10. The Basics About Infrared Cameras

There are many infrared cameras on the market. Some manufacturers offer a suite of cameras with distinctive differences, intended for different markets.

The most obvious characteristic of a camera will be the size of its view screen. Another one which is not obvious but is important is the camera's number of detection pixels. A camera with a view screen of 160 pixels width and 120 pixels height will have 19,200 pixels. The number of pixels available is generally related to the amount of detail that a camera can capture.

Another characteristic is the camera body style. Some have a pistol grip; some are meant to be supported by one hand during imaging; some can be mounted on a tripod.

The type(s) of and numbers of operator controls vary a lot from camera to camera. It's also possible to fit a different lens – for example, a telephoto lens – on some cameras but not all. Some manufacturers provide an optional sunshade for the viewing screen. A sunshade can be very helpful. Other features which a camera or its accessories may or may not have include, but are not limited to: a laser pointer; an illumination lamp; an adapter allowing the camera's battery to be charged from a car cigarette lighter; ability to accept readings from a measurement device such as a current meter or dew point meter; ability to record video, etc.

Manufacturers also offer essential computer software. Windows compatibility is typically required and desirable; Mac O.S. software compatibility is also frequently available. Software which allows the printing of images and construction of reports is usually supplied as standard. Some manufacturers offer higher end reporting software as an option.

The calibration of an infrared camera should be checked if its performance is suspect. Generally, this involves sending the camera back to the manufacturer. An owner can expect that this will cost about $1,100 and that it will take the manufacturer a few weeks. However, camera owners can do two simple checks of a camera's calibration by seeing if the camera correctly reads 32°F for ice water, and 212°F for simmering water at a low boil. Appropriate emissivity settings must be used for these tests.

An introductory course cannot cover this topic in detail. Prospective buyers or renters of infrared cameras should check available product literature. They will have no trouble finding salespeople able to help.

11. Infrared Camera Specifications

Infrared cameras are described by a set of technical specifications. The most important ones are mentioned here.

An important spec is the *temperature range*. 0°C to 200°C (32°F to 392°F) is one temperature range. Sometimes the same camera's temperature range can be changed from something less than the maximum range available. For example, -20°C to 650°C may be the full range of the camera, with 0°C to 120°C range available. A user who will be getting thermal images only of homes, buildings and roofs will be able to get by with a narrower range than -20°C to 650°C. However, those who need to detect the temperatures of molten metals may find that range too low.

Field of View, a.k.a. *FOV*, is the angle in front of the lens that the camera can image, for example, 25° horizontal X 19° vertical. A camera's *Instantaneous Field of View*, or *IFOV*, is another noteworthy spec. *IFOV* is a measure of the three-dimensional solid angle (in milliradians) that each of a camera's pixels can sense in an image. The lower this number is, more sensitive the camera is. 2.5 mRad is a typical specification for *IFOV*. The Measurement Field of View, $IFOV_{meas}$, is a measure of the smallest object that the camera can detect clearly at a given distance.

Another important spec that relates to the camera's precision is the *Noise Equivalent Temperature Difference (NETD)*. The lower it is, the more precise the camera is. 50° millikelvin (mK) is a common spec for NETD. Some manufacturers will refer to the camera's *Minimum Resolvable Temperature Difference (MRTD)*. It, too, is a measure of its precision. The lower *MRTD* is, the more precise it is. *Accuracy* as a percent of range is another noteworthy specification.

A camera's *spectral range* is also important. The spectral range of most cameras these days lies in the long-wave infrared range. Most "long-wave" cameras will have a bandwidth than lies at or above 7 µm (microns) on its low end, and at or below 14 µm on its high end. In this range, a camera will detect thermal radiation emitted by virtually all objects examined. For some applications, a mid-wave infrared camera is the appropriate choice, but infrared cameras which sense long-wave radiation dominate in the market.

12. User-Adjustable Camera Features

Infrared cameras come with a variety of user-adjustable features. Not all cameras will have all of the features mentioned below, but most will. In some cases, a manufacturer may use terminology which differs from that presented below for some features.

A manual *focus* button, or manual *focus controls*, is (are) nearly universal. Many cameras also have an *auto focus* control. This very convenient feature will adjust the camera lens to automatically provide the sharpest possible image for the objects shown on the view screen. A *zoom* control to allow the user to limit the field of view of the image to something smaller than the default image size is another widely available feature.

Some IR cameras allow a rectangular infrared image to be embedded within a surrounding digital picture. (Generally called "Picture-In-Picture" selection.) When offered, the size of the infrared image is usually adjustable, too. Many cameras also allow a separate digital picture to be taken at the same time an infrared image is captured.

Most cameras have two or more *palette* choices. Rainbow, gray (white hot), and gray (black hot) are three widely used *palettes*. The rainbow palette uses the colors of the light spectrum – red, orange, yellow, green, blue, indigo, and violet – to depict the hottest through the coldest objects. The gray (white hot) palette will show areas of highest temperatures as a light gray with the darkness of the gray increasing with decreasing temperatures. Objects with temperatures outside the selected range will appear white if they are above the range, and black if they are below the range.

During actual use, most cameras will automatically sense the temperature range of objects in view and show the high and low ends of the range on the view screen. Exceptions are object temperatures outside the camera's limits of detection. Automatic temperature sensing is very helpful in that it gives the user a sense of the variations in object temperatures.

Manual controls let the user select the temperature range, and are essential to do professional work. This is done by first selecting a manual mode, then using *level* and *span* adjustment controls. The *level* control lets one adjust the midpoint temperature setting. The *span* control lets one adjust the upper and lower limits of the temperature range in relation to the level. For example, a camera whose level and span are set to 80°F and 40°F will have a range of 60°F to 100°F. Level and span controls let users examine objects in greater detail.

An *emissivity* adjustment is usually essential. The next useful adjustment is one for *background temperature*. It helps the camera figure how much radiation impinging on its lens is due to radiation from objects in the background, instead of from the objects in view. Many cameras often also have adjustments for *air temperature, relative humidity* and *distance to target*. These controls help a camera calculate how much thermal radiation between the objects in view and the camera is absorbed in the atmosphere.

The last adjustment to be mentioned is a *transmissivity* correction. It was mentioned earlier that most objects are opaque - they don't allow passage of IR through them. Sometimes heat emitting objects are located behind windows which permit passage of some thermal radiation. This is true of *infrared viewports*, also known as *infrared windows*. Infrared viewports are now standard options for motor control center (MCC) and switchgear doors, and they can also be retrofitted into existing doors. These viewports are very convenient for persons inspecting electrical equipment; they allow camera users to inspect electrical equipment without subjecting themselves to arc-flash hazards that can occur when the doors of electrical equipment enclosures are opened. Most viewports will absorb a minor amount of IR impinging on their surfaces, so a *transmissivity* control allows an infrared camera user to compensate for this reduction in IR intensity.

Some infrared viewports have excellent transmissivity of mid-wave IR but don't pass any long-wave IR. Conversely, some viewports are designed for transmissivity of only long-wave IR. Also, some viewports can have good transmissivity of both mid-wave IR and long-wave IR. Before a thermographer seeks to capture images through an infrared viewport, he or she must first check the characteristics of the viewport(s) to make sure his or her camera's spectral range is compatible with the viewport. Readers who have or expect to encounter IR viewports are encouraged to read "10 Things You Need to Know About IR Windows".[6]

13. Options for Infrared Inspections

Organizations interested in utilizing infrared cameras basically have three options: purchase, rental, or contracting with an outside firm to perform inspections. Each option is discussed below.

In 2019, a buyer can expect to pay between $5,500 and $10,000 to purchase a new infrared camera, including useful extras that will be well-suited for all non-specialized applications. A large price range is given because it is up to the buyer to determine what he or she considers a suitable camera. Each buyer has to determine what its needs are, and assess the options. In general, the buyer will get what they pay for. There is also an active market for resale of used cameras. A prospective buyer should expect to pay a lower price for a used camera. The camera software must be transferrable to a new owner, and if a warranty is still in effect on the camera, it, too, needs to be transferred. To use the camera(s), the firm's personnel must have adequate expertise in infrared thermography. So personnel training may be another cost. Formal training by either a camera manufacturer or an independent provider may be warranted. Neglecting travel expenses, a one-week training seminar will cost about $2,000.

If the buyer's personnel will be doing electrical equipment inspections, minimum expenses of about $1,100 (as of 2019) will be incurred for Personnel Protective Equipment (PPE) for each inspector.

Camera rental is a 2nd option. Infrared camera rental firms can be found quickly in a web search. Typically an IR camera renter will pay by the day, week or month. The rental fee can easily reach $1,000 per week when transportation costs are included. However, this may still be the most economical choice for many firms.

Contracting with an outside firm is the last option. A minimum cost figure for IR inspections by an outside firm is approximately $1,300 per day. (Additional costs will be incurred to develop a report.) Despite the high cost, this option has many benefits. Firms using this approach will benefit from utilizing the contractor's experience. This option will require advanced planning and coordination between the contractor and client. In general, the longer a firm has been in the business of thermography, the greater a customer can be assured of the firm's competence.

There is no one best option suitable for everyone. By way of example, a plant with 10 Motor Control Centers (MCCs) may find that purchase of an infrared camera is worthwhile for its own internal use. It would have the camera available for diagnosis if an overloaded motor phase, loose wire connection, or a hot-running bearing was suspected somewhere. But the same plant might hire an outside firm to inspect its utility feed transformers and fuses bi-annually. The writer's opinion is if a customer has a substantial number of units to inspect, like 40 MCCs, or a particularly a challenging application, like a roof inspection – then reliance on an outside firm is the best option.

Appendix B has an explanation of the 3 levels of qualifications of Thermographers used by the American Society of Nondestructve Testing (ASNT). Some companies that provide thermal inspection services judge thermographer employees by their level of ASNT qualification.

14. Applications for Infrared Thermography

This section surveys some main applications for infrared thermography. Only highlights are discussed. Specialized applications are not mentioned. A professional's detailed expertise is needed for each of the four types of inspection.

Electrical Equipment Inspections

Electrical equipment inspection is the primary use for infrared cameras. Electrical equipment failures are often costly in both monetary and human terms. The potential benefits of electrical equipment thermography are significant. Problems areas can be found before an expensive equipment failure occurs. Many organizations have yearly inspection programs.

IR cameras are excellent tools for finding the hot spots associated with electrical problems. There are two important things that thermographers must observe for this type of inspection.

First, the equipment to be inspected should be loaded to at least 80% of its rated current to get a really good thermal image. Second, electrical inspections expose thermographers to the potential danger of an "arc flash" (short-circuit) incident when they are in close proximity to power-handling equipment such as motors control centers and switchgear[2]. Arc flashes release dangerous levels of heat, and trigger a blast of heated air with explosive force. It's essential that thermographers abide by NFPA 70E[3], when they are very close to powered equipment with open covers[4]. This usually requires that appropriate **Personnel Protective Equipment**, or **PPE**, be worn. PPE can be uncomfortable to wear, especially in hot weather. But if used properly it will protect a person from arc flash burns.

Electrical equipment thermographers will often find either high temperatures due to a phase overload, or one or more "hot spots", which are usually attributable to poor or failing electrical connections. However, some electrical problems cannot be found by thermography. One example is a poor stab connection between a motor control center phase conductor and a bus bar which is hidden from the view of an IR camera.

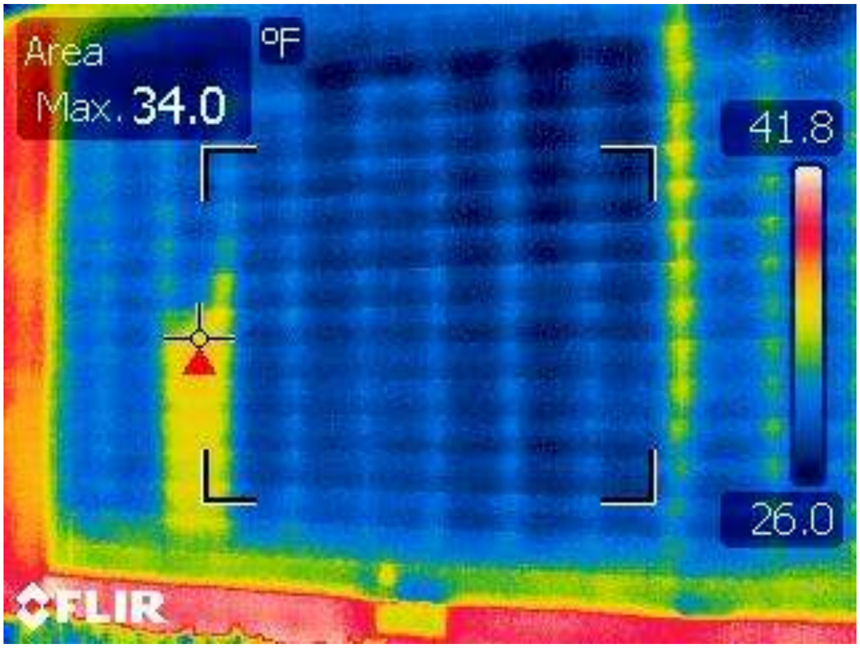
The level of professionalism and experience are important considerations in electrical equipment inspection. Those experienced in electrical equipment thermography usually know helpful "tricks of the trade".

This thermogram shows a fault with an industrial electrical fuse block.

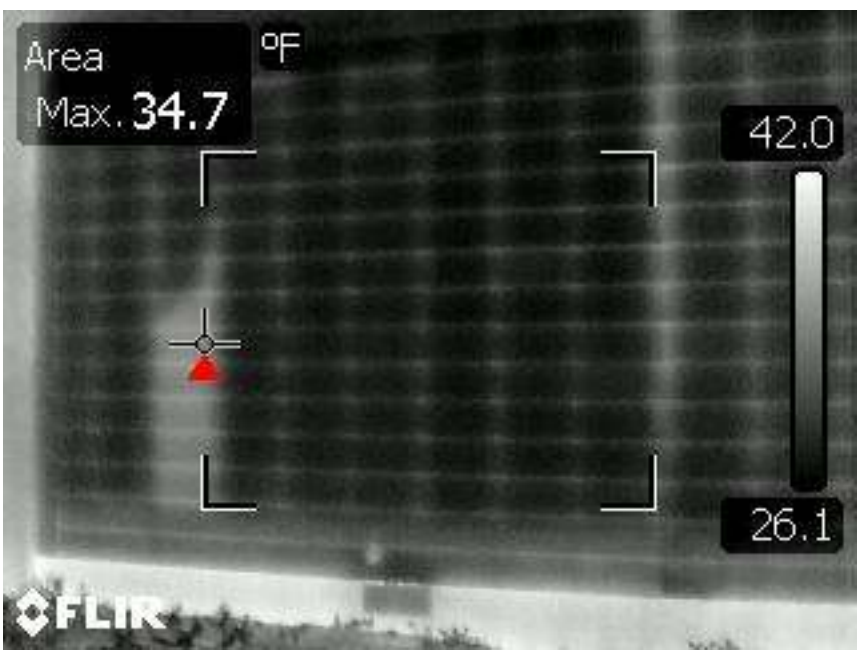
[2] Switchgear consists of electrical enclosures containing large power breakers, fuses and disconnect switches.
[3] Standard for Electrical Safety in the Workplace
[4] Be forewarned: the rules within NFPA 70E regarding when PPE is required, and what level of PPE is required, are rather complicated. NPFA 70E refers to a "Limited Approach Boundary" and a "Prohibited Approach Boundary."

Home and Building Inspections

Infrared cameras are good tools for finding deficiencies in homes and buildings which lead to heat loss. Examples of such shortcomings include missing insulation in a wall, or separated caulk beads. Some jurisdictions require thermographic inspections of new homes. Such inspections should be left to trained thermographers. A professional will limit survey periods to times when the effects of sun and wind will not result in erroneous readings.



This is a thermal image of the outside wall of an apartment building. The "rainbow" palette was used. The yellowed area on the left is warm, and insulation behind the wall is likely either missing, torn or wet. Viewed from the inside of the apartment, this area would appear cold in a thermal image.

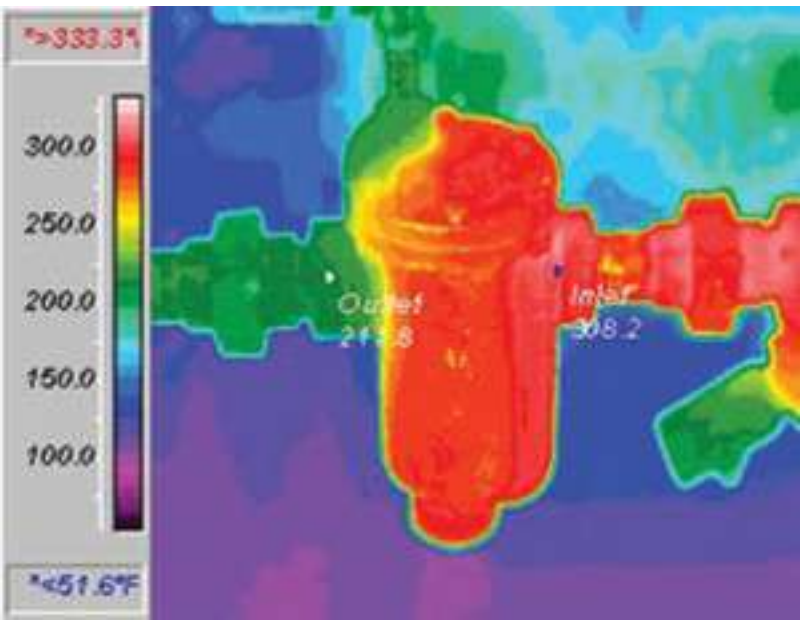


This is a thermal image of the wall of the same apartment building, taken about 2 minutes later. The grayscale (white hot) palette was used.

Utility companies often will do a complete home energy audit for a nominal fee. Such audits are likely to include infrared camera inspections. An audit may include a “blower door test”, in which a collapsible door is fitted over the main entrance, and a fan is used to pull air out of the structure. Areas of air leakage and missing insulation within a home can usually be spotted readily in a blower door test.

Other Equipment Inspections

Infrared cameras can also be used to find a variety of problems which have thermal effects in industrial plants, municipal plants, and commercial and governmental buildings. Examples include a failed steam trap; failing bearings; and a plugged cooling line. One application is depicted in the image below and explained in the box to its right.



A **steam trap** is a device that allows water condensed from steam to be passed to a drain line. They are closed most of the time, but open when the level of condensed water reaches a trigger point. They are widely used in many applications where steam is used, such as in heating systems. This image shows a properly functioning steam trap.

The interested reader may read an explanation on **Roof Inspections** in Appendix A.

15. Useful Tips for Thermographers

The practice of obtaining useful results through infrared thermography can sometimes be frustrating. Perhaps the greatest challenge is trying to find the temperature, or hots spots, of highly reflective materials of low emissivity. But other challenges exist. Eight tips to assist thermographers are listed below.

1. Wires are often secured to terminals with a highly reflective screw or bolt of low emissivity. Normally it's difficult to accurately measure temperatures of such screws. But if such screws have a slotted or Phillips-head screwdriver recess, it will act as a cavity that raises emissivity through internal reflection before emission. By aiming for the recess, and assuming a 90-95% emissivity, you can obtain a fairly close estimate of the object's real temperature.

2. As mentioned in Part 14, it is recommended that motors be running at 80% of rated load before doing thermographic inspections of motor circuits.

3. When working with a rather reflective surface of low emissivity, one may be able to measure its temperature by applying a piece of duct tape of known emissivity to the surface. However, that may require that the equipment be de-energized, then repowered.

4. Thermographers should strive to set background temperature as accurately as possible. The closer one is to the target, the more sense it makes to assume that background temperature is one's own body temperature. For distant objects, it can be assumed to be outdoor temperature.

5. Thermal surveys are best avoided during windy conditions. When wind in present, it makes it harder find hot spots and areas of heat leakage by reducing temperature differences. However, useful thermal images may be obtainable when breezes are occurring off and on.

6. A stable 18°F (10°C) or more difference between indoor and outdoor temperatures is recommended by ASTM[5] for doing home and building inspections while outdoors. Also, the higher the sun is in the sky, and the longer it has been sunny on a given day, the harder it will be to obtain thermal images showing deficiencies.

7. Accurate temperature measurements are not feasible when the emissivity of an emitting surface is 60% or less. That's because so much of the energy sensed by the camera is reflected by radiation.

8. In using a camera, one should do so it a way that it can't be dropped easily. (The author has an opening in his camera through which he fitted a cord worn around his neck to prevent accidental dropping of the camera.)

16. Course Summary

This course began with a discussion of the basics of heat transfer. This is appropriate, because a firm grasp of the subject of heat transfer help users of infrared cameras be aware of the power and limitations of infrared thermography. Important information regarding infrared cameras was conveyed. Readers should now have enough of an understanding about infrared cameras, thermography, and options for training & inspections to make intelligent decisions.

[5] American Society for Testing and Materials

Disclaimer

Readers are cautioned that *this text is not a substitute for formal training in infrared thermography*. Training is provided by several companies and organizations. Training sessions are also provided by some of the various reputable manufacturers of infrared cameras. Those who are interested in formal training are encouraged to engage in a web search, or contact some suppliers of infrared cameras.

Selected References

NFPA 70E	Standard for Electrical Safety in the Workplace
NFPA 70B	Recommended Practices for Electrical Equipment
ASTM 1153-10	Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging

Selected Web Resources

http://weatherization.org/ (Montana Weatherization Training Center)
http://www.thesnellgroup.com/ (The Snell Group)
http://www.infraspection.com/ (The Infraspection Institute)
http://www.asnt.org/ (The American Society for Nondestructive Testing)

Appendix A: Roof Inspections

The roofs of the large buildings which cover most commercial, industrial and governmental buildings are flat. These roofs are expensive to install. It is also expensive to replace these roofs, or portions of them. Water does not drain from these roof surfaces as readily as it drains from sloped roofs. Infrared cameras are a valuable tool for finding leaks in flat roofs.

When water leaks into a flat roof, it usually degrades a limited portion of it. Also, when these leaks occur, it is often difficult to find the area or areas where leak(s) are occurring by methods used decades ago. Replacing only the failed area(s) of a roof is cheaper than replacing all of a roof. Entire roofs have sometimes been replaced at a high cost when a replacement of the failed sections of roof would have sufficed.

A roof with water leaks will have water trapped below its surface, usually in insulation boards. However, effective infrared inspections of roofs can only be done when conditions are favorable. The roof surface must have no standing water or dew. Inspections are usually done after a sunny & a warm (preferably hot) day, and start about an hour after sunset. It's best to have a clear or mostly clear night sky with little or no wind at survey time. Under these circumstances, wet areas below the roof surface will be apparent to an infrared camera, because they will be warmer than dry areas. This is because wet insulation, and wetted areas between insulating boards, cool off more slowly than dry insulation. Infrared inspections of roofs are often done from helicopters or low-flying aircraft. This is the most economical means of surveying large roofs or complexes of buildings. This type of survey can only be done by a well-capitalized firm.

Coordination with the building owner or operator, and the thermographer(s) is essential for roof inspections. The thermographer should determine as much as possible about the roof's construction before inspections are done. Safety measures must also be observed.

Appendix B: Qualifications for Thermographers

In the United States, the organization which has developed standards and classifications for non-destructive testing (NDT) personnel such as thermographers is the **American Society of Nondestructive Testing (ASNT)**.

Three categories were developed by ASNT. Highlights pertaining to each classification, which were developed by ASNT, are listed below[7].

Level I Responsibilities:

- Perform calibrations, tests and evaluations for determining the acceptance or rejection of tested items in accordance with specific written instructions.
- Record test results but have no authority to sign reports for the purpose of signifying satisfactory completion of Non-Destructive Testing (NDT) operations.
- Receives instructions or supervision from a Level III or designee.

The minimum initial experience requirements for Level I personnel are 210 hours in the time frame of 1.5 – 9 months.

Level II Responsibilities:

- Be familiar with the scope and limitations of each method for which the individual is certified.
- Set up and calibrate equipment.
- Interpret and evaluate results with respect to applicable codes, standards and specifications.
- Organize and report the results of nondestructive tests.
- Train and guide Level I and trainee personnel as assigned when designated by a Level III certified in the application method(s).

The minimum initial experience requirements for Level II personnel are 1260 hours in the time frame of 9 - 27 months.

Level III Responsibilities:

- Be responsible for NDT operations to which assigned and for which assigned.

- Establish test methods and test techniques and authorize use of all NDT procedures to be used at the company by Level I and Level II personnel.
- Interpret test results in terms of applicable codes, standards, specifications and procedures.
- Be sufficiently familiar with thermal/ infrared testing to establish techniques and assist in establishing acceptance criteria where none are available.
- Be generally familiar with other applicable NDT methods.
- Be responsible in thermal/ infrared thermography for the training and examination of NDT Level I and Level II personnel.

ASNT guidelines allow training of Level I and Level II personnel to occur under the direction of a person with Level III certification, or a certified outside organization with Level III personnel. Level III personnel must be tested and certified by ASNT. Infrared thermography is just one of many methods of nondestructive examination.

FOOTNOTES

[1] A joule is the metric unit of work and equals the energy expended by a force of 1 newton acting through a distance of 1 meter. 1 newton equals the force which will accelerate a mass of 1 kilogram at a rate of 1 second per second.

[2] See http://itl.chem.ufl.edu/4412_aa/origins.html

[3] See, for example, *Heat Transfer*, p. 277, J.P. Holman, McGraw-Hill, Inc., 1976.

[4] A micron is one-millionth, or 10^{-6} meter.

[5] Infrared Training Center (ITC) Technical publication 29.

[6] “10 Things You Need to Know About IR Windows”: See www.iriss.com

[7] Courtesy of The Snell Group.