



Emissivity: Understanding the difference between apparent and actual infrared temperatures

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Application Note

Taking infrared temperature measurements is certainly a lot easier than it used to be. The tricky part is understanding when an infrared reading is accurate as-is, and when you need to account for certain properties of the materials you're measuring, or for other things like heat transfer.

The most common use of infrared temperature measurement is for the inspection of electrical power distribution equipment. Let's look at a typical three-phase fused power disconnect (Figure 1) and the corresponding infrared image (Figure IR1) below.

Figure 1 shows a typical 3-phase fused power disconnect. The corresponding infrared image, figure IR1, was taken with the emissivity setting at 1 on our thermal imager. The temperature span and color scale for the infrared image is set to 95.5 °F referring to black, with warmer temperatures indicated progressively by blue (105 °F), green (115 °F), red (125 °F) and white (133 °F and hotter). We also measured the load in phases A, B and C (from left to right), at approximately 34 amps each.

A simple analysis of the thermal image indicates that phase A is significantly hotter than phases B

and C. The fuse clip at the top of phase A indicates 133.4 °F, while the end of the fuse, specifically the metal cap of the top of the fuse, appears much cooler with a temperature of 103.6 °F and the fuse body just below the cap appears to be 121.9 °F.

Can this be true? Is the metal cap only 103 °F? No. You are seeing an example of the apparent temperature and the effect of emissivity. The fuse end cap is a highly reflective metal, in this case copper. Notice that the body of the fuse also appears hotter than the metal cap. The temperature of the cap is actually as hot as the fuse body it's in contact with.

To explain why the apparent temperature seen through a thermal imager can be significantly different than the actual temperature, let's review our knowledge of physics.

Thermal radiation and properties of materials

All objects emit infrared (thermal) radiation. The intensity of the radiation depends on the temperature and nature of the material's surface. At lower temperatures, the majority of this thermal radiation is at longer wavelengths.

As the object becomes hotter, the radiation intensity rapidly increases and the peak of the radiation shifts towards shorter wavelengths. The relationship between total radiation intensity (all wavelengths) and temperature is defined by the Stefan-Boltzmann law:

$$Q = e\sigma T^4 \text{ where:}$$

Q = radiation intensity

e = emissivity of material

σ = Stefan-Boltzmann constant

T = absolute temperature

At a given temperature, the maximum radiation is achieved when the object has an emissivity of 1. This is referred to as blackbody radiation, because with an emissivity of 1, the object is a perfect radiator. However in our real world, there are no true blackbodies, that is, no perfect radiators. Since real materials are less than perfect radiators, the relevant issue is "How much less than perfect are they?" **Emissivity is defined as the measure of how much less than perfectly a material radiates when compared to a blackbody.** But, emissivity is only one of three factors that cause an object to be less than a perfect radiator.



Figure 1: Fused power disconnect.

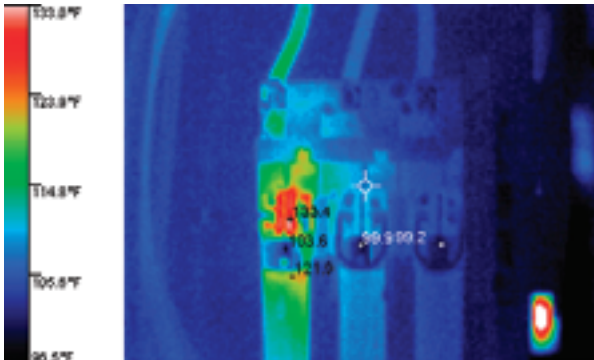


Figure IR1: Corresponding infrared image.

The thermal nature of materials

Materials (objects in everyday life, whether they are solids, liquids or gases) are constantly affected by their surroundings. Thermally, all objects attempt to exchange energy with other objects in their natural drive towards thermal equilibrium with their surroundings. In this search for thermal equilibrium, heat is exchanged between objects via three mechanisms: conduction, convection and radiation.

Conduction is defined as heat transfer between two solid bodies that are in physical contact with each other. **Convection** is heat transfer, usually between a solid material and a liquid or gas. Conduction and convection are dependent on physical contact between materials. **Radiation** is a process of heat transfer, characteristic of all matter (at temperatures above absolute zero). Radiation passes through a vacuum, and can also pass through gases, liquids and even solids.

When radiative power is incident on an object, a fraction of the power will be reflected (**r**), another portion will be absorbed (**a**), and the final portion will be transmitted through the object. The transmitted fraction is **t**. All of this is described by the Total Power Law:

$$r + a + t = 1 \quad \text{where:}$$

- r** = fraction reflected
- a** = fraction absorbed
- t** = fraction transmitted

The ability of an object to absorb radiation is also related to its ability to emit radiation. This is defined by Kirchoff's law

$$a = e \quad \text{where:}$$

- a** = absorbance coefficient
- e** = emissive coefficient

So in plain English, when the thermal imager observes the thermal radiation from real objects, part of what the thermal imager sees is reflected from the surface of the object, part is emitted by the object, and part may be transmitted through the object. In our example of a steel part, the

transmission is zero, but to the degree that the part is reflective, it is less emissive and therefore real objects will usually appear cooler than they actually are. Except when there is something hotter in the vicinity; since with opaque materials, the lower the emissivity, the higher the reflectivity. The result in this case is materials appear to be hotter than they actually are! Let's examine some real objects to illustrate these effects.

Applying emissivity to real objects

In the figure IR1 example, not only is the fuse end cap temperature actually much hotter than the 103.6 °F that it appears, the hot spot above it is most assuredly hotter than the 133.4 °F that it appears.

So, how much hotter might it be? This fused power disconnect is electrically energized, so let's conduct a simple experiment with a metal part that is **not** electrically energized. **Note: While this experiment may not be shocking, it can still burn you.**

Picture a round stainless steel block sitting at ambient temperature. Observed with our thermal imager (with emissivity set to 1), the metal appears to vary in temperature from about 74 °F to 87 °F. This seems to make sense, since the block could have picked up a little heat from our hands during handling.

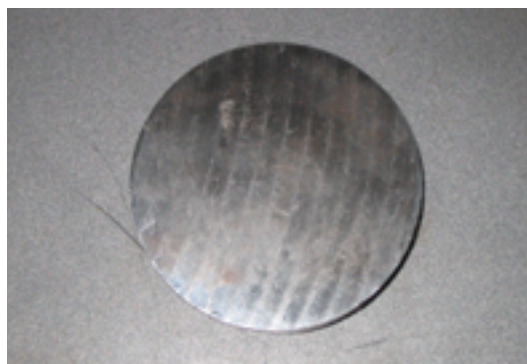


Figure 2: Stainless steel block.

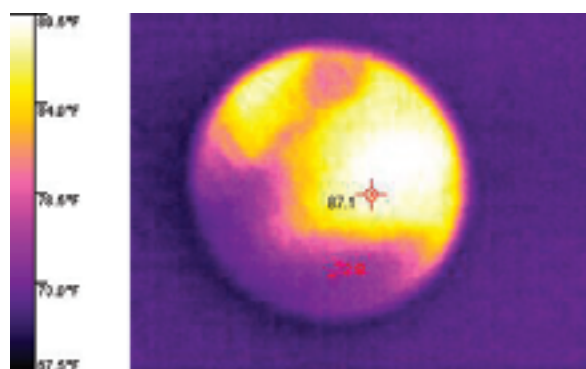


Figure IR2: Thermal image of stainless steel block.

Actually, the metal block is very uniform in temperature. The apparent hot spot is a reflection of my face on the surface of the metal. Can you see my eye glasses in the image? (Figure IR2)

Now let's take this block and place it in a warm oven and bake it for three hours. We remove the block from the oven and inspect it with the thermal imager [see Figure IR2a]. The block appears to vary in temperature from about 92 °F to 110 °F—and you can see the image of my face in the warm metal surface even more clearly than before. Using a thermocouple, we measure the surface temperature and find that it's actually 169 °F (see Figure 2a).

How can the thermal imager's readings appear reasonable when the metal part is at room temperature and be so wrong (still producing a mirror image of my face on the hot surface) when the part is 169 °F?

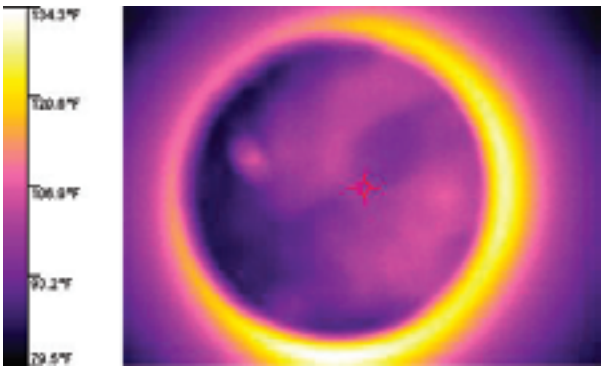


Figure IR2a: Thermal image of steel block after heating.

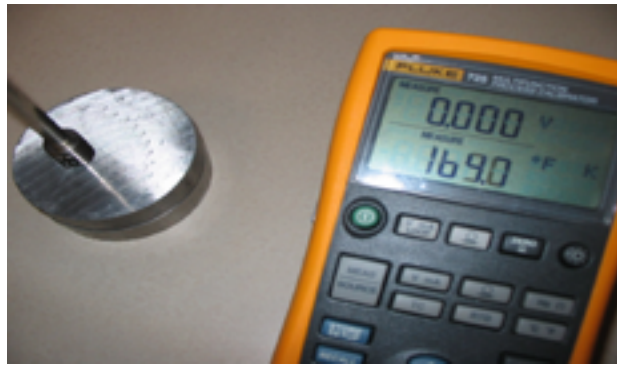


Figure 2a: DMM with thermocouple, measuring surface temperature of the steel block.

At room temperature, the block appears to be room temperature because the block is primarily reflecting the thermal radiation from everything around it. Since the ambient temperature in the room is in the 70s, the reflection from the surface of the block appears also to be similar. When the same part is heated in the oven, the part becomes much hotter than the surroundings, so the thermal imager is able to see an increase in radiant energy, albeit much lower in apparent temperature because of the low emissivity value of the surface. Let's modify our experiment to better demonstrate what the thermal imager sees.

We take another stainless steel block and paint half of it with a flat black paint (flat black paint has an emissivity of 1) and bake it (in a slightly warmer oven) another three hours (Figures 3 and IR3). When we remove the block from the oven this time, the unpainted side appears to be 92 °F but the thermal imager now indicates the painted side to be 198 °F. We can make a very good estimation of the actual emissivity of this material by observing the unpainted surface with our IR camera and adjusting the emissivity value on the thermal imager until the reading matches the temperature observed on the painted side. In this case, the emissivity is found to be approximately 0.12.

Emissivity is a cantankerous variable

As we've seen, emissivity varies by surface condition, but also by viewing angle, and even by temperature and by spectral wavelength. A table of common emissivity values is published in the operating manual for your thermal imager. The table should be considered only a rough guide in estimating an emissivity value to use with any particular material. If actual temperature values are required, it is best to perform experiments as described here, to properly characterize the emissivity for the material and its application. The two most

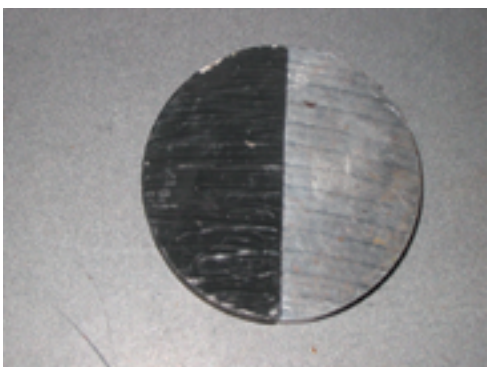


Figure 3: Steel block, left side painted black.

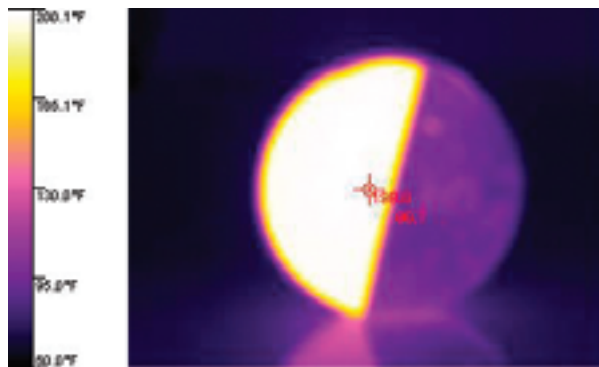


Figure IR3: Corresponding thermal image of steel block.

common techniques for providing a higher emissivity reference surface are the application of a flat black high emissivity paint to the surface (as discussed in the previous section), or application of common black electrical tape to the material's surface. Both black electrical tape and flat black tape have an emissivity of approximately 0.96. Another option is to use an infrared thermometer with adjustable emissivity, and a contact probe, adjusting the emissivity until the contact probe and infrared temperature displays equilibrate.

In this experiment we see that the difference between the apparent temperature on the unpainted side and actual temperature is an error of 106 °F. If we were to conduct a similar experiment with a high temperature infrared sensor, and examine steel at 2000 °F, the error between the actual and apparent temperatures could be more than 400 °F. Of course, neither black paint or tape could survive 2000 °F.

It's often useful to use a narrow spectral band similar to the wavelength of the object's radiant energy. Wien's Displacement Law helps us determine the peak wavelength of the object's peak radiant energy for an object at a certain temperature.

$$\lambda_{\max} = b / T \quad \text{where:}$$

λ_{\max} = peak wavelength of radiant energy
 $b = 2897 \text{ micron} / ^\circ\text{K}$
 $T = \text{temperature (Kelvin)}$

When you are working with high temperature materials, you can greatly reduce the errors due to uncertainty in emissivity by selecting infrared detectors that operate at narrow wavelength bands at shorter wavelengths.

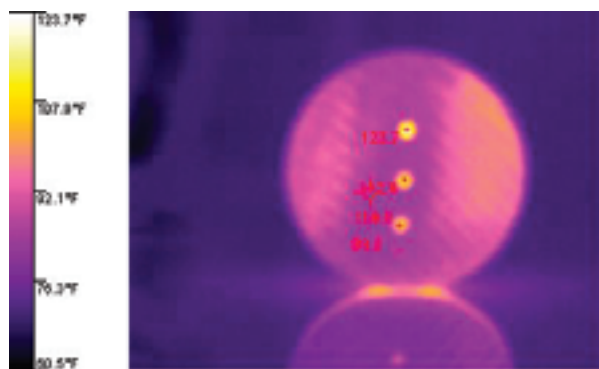


Figure IR4: Thermal image of steel block with three holes.

The math and physics necessary to prove this is beyond the scope of this application note. However, calculations demonstrate that by choosing an infrared sensor with a wavelength band close to one micron (rather than the 8-14 micron spectral band used by most thermal imagers), the maximum difference between the 2000 °F actual and apparent temperatures would be closer to 50 °F, (without knowing the precise emissivity of the material with better certainty).

To summarize: Temperature measurement without knowledge in this case would result in an error of more than 400 °F. Making the same measurement with knowledge would reduce the error to 50 °F, with no better determination of the material's emissivity.

Emissivity, the variable variable!

Back to our steel block example, let's discuss another very significant phenomena. We will take our unpainted metal block and drill three holes part way into the body. All three holes are 1/8 inch diameter. The first is 1/8 inch deep, the second is 1/4 inch deep, and the third is 3/8 inch deep. Bake the block for another three hours, then remove the block and observe it again with the camera. [See Figure IR4.]

Interestingly, the hot block surface appears to be about 84 °F, and now appears to have three hot spots. The 1/8 inch deep hole appears to be 106 °F. The 1/4 inch deep hole appears to be 112 °F; and the 3/8 inch deep hole appears to be 125 °F.

We know that the metal block is actually about 175 °F (measured by a thermocouple) and the surface finish is uniform and has an emissivity of approximately 0.12. The reason the temperature appears to be higher in the holes is that a hole in a body enhances the emissivity. The greater the depth/diameter ratio of the hole, the greater the emissivity enhancement. By adjusting the emissivity on the thermal imager to match the actual temperature at each hole, we find that the emissivity appears to be 0.25 for the 1/8 inch deep hole. The emissivity of the 1/4 inch deep hole appears to be 0.35 and the 3/8 inch deep hole appears to have an emissivity of 0.45.

This is an extremely important effect. Let's look at another piece of electrical equipment to see why.



Figure 5: Three-phase power disconnect.

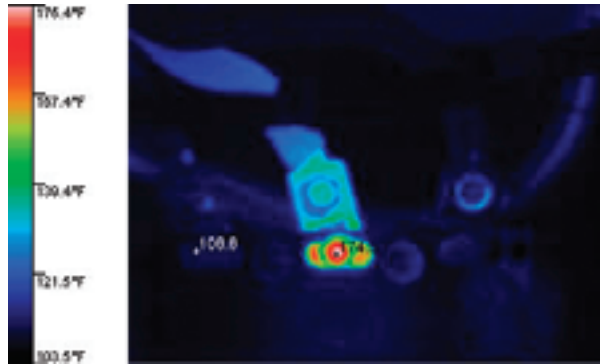


Figure IR5: Corresponding thermal image.

Emissivity and electrical equipment

In Figures 5 and IR5, you see another power disconnect with the conductors bolted in place using Allen head bolts. The corresponding infrared image shows a hot connection on the middle phase. Notice the apparent hot spot in the hot Allen socket head. The well of the bolt head appears hotter primarily because the well illustrates the blackbody effect of a hole.

In manufacturing processes, steel or aluminum rolls are often used to heat or cool a material such as in paper or plastic film processing. These rolls are usually polished metal surfaces, and it's important to understand the thermal profile since the manufacturing process depends on thermal uniformity across the rolls. The temperature of these rolls can be difficult to measure with a thermal imager because they have

very low emissivities. However, there are often points where the material passes between two rolls. The tangent point between two rolls also tends to simulate the blackbody effect, allowing for effective temperature measurement in an otherwise difficult situation.

This effect is illustrated in common electrical equipment as well. Look at Figure 6. In this case, we have another power disconnect with knife blade switches. This type of switch utilizes shiny metal blades, and the proximity of the blades with narrow gaps simulates the blackbody effect for greatly improved effective emissivity.

The important message here is to develop your understanding of apparent and actual temperature measurement. Actual temperature measurement requires an intimate understanding of physics, heat transfer and characteristics of materials.

Qualitative vs. quantitative infrared thermography

Emissivity difficulties are not a barrier to effectively using infrared thermography for predictive maintenance (PdM). ASTM standards exist to guide thermographic PdM inspections. These standards describe the use of thermal imagers for qualitative and quantitative infrared inspections.

Quantitative infrared inspections require determining the emissivity of each component, to make accurate temperature measurements possible. This practice may not always be necessary for routine inspections, unless the exact temperature value is needed for long term tracing. Qualitative methods, in contrast, allow you to leave the emissivity at 1.0 and evaluate the equipment on a relative basis: Has it changed, or is it different? The basis for qualitative evaluation is comparing similar equipment under similar loads.



Figure 6: Power disconnect with knife blade connectors.

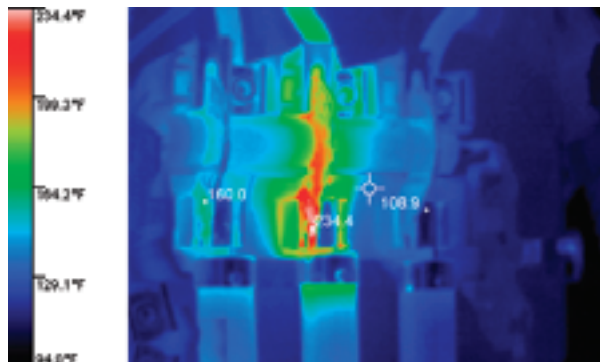


Figure IR6: Corresponding thermal image.

Looking back at Figures 1 and IR1, you can see that there is little value to be gained in spending time estimating or debating the emissivity of the various parts in the power disconnect. The value is in understanding that phase A is hotter than phases B and C. In addition to realizing that a phase is hotter, it is essential to measure the load of the three phases. Greater electrical load inherently means more heat is present:

$$P = I^2 R \quad \text{where:}$$

P = power in watts (heat)
 I = current in amps
 R = resistance in ohms

First rule of infrared thermography: Comparable equipment under comparable loads

The first rule of thermography in predictive maintenance is to compare comparable equipment under comparable loads. In electrical power distribution, comparable equipment is usually the easy part since each electrical phase is usually similar in materials to the phase next to it. Load is a very different matter. Figure 7 illustrates an electrician measuring the electrical load.

So, just observing that there is a hot spot does not indicate a problem. Electrical components can be appropriately hot for the electrical load and conditions. If you measure the loads, you can determine if the presence of a thermal anomaly indicates a problem. Thermal imagers do

not identify thermal problems—trained, knowledgeable, qualified people make educated assessments of equipment. This leads to real value in preventive maintenance and reduced frequency of equipment breakdowns.

Summary

Predictive maintenance with a thermal imager can be effectively performed by utilizing qualitative analysis of equipment. Qualitative techniques allow the emissivity setting on the thermal imager to be kept at 1.0 and apparent temperatures used for comparisons between similar equipment under similar load. With basic training, most technicians can reliably perform qualitative analysis.

Quantitative infrared analysis requires a deeper understanding of thermal theory and application to be truly effective. It refers to the attempt to measure actual temperatures of materials using infrared thermography. Actual temperature measurement involves more than simply adjusting for emissivity. Total incident radiance requires dealing with the effect of reflection and transmission in addition to emissivity.

Today's thermal imagers are becoming increasingly affordable and easy to use. But what does easy mean? The practice of infrared thermography looks straight forward and simple; but it has its tricks. It is much like most endeavors in life: The more you learn, the more you discover that there is more to learn.



Figure 7: Measuring the loads on a power disconnect.

References

The American Society for Nondestructive Testing publishes the **Nondestructive Testing Handbook, 3rd Edition, Volume 3, Infrared and Thermal Testing**. This work is referenced as the general source for the equations and technical data for the content of this paper.

Qualitative and quantitative infrared thermography are referenced to **ASTM E1934 Standard Guide to Inspecting Electrical and Mechanical Equipment Using Infrared Thermography**. This industry consensus document describes the recommended procedures for conducting infrared inspections for predictive maintenance.

Safety note: Infrared thermography is often used to inspect electrical power distribution equipment. This paper discusses the technical aspects of performing infrared analysis, especially as it relates to electrical equipment predictive maintenance. All persons working on or around energized electrical equipment should consult NFPA 70E for OSHA safety requirements.

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