Guideline for Developing and Managing an Infrared Thermography (IRT) Program

Technical Report

Guideline for Developing and Managing an Infrared Thermography (IRT) Program

1004019

Final Report, September 2001

EPRI Project Manager
P. Abbott

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRIsolutions

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Customer Fulfillment, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2.

CITATIONS

This report was prepared by

EPRIsolutions
1300 W. T. Harris Boulevard
Charlotte, NC 28213

Principal Investigators
R. Hammaker (Innovative Maintenance Optimization, Inc.)
R. Madding (Infrared Training Center, FLIR Systems, Inc.)

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Guideline for Developing and Managing an Infrared Thermograph (IRT) Program, EPRI, Palo Alto, CA: 2001. 1004019.

REPORT SUMMARY

The *Guideline for Developing and Managing an Infrared Thermography Program* is an extension of a number of reports addressing the use and benefits of InfraRed Thermography (IRT) as a diagnostic tool. This document expands on more of the technology's intricacies, as well as defining procedures for setting up a comprehensive IRT program.

Background

The EPRI M&D Center has worked with a large number of EPRI member utilities over many years to develop IRT instrumentation, applications, and techniques. Their efforts resulted in publication of several EPRI reports covering general use of IRT, identification of anomalies, establishment of fault criteria, and the calculation of cost benefits. This guideline focuses on how to establish an effective IRT program.

Objectives

- To provide the user with a procedure that will enhance IRT use.
- To offer useful information on the application of IRT, recommended training, and safety issues.
- A summary of the benefits of a good IRT program.

Approach

The EPRI M&D Center has conducted many IRT surveys, has instructed many utility personnel on the proper use of IRT equipment, and has documented the benefits. A large number of EPRI member utilities have now implemented IRT programs, either stand-alone or as part of a comprehensive predictive maintenance program; however, others have done very little or nothing at all. Because of the documented benefits of IRT, EPRI has sponsored preparation of this IRT program guideline, which will benefit thermographers of all levels, even experienced thermographers with established programs.

Results

The *Guideline for Developing and Managing an Infrared Thermography Program* will demonstrate the use and benefits of IRT and provide guidance on establishing a meaningful program.

EPRI Perspective

Support for plants employing new maintenance strategies is becoming increasingly important to EPRI members as they continue the search for ways to reduce cost while maintaining high reliability and availability. Development of technologies, such as IRT, is vital to achieving those objectives. Collaborative research and development efforts conducted by EPRI in the area of IRT

have contributed significantly; however, there is more that can be done. This guideline will enhance use of the technology and will further contribute to the program's stated objectives.

Keywords
Diagnostic technologypredictive maintenance
Infrared thermography
EPRI maintenance & diagnostic center
Equipment condition-based monitoring

ABSTRACT

This document is one of a number of EPRI Guidelines and Reports related to IRT technology. These Guidelines include in-depth information on the science of IRT and is a combination of a great deal of experience and expertise. The information contained is a result of the efforts made by EPRI and the EPRI M&D Center, by various experts in the field, and by the IRT equipment manufacturers.

In addition to valuable information on the IRT technology, the Guidelines cover how to set up an effective IRT program including nomenclature of terms, heat transfer considerations, equipment selection, how to conduct IRT surveys, benefits, training, and safety issues. It is of value both to the experienced thermographers or the novices.

ACKNOWLEDGMENTS

Gary L. Orlove, Infrared Training Center, FLIR Systems, Inc.

Stephen Braden, Red-Inc.

John Snell, Snell Infrared

John Niemkiewicz, Insertkey Solutions, Inc.

Ellie Cherry, EPRIsolutions

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Infrared thermography (IRT) provides a non-intrusive measurement of temperature and thermal behavior of plant equipment. Its principle purpose is to detect changes in temperature that can indicate the onset of problems which, if ignored, will eventually lead to failure. When a problem is detected in the early stages, maintenance planning can be accomplished more effectively, as personnel and replacement parts can be made available when needed.

IRT is a very versatile diagnostic technique that can be used in many different ways; therefore, in the planning stage it is essential to identify its intended purpose. IRT, for instance, can be used as a troubleshooting tool, as a pre-outage tool to assist with outage planning, or as a vital technology in support of a Predictive Maintenance (PDM) Program. Using IRT as a troubleshooting tool, or prior to an outage, of itself can be very effective; however, using IRT in this fashion will not provide nearly the amount of benefits when it is used as part of a PDM Program.

The versatility of IR thermography is further extended in that it can assist in the diagnosis of most plant equipment. In addition to its wide range of applicability, it is non-intrusive and provides equipment condition information almost instantly.

The purpose of the Infrared Thermography (IRT) Program Guideline is to delineate the elements that makeup a comprehensive IRT Program. In addition, the Guideline can be beneficial to the beginner as well as to the experienced thermographer.

Objectives

As a result, this Guideline describes the requirements of an IR program, whether it be used periodically as a trouble-shooting and pre-outage tool, or as part of a more extensive PDM program.

The IRT Program Guideline is written in a fashion that identifies each phase of an infrared thermography program. The Guideline is organized in a sequential manner, starting with pre-survey and program design considerations and ending with continuous improvement metrics.

Program Planning

As mentioned previously, the first step in establishing a thermography program, therefore, is to define its intended use. A preliminary plan will determine the equipment and resources needed, and their associated costs.

Troubleshooting/pre-outage tool

When used in this mode, it is necessary to define the equipment to be surveyed, the IR equipment needed, the personnel training required, and the man-hours to be expended. The bulk of the costs are spent in the first year setting up the program. After these initiate costs, the man-hours needed to do random surveys is minimal.

PDM Program

As mentioned, IRT is most beneficial when it is part of an overall PDM Program. PDM is a process of collecting data, assessing the data, and then converting the data into information that defines the appropriate time to perform maintenance. Identifying the health of plant machinery saves money and improves plant reliability as compared to preventative or corrective type maintenance strategies. PDM is a process that utilizes data from many different technologies such as IRT, vibration, lube oil analysis, acoustics, etc., as well as other data such as operators log, maintenance histories, process data, etc. Combining the data from all of these areas can better define the health of a component. However, even though IRT is part of an overall PDM the steps to be taken are the same as those needed to conduct trouble-shooting/pre-outage surveys only.

Nomenclature

IR Thermography includes the use of many unique terms. In order to help the thermographer learn the proper nomenclature and fully understand the definitions, a glossary of thermography terms is included in Appendix A: Glossary of Thermography Terms.

2
INFRARED THERMOGRAPHY

Basic Theory

Infrared energy is part of the electromagnetic spectrum and behaves similarly to visible light. It travels through space at the speed of light and can be reflected, refracted, absorbed, and emitted. The wavelength of IR energy is about an order of magnitude longer than visible light, between 0.7 and 1000 µm (millionths of a meter). Other common forms of electromagnetic radiation include radio, ultraviolet, and x-ray.

Electromagnetic Spectrum

It is known that infrared radiation is a form of electromagnetic radiation, which is longer in wavelength than visible light. Other types of electromagnetic radiation include x-rays, ultraviolet rays, radio waves, etc.

Electromagnetic radiation is categorized by wavelength or frequency. Broadcast radio stations are identified by their frequency, usually in kilohertz (kHz) or megahertz (MHz). Figure 2-1 illustrates graphically the electromagnetic spectrum and types of electromagnetic radiation fall within the wavelength ranges; and, the expanded infrared measurement region.

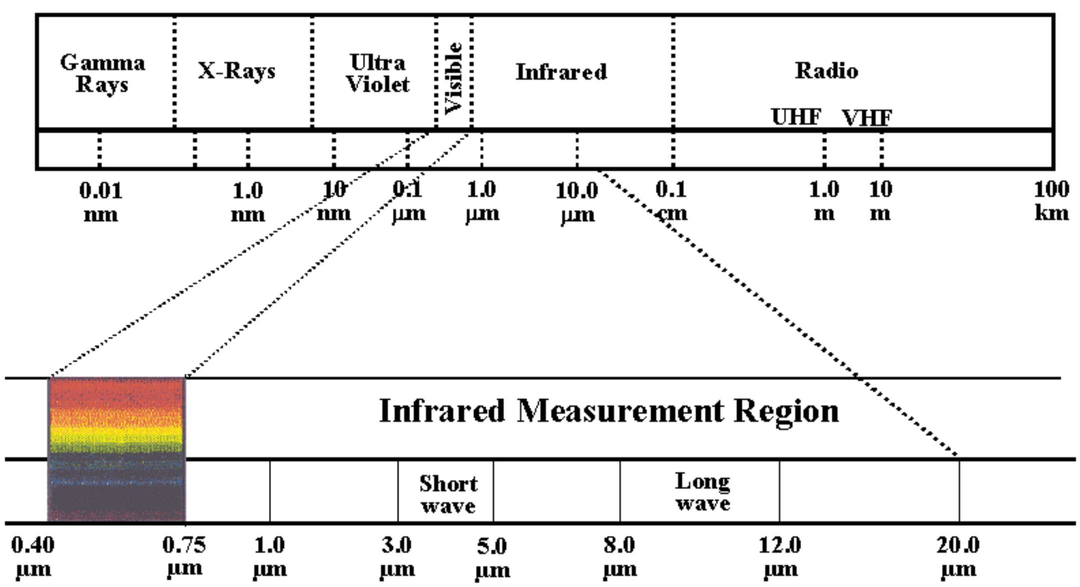


Figure 2-1
Electromagnetic Spectrum

Infrared detectors or systems are therefore categorized by their wavelength. The unit of measurement used is the micrometer, or micron, (µm, where µ is the Greek letter mu) which is one millionth of a meter. A system that can detect radiation in the 8 to 12 µm band is usually called ‘longwave.’ Alternately, one that detects radiation between 3 to 5 µm is termed ‘shortwave.’ (A 3 to 5 µm system can also be classified as ‘midband,’ because there are systems that can detect radiation shorter than 3 µm.) The visible part of the electromagnetic spectrum falls between 0.4 and 0.75 µm. Different colors can be seen because they can be discriminated between different wavelengths. If a laser pointer is available it can be noticed that the radiation is specified in nanometers; usually about 650nm. If a chart of the electromagnetic spectrum at 650nm (.65 µm) is examined, it can be seen that it is the radiation of red light.

Infrared Energy

All objects emit infrared radiation as a function of their temperature which means that all objects emit infrared radiation. Infrared energy is generated by the vibration and rotation of atoms and molecules. The higher the temperature of an object, the more that these nuclear particles are in motion and hence the more infrared energy that is emitted. This is the energy detected by infrared cameras. The cameras do not ‘see’ temperatures, they detect thermal radiation.

At absolute zero (-273.16°C, -459.67°F), material is at its lowest energy state so infrared radiation is almost non-existent.

Infrared Thermography

Infrared Thermography is the technique of producing an image of invisible (to our eyes) infrared light emitted by objects due to their thermal condition. The most typical type of thermography camera resembles a typical camcorder and produces a ‘live’ TV picture of heat radiation. More sophisticated cameras can actually measure the temperatures of any object or surface in the image, and produce false color images that make interpretation of thermal patterns easier. An image produced by an infrared camera is called a ‘thermogram’ or sometimes a ‘thermograph’.

Figures 2-2 and 2-3 show black and white and thermogram images, respectively, of a person. A photograph, or a visible light image, is shown in Figure 2-4 for comparison. Thermal patterns on the face of Figure 2-3 indicate that reds are warmer, yellows and greens are cooler.

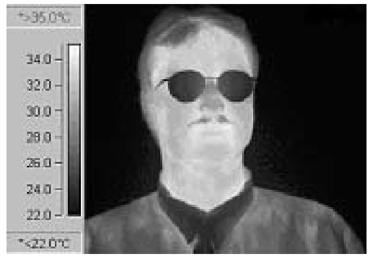


Figure 2-2
Grayscale

Figure 2-3
Thermogram

Figure 2-4
Visible

Note that the glasses appear cool because they are cooler than the skin and longwave infrared energy will not pass through glass.

Infrared Image

The IR camera captures the *radiosity* of the target that it is viewing. Radiosity is defined as the infrared energy coming from a target modulated by the intervening atmosphere, and consists of emitted, reflected and sometimes transmitted IR energy. An opaque target has a transmittance of zero. The colors on an IR image vary due to variations in radiosity. The radiosity of an opaque target can vary due to the target temperature, target emissivity and reflected radiant energy variations.

Figure 2-5 shows two images of three metal cans, one hot, one ambient and one cold (left to right). The upper image is visual and the lower image is infrared. There is a piece of electrical tape on each can. The can surface and the electrical tape are at the same temperature for each can; but, in the infrared images, the tape looks hotter than the metal surface on the hot can, colder on the cold can, and the same on the ambient can.

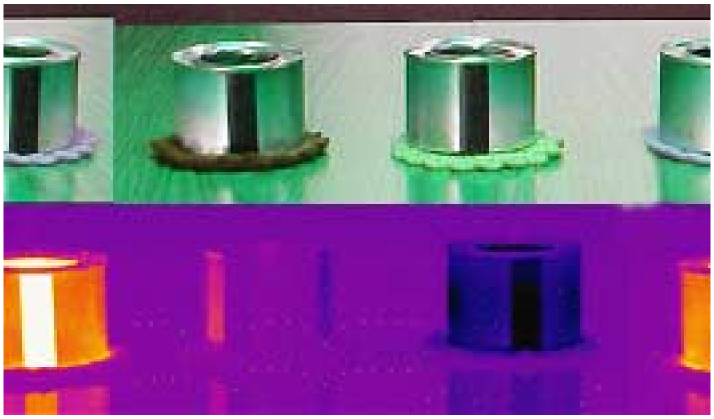


Figure 2-5
Aluminum Cans with Partially Oxidized Surfaces

What is occurring is that the electrical tape has a higher emissivity than the metal. This means the tape has a higher efficiency as a radiator than the metal has. Alternately, the metal has a higher reflectivity than the tape and is therefore more efficient as an infrared mirror. Thus, the tape will indicate the target temperature more closely; and, the metal will indicate the background temperature, or that which is reflected off the can. So, if the can is hotter than the background, the tape looks hotter than the metal. If the can is colder than the background, the tape looks colder than the metal. If the can is the same temperature as the background, the tape and the metal will look the same.

This is an extremely important concept. Thermographers see targets exhibiting this emissivity contrast behavior every day. It could be an insulated electric cable with a bare metal bolted connection, it could be a bare metal nameplate on a painted surface such as an oil-filled circuit breaker or load tap changer, or could be a piece of electrical tape placed by the thermographer on a bus bar to enable a decent reading.

It turns out that for opaque objects, the emissivity and reflectivity are complementary. High emissivity means low reflectivity and *vice versa*. Kirchhoff showed that in thermal equilibrium the absorptivity of an object equals its emissivity. Combining this with the law of conservation of energy results in an equation that quantifies these concepts:

$$\varepsilon + \rho + \tau = 1$$

Greek letters for e, r and t are typically used, where emissivity is, ε, reflectivity, ρ, and transmissivity, τ. For opaque targets, $\tau = 0$ and the equation reduces to:

$$\varepsilon + \rho = 1$$

In simple terms the above equation says that a high emissivity means a low reflectivity and low reflectivity means a high emissivity. Thermographers like the emissivity to be as high as possible. This allows them to obtain the most accurate readings as most of the radiosity is due to radiant energy emitted by the target. Modern IR cameras correct for emissivity with a modicum of user input. But the uncertainty in the measurement increases with decreasing emissivity. Calculations show that the measurement uncertainty gets unacceptably high for target emissivities below about 0.5.

Emissivity tables abound, but establishing the exact emissivity of a target is sometimes difficult. Emissivity was discussed above as a material surface property; however, it is that, and much more because it is a function of many factors. For example, the surface properties are continually changing. In addition, the shape of an object affects its emissivity, for semi-transparent materials the thickness will affect emissivity. Other factors affecting emissivity include: viewing angle, wavelength and temperature. The wavelength dependence of emissivity means that different IR cameras can get different values for the same object. and they would all be correct! It is recommended that the emissivity of key targets be measured under conditions they are likely to be monitored during routine surveys.

In general, dielectrics (electrically non-conducting materials) have relatively high emissivities, ranging from about 0.8 to 0.95, which includes well-painted metals. Unoxidized bare metals have emissivities below about 0.3 and should not be measured. Oxidized metals have emissivities ranging from about 0.5 to 0.9, and are considered the problematic category due to the large range of values. The degree of oxidation is a key ingredient to an object's emissivity. The higher the oxidation, the higher the emissivity.

For opaque objects, if the emissivity and the background (reflected) temperature are known, an IR camera with a temperature measurement feature can give temperatures accurate to within a few percent. To get temperature, the IR camera must extract just the fraction of the radiosity due to the energy emitted by the target. Fortunately, modern IR cameras are smart and can do this. They subtract the reflected component, then scale the result by the target emissivity. The resulting value can then be compared to a calibration table and temperature extracted.

Blackbody, Graybody, and Realbody

A Blackbody is a perfect radiator because it has zero transmittance and zero reflectance. According to the emissivity equation, the emissivity of a blackbody is one. Blackbodies were first defined for visible light radiation. In visible light, something that doesn't reflect or transmit anything 'looks' black, hence the name. A Graybody has an emissivity less than one that is constant over the wavelength. A Realbody has an emissivity that varies with wavelength. IR cameras sense infrared radiant energy over a waveband. To get temperature, they compare the results explained above with a calibration table generated using blackbody sources. The implicit assumption is that the target is a graybody. Most of the time this is true, or close enough to get meaningful results. For highly accurate measurements, the thermographer should understand the spectral (wavelength) nature of the target.

Max Karl Ernst Ludwig Planck is credited for developing the mathematical model for blackbody radiation curves. Figure 2-6 shows the magnitude of emitted radiation due to an object's temperature versus wavelength for various temperatures. *Note that the sun has a peak wavelength in the middle of our visible light spectrum.*

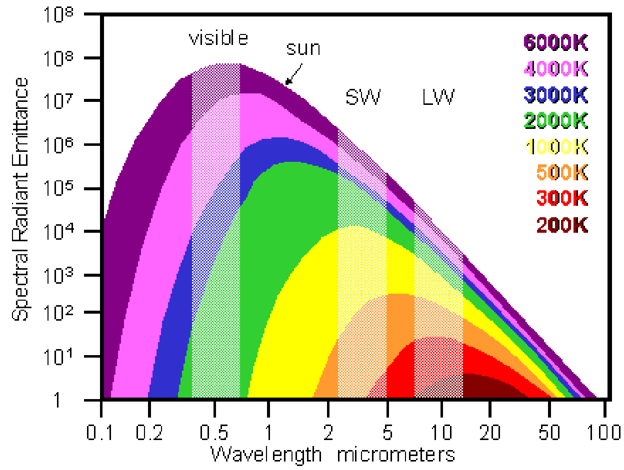


Figure 2-6
Emittance versus Wavelength

Blackbody curves are 'nested' because they do not cross each other. This means that a blackbody at a higher temperature will emit more radiation at every wavelength than one at a lower temperature. As temperature increases, the wavelength span of radiation widens, and the peak of radiation shifts to shorter and shorter wavelengths. Note: the peak of infrared radiation at 300ºK (about 27ºC, 81ºF) is about 10 µm. Also, an object at 300ºK emits radiation only down to about 3 µm. Since human eyes are not sensitive beyond about 0.75 µm, this cannot be seen. But if the object is warmed up to about 300ºC, a faintly red glow can begin to be seen.

How to Read a Thermogram

In order to analyze a thermal image, it is essential to understand how to properly read the image. There are various manufacturers of infrared equipment, and many different types of systems available for use in the field. Each instrument displays its data in slightly different formats, and there is a learning curve necessary to gain familiarity with each one. However, it can be said that there are similarities between all of these infrared instruments; and, they are all designed to yield the same result, which is a thermal pattern of a particular target. Therefore, an analysis of the method of one type of camera should be sufficient enough to give the reader a basic understanding of thermal image analysis. One such analysis is discussed below.

Figure 2-7,Visual Image, and Figure 2-8, Thermal Image, depict flue gas leaks on flue gas ductwork. Focusing on the Thermal Image, observe the numerical information on the color temperature scale on the right hand side of the image. The 51.8°F displayed at the bottom of the scale is the lowest temperature on the color scale in this particular temperature range of the IRT camera. Any areas of the image that show up in black are off the color scale on the low end (below 51.8°F) of this particular temperature range of the IRT camera. Moving up the color scale toward the high-end value, the magenta, blue, green, yellow and red colors represent temperatures ranging linearly from the low-end value of the scale (51.8°F), to the high-end value of the scale (246°F). At this particular setting, 246°F is the highest temperature indicated on the color scale. Any areas of the image that show up in white are above the 246°F scale on the high end (above 246°F), but not necessarily above the temperature range setting for the IRT camera.

This setting, which enables measurement of temperatures between 51.8°F and 246°F, is called the temperature span. Most infrared instruments are versatile enough to allow the user to change temperature spans (low end values, high end values, colors scales etc.), depending upon necessity dictated by the temperatures of the targets being observed and/or personal choice. Some infrared instruments also allow changing of temperature ranges to allow for more accurate temperature measurements. At the bottom of the image is the 'data line,' which includes, date, time, emissivity setting, etc. The upper right hand box indicates the actual spot temperature being measured at the 'cross-hairs.' Some infrared instruments also allow indication of temperature differentials from a reference temperature to the spot temperature in the same upper right hand box. Regardless of the color scales, or any parameters that are set, the methods of interpretation remain as described.

Figure 2-7
Visual Image

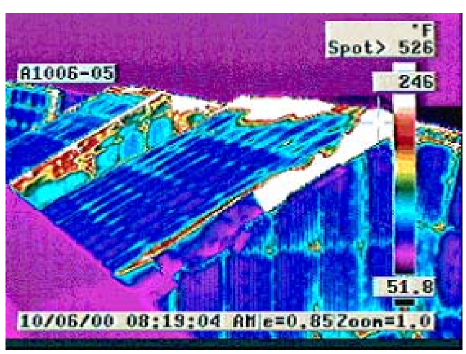


Figure 2-8
Thermal Image

Types of Detection

Many Industrial Power Plants throughout the country have systems with at least two operating components performing the same service at the same time. These similar service components allow an IR thermographer the advantage of comparing the thermal profile of one component versus the other. This process throughout the industry is referred to as **'Comparative Thermography'**. Depending on the nature of the component(s) being observed, comparative thermography can be used to obtain qualitative or quantitative data.

Qualitative data is used when a component **'does not require numerical data'** to determine the severity of a component's condition. For example: an underground water main break. The water main break is the fault, and the recommended action would be to repair the piping. Recording an absolute temperature measurement or a temperature differential as compared to the surrounding area is not required to further diagnose the condition of the piping. Finding the area of the ground that displays a difference in temperature indicating the location of the leak is sufficient. Recording the temperature or temperature difference is irrelevant to locating and repairing the break.

Quantitative data is used when a component **'requires numerical data'** to determine the severity of a components condition; for example: a 480VAC three-phase breaker where the breaker has one phase that is hotter than the other two phases. The hottest spot is located on the A-phase line side connection. The temperature at the A-phase connection is 85º Fahrenheit; phases B and C are both indicating 75º Fahrenheit. With this data a 10º Fahrenheit temperature rise is calculated. Since this is a molded case breaker with a screwed connection, the 10 degree temperature rise would be considered a minor problem that can be repaired as part of routine maintenance. However, if the connection were 100º Fahrenheit above the other two phases, the recommendation would be that it is a serious problem and should be repaired within one week. It is also recommended that the temperature be trended until it is repaired. Identifying the fault without providing the temperature rise for this application does not define the severity of the condition or what recommended action should be taken. Therefore, numerical data is essential in determining the condition of this component.

When there are no similar service components available to perform a comparative analysis, then recording **'Baseline'** data is recommended. Baseline data is a method in which a thermogram, or several thermograms, are taken of the component being observed. The baseline thermogram(s) are then compared to the data taken on subsequent surveys in the same fashion that a similar service component would be analyzed, i.e., any changes from the original baseline data would be recorded as a temperature rise above normal.

Recording additional information such as process data, environmental conditions, time, season, location, nameplate data, etc., can also be beneficial when performing an analysis. The type of additional data being collected would depend on the specific application. For example, a motor's thermal profile can fluctuate for many reasons such as; load (amps), ambient temperature, location (inside, outside, shade, sunlight, etc.), type of coolant system, duty, casing construction, insulation type, etc. Any one of these conditions, or a combination of these conditions, can cause havoc in trying to determine the condition of a motor by the external casing temperature. Even like motors of the same manufacturer and model number, can have different thermal profiles due to the location of the motors. Therefore, recording additional data can assist in defining the external motor's thermal profile.

Heat Transfer

In order to be an effective thermographer and arrive at the most accurate results, a basic knowledge of the mechanisms of heat transfer is a must. The thermographer has to understand conduction and convection but, most importantly, radiation since Infrared Thermography is based primarily on radiant energy. A complete dissertation on the types of heat flow, how to quantify them, and how to understand their interrelationships is included in Appendix B: Heat Transfer. The sections on radiation are particularly essential, and thermographers should learn this technology as much as possible to enhance their expertise.

Infrared Equipment

Regardless of the type of program planned, careful attention should be paid to the selection of the IR equipment to be purchased and used. This section describes some of the IR equipment available to guide the user in making the proper IR equipment selection for a particular application(s).

Infrared sensing instruments are traditionally classified into three groups: point sensing; line-scanning; and, thermographic (two-dimentional scanning). Point scanning devices (called Infrared Radiation Thermometers) collect radiant energy of an object to be measured (the target) and provide an output indication, usually in terms of target temperature. Line scanning instruments provide an output, generally an analog trace of the radiant energy (or, in ideal cases, temperature) distribution along a single straight line projection from the target surface. Thermographic instruments provide an image of the energy distribution over a scanned area on the target surface which is presented in the form of an intensity-modulated black and white picture or a synthesized color display. The infrared sensing instruments that will be discussed in this section are point sensing and thermographic scanners.

Probes

Temperature probes are characterized as low price, pocket-portability, and wide collecting angle. They are battery powered and are generally optically pre-adjusted for minimum spot size at short working distance (a ¼ inch spot at a ¾ inch working distance is typical). Some models are designed to operate into a conventional multimeter and some incorporate their own readout box with an LCD display. Temperature ranges are from about 0ºF, or slightly below, to 600ºF, and a sensitivity of ± 1ºF is easily achieved. Emissivity adjustments are available on some models.

Probes are ideal for close-up measurements and find applications in circuit board analysis, troubleshooting of small electrical connections, and inspection of small fluid leaks.

Portable Hand-Held

These instruments are designed are designed for middle-distance measurements. They are usually optically pre-adjusted for infinity focus. A typical 2 degree field of view resolves a 7.5 centimeter spot at a 150 centimeter working distance, and a 30 centimeter spot at a 9 meter working distance. Sighting and aiming methods vary from simple aiming notches to enclosed illuminated reticles. There are instruments with extremely narrow fields of view (0.5 degree), and most incorporate emissivity adjustments. Some include microcomputers with limited memory and datalogging capabilities. The displays are analog, digital and, more recently LCDs, which are now used almost universally because of its tiny power drain on the battery. Some instruments in this group have zeroing adjustments, and the newer ones include auto-zeroing features. Temperature ranges are, typically, from 0ºC to 1500ºC. Temperature sensitivity and reliability are usually 1º (C or F), or 1 percent of scale, although sensitivities on the order of 0.1º (C or F) are achievable.

This instrument group is particularly suited to applications where spot checking of target temperatures is sufficient and continuous monitoring is not required. A typical use would be for periodic maintenance checks of rotating machinery to detect for overheating of bearings. Although many of these instruments provide extremely accurate readings, accuracy, like the recorder output, is less important to most users than repeatability, ruggedness, portability, reliability, and ease of use.

Thermographic Raster Scanners (Imaging Radiometers)

Thermographic scanners (also called imaging radiometers) provide essentially quantitative temperature measuring capability and high resolution image quality. Detector cooling is almost always required, and this is done using several means, including: thermoelectric (Peltier effect) coolers; compressed argon; refillable liquid nitrogen containers; and, electric-powered cycle nitrogen coolers. Most commercially available thermographic scanners use a single detector; but, some use dual-detector or multidetector (linear array) instruments. All provide a means for measuring target surface temperature.

Thermographic scanners use refractive, reflective, or hybrid scanning systems, and operate in either the 3-5μ or the 8-14μ atmospheric window. In addition to quantitative temperature measuring capability in idealized circumstances, these instruments feature excellent capabilities for both spatial resolution (about 1 mrad) and minimum resolvable temperature (0.05 to 0.1°C). Most models offer isotherm graphics features, spectral filtering, interchangeable optics for different fields of view, color or monochrome (black and white) displays, flexible video recording capabilities, and computer adaptability. Most general-purpose systems in use today feature compact, field-portable, battery-operated sensing heads and control/display units, some of which are integrated into 'camcorder' configurations. A complete system, including battery and video recorder, can usually be handled by one person, by either mounting the components on a cart or assembling them on a harness. Detector cooling for all new models intended for field operation is now accomplished by means of thermoelectric or Stirling-cycle coolers, eliminating the inconvenience of nitrogen refills in the field.

Focal Plane Array (FPA) Imagers (qualitative)

High resolution imagers featuring infrared focal plane array (IRFPA) detectors are readily available. They are commercial versions of military Forward-Looking Infrared (FLIR) systems used for night vision and surveillance operations. Generally, the emphasis is placed on picture quality rather than measurement capability. FPAs are frequently used to optimize spatial resolution. Instruments using cooled platinum silicide (PtSi) ‘staring’ arrays with as many as 512 x 512 elements/frame have been available for several years; and, instruments using cooled indium antimonide (InSb) focal plane arrays have also become available. The newest models in this category are offered in the size and weight of a commercial ‘palmcorder’ (refer to Figure 2-9).

Figure 2-9
PtSi, Stirling Cooled FPA Camera

Inexpensive uncooled models are now commercially available. Their developments were aimed at improved night vision devices using both bolometric and pyroelectric FPAs. While these thermal detectors are relatively slow in response, on the order of milliseconds, every element in the 80,000 element array is always exposed to the incoming radiation target, and fast enough to respond fully to a typical 30Hz video scanning rate. These imagers have great potential for a wide variety of commercial and industrial applications.

FPA Imaging Radiometers (quantitative)

This type of infrared measuring system has been in the process of development for some time due to the complexity of the task. Accurate temperature determinations with thermography has been extremely difficult; however, limited measuring capabilities are now being offered, and they are continually improving. Where the measurements are made under controlled laboratory conditions, this is sufficient for accurate and dependable measurement capability. Some models can now provide true temperature measurement on microelectrics with full emissivity compensation and spot sizes down to 4µm. On some portable models of FPA imagers it is currently possible, by means of diagnostic software, to select a group of pixels (8x8) on the live thermogram, insert an emissivity correction and derive a temperature reading. Corrections for field measurement mission conditions such as working distance to the target (media attenuation) and imager background temperature (ambient reflections off the target), however, are not yet available but are being addressed.

Microbolometer Array

The microbolometer was developed jointly for military and commercial applications with funding provided by both the public and private sectors. The term microbolometer, stems from the bolometer, which is physically a much larger single detector element. As discussed above, the bolometer was introduced years ago as the first radiometric IR device. Now we have come full circle from bolometers to quantum detectors and back to microbolometers.

A microbolometer operates as a bolometer but is 'micro-sized' and it is produced using silicon processing methods which are similar to those employed in manufacturing microprocessors. Modern processing and micro-machining techniques are used to create an array of microbolometers, each of which is less than 47 micrometers wide. Figure 2-10 shows a sketch of an individual element or pixel. These elements possess highly uniform characteristics and are formed into an array of 320 x 240 detector elements. Each element is a thermally isolated micro-bridge suspended over a silicon substrate that contains the readout integrated circuit (ROIC) and analog-to-digital converter.

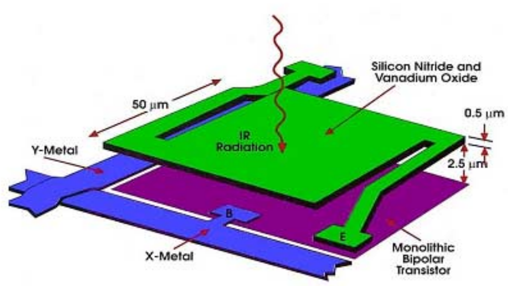


Figure 2-10
Pictorial Sketch of Microbolometer Element

The microbolometer's individual micro-machined elements consist of a vanadium oxide film, supported on silicon nitride 'legs' of low thermal conductance. This collection of detector elements is integrated onto a substrate that is held at a stabilized temperature to minimize gain and to compensate for drift. Stabilization of the detector environment is necessary, because each 1/3000ºC change in detector temperature indicates a 0.1ºC change in scene temperature.

Now microbolometer arrays are routinely fabricated and today's IR cameras are on Gen III of these detectors. The image quality approaches that of cooled quantum detector arrays for IR cameras similarly priced. This is good news since it eliminates cryogenic cooling and is a real bonus as Stirling coolers eventually wear out and need refurbishing. Camera ruggedness is also improved. Operationally, the dynamic range of microbolometers is significantly greater than that of cooled FPAs. The Microbolometer IR camera in Figure 2-11 has autofocus as well as the capability of recording a visual image, and text comments and voice, all attached to the IR image file so that tracking of data is ensured. This makes the capturing of quantitative thermal imagery orders of magnitude easier, and the cataloging of the data and generating the reports much simpler.

Figure 2-11
Microbolometer IR Camera

3
PROGRAM DESIGN AND IMPLEMENTATION

A successful IRT Program takes a commitment all the way from Management, down through the organization, and eventually to the IR thermographer. With the current competitiveness of the utility industry, capital equipment budgets are tight and plant personnel have several job descriptions all of which are difficult to perform properly in the amount of time provided. It is important that the total cost of the IRT Program is identified and submitted to management for approval.

After the cost analysis is performed and approved by management, then, the IR thermographer should select the list of critical components that would most benefit the plant. This generally includes those pieces of equipment that would cause a de-rate; or, have a high maintenance or replacement costs.

Program Selection

Troubleshooting

Using IRT once per year, prior to an outage, or as a troubleshooting tool can provide a significant amount of benefit; however, in these modes it is no longer being used as a condition-monitoring tool but more as a troubleshooting tool. The difference being that when using IRT in these modes only identifies an existing equipment condition, good or bad, as compared to IRT being used as a Predictive Maintenance (PDM) tool which monitors the condition over time to facilitate. Figure 3-1: Infrared Thermography Planning and Estimating Guide, includes typical startup costs for an IRT program, whether it be used as a troubleshooting or pre-outage tool, or as part of a more extensive PDM program. The contract services estimates, and the estimates for in-house labor, may vary from plant to plant. Figure 3-2 are recurring annual estimates if the IRT program is part of a comprehensive PDM program. If used only periodically, the annual cost would be significantly less.

Condition Monitoring/PDM

Identifying the health of plant machinery saves money and improves plant reliability as compared to preventative or corrective type maintenance. PDM is a process that utilizes data from many different technologies such as IRT, vibration, lube oil analysis, acoustics, etc., as well as other data such as operators log, maintenance histories, process data, etc. Combining the data from all of these areas can better define the health of a component. Even though IRT is part of an overall PDM Program it still needs to be set-up as an individual comprehensive IRT Program.

Infrared Thermography Planning and Estimating Guide

Startup Costs							
Material	**Item**	**Qty**	**Unit**	**Note**	**Unit Cost**	**Total**	**Notes**
Hardware							
	Thermography Camera	1	each		$50,000	$50,000	(1) Computer/printer required for thermography report generation
	Computer/Printer	1	each	(1)	$5,000	$5,000	(2) Off the shelf report software IR-SIP
Rpt. Software	IR-SIP	1	each	(2)	$1,500	$1,500	
Miscellaneous		1	N/A		$1,500	$1,500	
					Material Subtotal	**$58,000**	
Initial Training	**Item**	**Qty**	**Unit**	**Note**	**Unit Cost**	**Total**	
	Training Tuitions	2	each	(3)	$1,000	$2,000	(3) Tuition based on average 5-day course cost
	Training Travel/Living Exp.	2	each	(4)	$2,000	$4,000	(4) Travel based on 1 week on the road with
					Initial Training Subtotal	**$6,000**	a $1,000 airfare plus out-of-pocket expenses
Contract Services	**Item**	**Qty**	**Unit**	**Note**	**Unit Cost**	**Total**	
	Initial Survey & Support	1	each	(5)	$17,240	$17,240	(5) Cost of 1st survey, training, and tech support for first 12 months
							plus 8 days to develop the component database and generate the
					Contract Services Subtotal	**$17,240**	initial IRT report at $800/day and out-of pocket travel and living expenses
Labor	**Item**	**Qty**	**Unit**	**Note**	**Unit Cost**	**Total**	
	Engineering	5	man-day	(6)	$400	$2,000	(6) Labor based on a burdened rate of $400/day for training and
	Training	20	man-day	(6)	$400	$8,000	contract survey support
	Survey/Rpt. Labor	215	man-day		$400	$86,000	
					Labor Subtotal	$96,000	
					Total Startup Costs	**$177,240**	

Figure 3-1
Startup Costs for an IRT Program

Annual O&M Costs						
Personnel	**Item**	**Qty**	**Unit**	**Note**	**Unit Cost**	**Total**
	Survey/Rpt Labor	230	man-day		$400	$92,000
	Training Labor	10	man-day		$400	$4,000
	Training Tuitions	2	each	(3)	$1,000	$2,000
	Training Travel/Living Exp.	2	each	(4)	$2,000	$4,000
					Subtotal Plant Personnel	**$102,000**
Contract Services	**Item**	**Qty**	**Unit**	**Note**	**Unit Cost**	**Total**
					Subtotal Contract Services	
					Total Annual O&M	**$102,000**

Figure 3-2
Annual Recurring Costs for an IRT PDM Program

Plant Equipment Applications

Plants that have implemented a Plant Maintenance Optimization (PMO) Program generally start with a study that defines their 'PM Basis'. A PM Basis is developed using the Reliability Centered Maintenance (RCM) process or some streamlined version of an RCM. This type of study defines the critical equipment in the plant and the activity required around each piece of equipment to ensure good operability, availability, and optimum performance. The result of the study is the PM Basis for each piece of equipment selected. The information can be lengthy; however, some studies consolidate this information into a spreadsheet format with the equipment listed, tasks required, and the frequency of when the tasks are to be performed. If the operating plant has developed a PM Basis then the components, technologies, and frequency of activity have already been developed for each person's technology responsibility.

In general, there are four primary areas that IRT have proven to be effective in regards to plant generation: electrical; rotating equipment; performance; and switchyard. Rarely does generation have responsibility for the switchyard; however, the main transformers and station transformers are usually observed during a routine IRT survey. As a novice IR thermographer, electrical and rotating equipment are typically the first two areas that are investigated. There are several reasons that these items are selected as the first components observed, two of which are that IRT is the only technology that can identify many electrical deficiencies while energized; and, secondly that the majority of the critical plant equipment is electrical or rotating.

Most electrical equipment is worth investigating. Exceptions may be: de-energized equipment; low voltage equipment; Motor Operated Valve compartments, which generally do not operate enough to show heat; and, motor lead boxes which are too dangerous to open when energized, just to name a few. Most plants have a generous supply of 480VAC and 4160VAC equipment. These are commonly found in load centers or motor control centers (MCCs). In most cases the 480VAC critical and non-critical compartments are randomly placed throughout the MCCs; therefore, viewing each compartment is essential because if a non-critical compartment catastrophically fails next to a critical compartment, possibilities of the critical compartment failing also are good.

Some plants no longer allow observation of 4160VAC cabinets due to their safety policies. It must be ensured, therefore that the IR thermographer has had electrical safety training and is familiar with the plant electrical safety policy before entering the plant. In addition, electricians do not work alone and neither should an IR thermographer. It is imperative that the plant provides an experienced electrician to open the compartments. Other pertinent electrical considerations are included in the Checklist in Appendix C: Checklist for Electrical Maintenance Inspections.

Infrared data for rotating equipment is beneficial in identifying undesirable conditions. Some rotating equipment conditions can be defined using infrared alone, such as a motor casing being overheated due to dirty air filters. However, unlike electrical deficiencies many rotating equipment deficiencies require support from other technologies to define the condition. For example, a hot bearing on a motor can be seen by infrared, but infrared cannot determine whether the condition is deteriorated oil or a deteriorated bearing. Therefore, an oil analysis would also be required to define the bearing condition.

Table 3-1 is a list of electrical equipment commonly observed in a fossil fuel plant. In addition, published EPRI Technical Reports are referenced and are available that will assist with the applications.

Table 3-1
Basic Component List

Electrical Components	EPRI Technical Report
480 VAC Load Centers 480 VAC Motor Control Centers 4160 VAC Switchgear Station Transformers	Thermal Anomalies Manual TR-108935 Infrared Thermography Guide NP-6973-R2
Rotating Equipment	**EPRI Technical Report**
Circulating Water Pump Condensate Pump Forced Draft Fan Induced Draft Fan Boiler Feed Pump Pulverizer Vacuum Pump	Thermal Anomalies Manual TR-108935 Electric Motor Predictive Maintenance (EMPM) Program TR-108773-V2 Electric Motor Predictive and Preventive Maintenance Guide NP-7502 Infrared Thermography Guide NP-6973-R2

Note: The rotating equipment is listed as an assembly. Surveillance of the assembly includes the driver and driven (i.e., motor and pump) and any other interconnecting components (gear box, coupling, etc.).

Once experience has been gained with performing an IRT survey on the basic equipment list, then there are many other areas that IRT has shown to be effective. The selection of these applications will vary depending on the specific needs of each plant. Two areas that have proven very beneficial are performance and switchyard. Performance areas include components such as valves; steam traps; and, condenser and boiler applications just to name a few. These areas should be selected depending on adverse plant conditions such as a high heat rate, high dissolved oxygen levels, etc. Providing a performance survey requires a known deficiency for direction, otherwise the thermographer may be looking for a problem that does not exist.

The switchyard is another area that has proven IRT very effective. Detecting faults on high voltage equipment, while energized and a fair distance away, is only possible using IRT; and, due to the environmental effects makes for a most likely source of problems.

Table 3-2 is a list of additional applications and components that are commonly observed at a fossil fuel plant. In addition, published EPRI Technical Reports are referenced and available to assist with the applications.

Table 3-2
Additional Applications

Performance Condenser Air-in Leakage Condenser Tube Leakage Boiler Air-in Leakage Internal Boiler Steam Cycle Valve Leak Detection	EPRI Technical Report Thermal Anomalies Manual TR-108935 Infrared Thermography Developments for Boiler, Condenser, and Steam Cycle TR-109529 Infrared Thermography for Plant Thermal Loss Management TE-114093
Switchyard Bushings Circuit Breakers Conductors Coupling Capacitors Current Transformers Disconnect Switches Distribution Lines Insulators Lightning Arrestors Load Tap Changers Power Transformers Transformer Cooling Systems Transformer Control Cabinets	EPRI Technical Report Thermal Anomalies Manual TR-108935

4
FIELD SURVEY

Performing a field survey effectively requires good planning. Good planning requires a great deal of thought starting with the pre-field readiness and ending with the proper follow-up on components that required maintenance. This section is separated into 5 categories, which are: Prerequisites; Data Collection; Analysis; Report Generation; and, Follow-up. Each of these categories is as important as the other in regard to ensuring field survey effectiveness.

Prerequisites

Preparing for the field survey first requires a list of equipment to be surveyed. It is suggested that the equipment being surveyed has been selected per the methods as described in Section 2: Infrared Thermography, Infrared Equipment. Once the equipment list is generated, then preparation of safety clothing (if needed), plant support, data sheets, etc. can be considered. The following areas are considerations that will help enhance the process.

Pre-Survey Plant Status

After the routine equipment list is defined, it is suggested that the IR Thermographer investigate the current plant status. There are several ways to find out what pieces of equipment or systems are not operating as desired. This can be accomplished in many ways, by interviews with cognizant personnel, reviewing maintenance records, or conducting a brief meeting with the appropriate plant personnel (Maintenance, Operations, Engineering, etc.) to discuss the current plant status.

Equipment Check

There is nothing worse than getting out into the field and realizing you forgot something. To eliminate this from taking place, review the list of equipment being surveyed and determine what support equipment is needed to perform the survey. The following is a checklist for consideration:

- Safety equipment (i.e., protective clothing, gloves, safety glasses, safety shield, safety boots, hard hat, and ear plugs).
- IR Camera equipment (i.e., batteries, IR lenses (zoom, close-up, and standard range), storage media, etc.).
- Digital Camera.
- Previous survey results.

- Equipment list, drawings (if applicable), and data sheets for recording anomalies, baseline data, and notes.

Support

Depending on the type of survey, plant support may be required. Plant staff can provide the vital support needed, such as: identifying equipment or systems; swapping equipment to allow a specific component to operate; or, opening electrical cabinets. If the equipment list includes electrical, rotating, performance, and switchyard components then ensure that the appropriate support is scheduled effectively. For example, if a full day's worth of work is needed surveying electrical compartments, then schedule an electrician to open cabinets for a full day and get it done all at one time rather than using an electrician for a few hours a day. If there are components that alternate service where motor 1A is always operating, and there is never an opportunity to survey motor 1B, then request that the Operator swap machines to provide the opportunity to survey both motors. Plan appropriately prior to starting the survey to ensure that the needed support is available.

Documentation

Accurate and complete documentation of each finding is instrumental to getting appropriate action. Many times IR thermography data requires additional data to identify and define the overall condition of a component. Knowing what data supports the IRT data depends on the type of equipment being surveyed and a good understanding of the equipments operation. Some examples of additional data sources may include: process indications (pressure, flow, etc.); operational data (running hours, starts, stops, load, etc.); diagnostic technology data (vibration, lube oil, motor current, etc.); environmental effects; IRT survey trends and baseline data; etc.

Experience is probably the best solution for determining when a temperature is unacceptable and what other data sources can support the evaluation. Unfortunately, experience comes at the cost of experiencing failures before the criteria for identifying the problem at the right time is discovered. However, there are many publications, technical papers, plant experts, Users Groups, Conferences, etc. that can assist with the operation of plant equipment and the detection and diagnosis of the various anomalies.

One method of making sure that the pertinent data is collected is to make a list of the data required for each application; or, develop data sheets that have entries indicating the pertinent data for the various applications. Figure 4-1 is an example of a vertical motor data collection sheet that was used during the EPRI Electric Motor Predictive Maintenance Project. The data sheet was used to collect vertical motor data and includes areas in which to write general information (Utility Name, Station, IR Thermographer, Date and Time, etc.); motor information (Motor ID, HP Rating); and, process data (Motor Amps, Plant Load, RTD Temperatures, Ambient Temperature, etc.). In addition, the motor outline is depicted for each side, including the coupling, and this graphic is used to record the highest temperature in the proper location, or to identify any other anomaly in the area of interest. Filling in this sheet provides information for trending that can assist with the diagnosis of the problem, as well as limiting the amount of thermograms taken by recording the temperature data numerically: in this manner, thermograms are limited to just anomalies or baseline data.

VERTICAL MOTOR IR THERMOGRAPHY FOLLOW-UP FIELD DATA SHEET

Utility Name ______________________ Date ____________

Station & Unit # ______________________ Time ____________

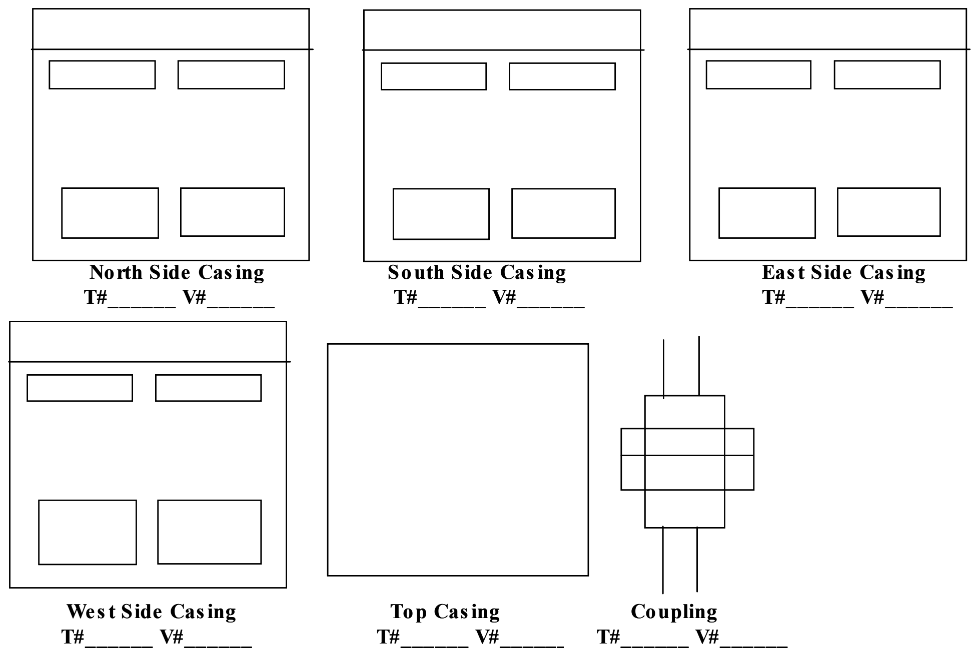
IR Thermographer ______________________ Emissivity Setting ____________

Ambient Air Temp. ______________________ Motor HP Rating ____________

Motor Identification ______________________ Breaker Compartment Surveyed: YES NO

Motor Load (Amps) Phase "A" __________ Phase "B" __________ Phase "C __________

NOTE: On the drawings below, record and indicate where the "Highest" temperature is indicated. Please, indicate temperature Engineering Units.



Air Inlet Vent *Surface* Temp. = __________ Air Outlet Vent *Surface* Temp. = __________

Motor RTD Temperature as indicated on Plant Computer:

RTD#______ Temp._______ RTD#______ Temp._______

RTD#______ Temp._______ RTD#______ Temp._______

Comments:

Figure 4-1
Example of IRT Data Sheet

Knowing where to start can eliminate a great deal of needless searching, especially when the problem does not even exist in the area being searched. For example, prior to the start of any performance study involving the surface condenser it is pertinent to check the process indications that would identify the type of problem. If the dissolve oxygen level is high that indicates that the problem is below the condenser water level. If the dissolved oxygen level is normal, but the condenser vacuum is low, then this indicates that the air leakage is in the steam side.

The EPRI reports referenced in Tables 3-1 and 3-2 contain similar pertinent information regarding the recommended procedures for performing surveys on specific applications, along with their respective data sheet formats.

Data Collection

Data collection extends beyond merely taking thermograms of the equipment. It is extremely important that the thermograms represent the actual thermal condition as accurately as possible. Therefore, the recommended procedures for capturing the images should be greatly respected.

Capture Images

IRT provides a visual representation of an anomaly that, when described to someone that is not a thermographer, that person can understand the nature of the problem. This is a unique characteristic of IR technology, and one which has made it one of the most utilized technologies in all industries. However, taking the image properly can pose a challenge for various reasons.

There are several camera adjustments that require attention in order to provide a proper temperature measurement. Some of these adjustments can be corrected during post-processing and some cannot. There are three critical adjustments that cannot be compensated for during post-processing and they are camera focus, temperature range, and operating distance.

Camera Focus

The focus of a thermogram can be critical for two reasons. First it is a poor reflection on the thermographer to provide a blurry image to the client. Secondly, the temperature measurements and temperature difference measurements will be incorrect for an improperly focused image, especially when trying to measure small hot spots. When a camera is out-of-focus, for example, the temperature dilutes; and, this temperature dilution is dependent on the size of the target, the smaller the target (area being measured) and the worse the effect.

To illustrate this effect, refer to the images of Figures 4-2 and 4-3. The unfocused image of Figure 4-2 shows a lower temperature, and a lower temperature difference, than the correctly focused image of Figure 4-3. **Always Focus Carefully**.

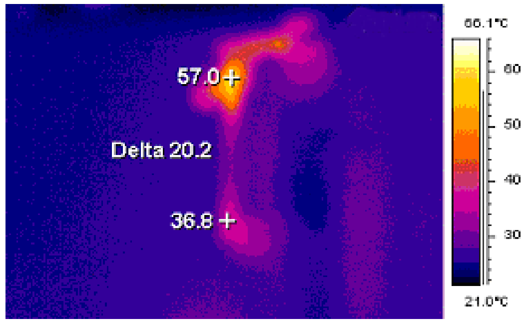


Figure 4-2
Out of Focus

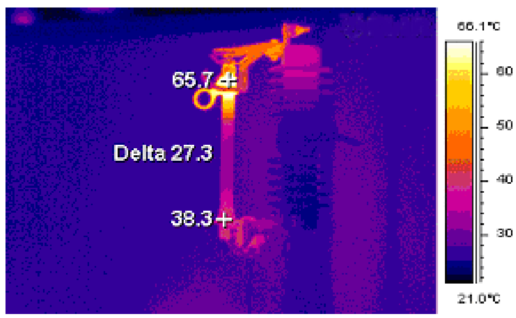


Figure 4-3
Correct Focus

Range

While many infrared cameras claim to be able to detect and measure objects from –20ºC to 1500ºC, they cannot do it within the temperature span of a single image. Most modern infrared cameras therefore break up the total temperature measurement specification into a number of defined temperature ranges, that is spans of blackbody temperatures that the detector is able to detect and image without going into saturation. Usually these ranges are digitized into a number of 'slices' usually called levels. Two common schemes are to divide each range into 4096 levels (12 bit) or 16384 levels (14 bit).

An example of this phenomenon is that when a thermographer is operating an infrared camera on Range 1 (-40º to 120ºC) and captures a thermogram of a scene where the temperatures of the objects varied between 20ºC and 200ºC. The hot objects above 120ºC would show up as white, but it can't be determined HOW hot they were because the data was captured on too low a range. The out-of-range and in-range conditions are illustrated in Figures 4-4 and 4-5, respectively.

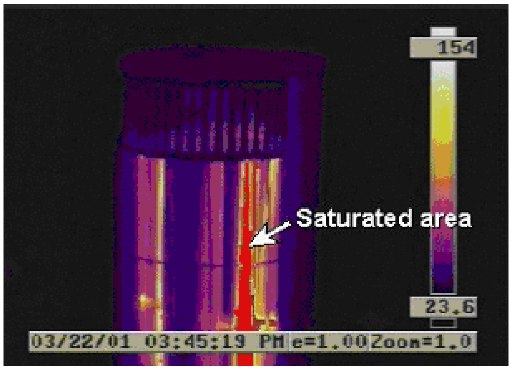


Figure 4-4
Incorrect Range

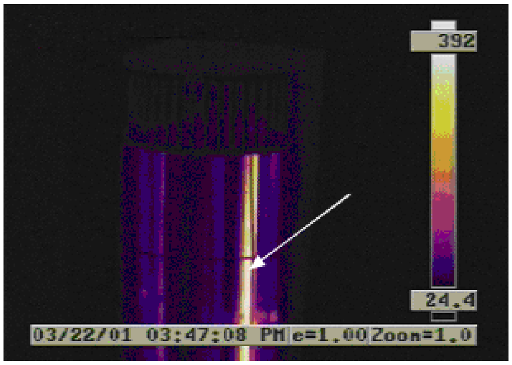


Figure 4-5
Higher Range

In Figure 4-4 an image of a quartz heater is captured in the incorrect range. The highlighted area in red cannot be analyzed. Switching to a higher range, as shown in Figure 4-5, allows the entire scene to be analyzed.

When analyzing thermograms, changing the emissivity can push the reading out of range. Not all software can correct for this. If the emissivity of the target is not established, the thermographer should save at least one thermogram on a range where the lowest emissivity value does not cause an out-of-range condition. Also, if the temperature difference cannot be reconciled on one thermogram within a given range, two thermograms should be taken that will allow calculation of the temperature difference later. Finally, there can be occasions where the IR image details are important, but are lost due to the range setting required to capture a hot spot. In these cases two thermograms should be taken, one that will give IR details and one that will give proper temperature measurement of the hot spot. It is much easier to take too many thermograms than not enough.

In order to make proper diagnoses and perform thermal focusing, all the important data needs to be available to process, so choose the correct thermal range(s) before saving thermograms.

One way to establish that the image is taken within range therefore is to ensure that the representative colors appear in the area of interest.

Operating Distance

Regarding the operating distance, when a target is being viewed at too great of a distance the surrounding area is averaged into the temperature indication. Therefore, a hot target with a cold background will indicate a lower temperature; and, vise versa for a cold target with a hot background where the temperature would be higher.

Thermal image data is dependent on distance for two reasons: the first has to do with optical or spatial resolution of the object being measured; and, the second with atmospheric attenuation of the infrared energy from an object. The effects of optical resolution far outweigh the atmospheric effects for most condition monitoring thermography.

In order to accurately focus on a target the proper distance between the camera and the target must be established. Just because a 'hot spot' appears in the image, it doesn't necessarily mean that a good temperature can be read. Knowledge of your camera's optical resolution, therefore, is imperative in determining the correct distance-to-object relationship before a thermogram is saved.

Figures 4-6 and 4-7 illustrate this point. Two thermograms of the same problem show two very different readings. One is taken with normal optics, the other just minutes later with a 3X telescope. This is a 'tulip' on a 230 KV, 1200 amp mechanical disconnect. A pair of the 20-plus contacts' alignment pins are hot due to overheating of the contact. These pins are ½ inch X ¼ inch at a distance of about 25 feet. Normal alignment pins were about 38ºC. For the set of severity criteria used by the thermographer, the temperature rise went from a minor problem showing a maximum temperature of 47ºC without a telescope (Figure 4-6) to a critical temperature of 298ºC with the telescope (Figure 4-7). The thermographer knew the spot size ratio was much too small to get a good reading without the telescope. Not knowing this would have resulted in an incorrect evaluation of the severity of the problem.

Knowledge of the 'Spot Size Ratio' sometimes called IMFOV (Instantaneous Measurement Field of View) is necessary to properly assess the maximum distance that the thermographer can be from the target and still get a good reading. Some camera manufacturers make it easy by designing a cursor that allows finding the correct distance easily. All that is necessary is to move close enough (or use a telephoto lens) so that the hot spot fills the interior of the crosshair, and the measurement will be correct.

If the target is too small to properly resolve, then the temperature reading will be lower (assuming a hot target with cooler surroundings) than the actual temperature. Don't be fooled into thinking that when only performing temperature difference measurements that everything is okay. Unfortunately the same thing is true for differentials, if the distance is too large, the ΔTs will be too low.

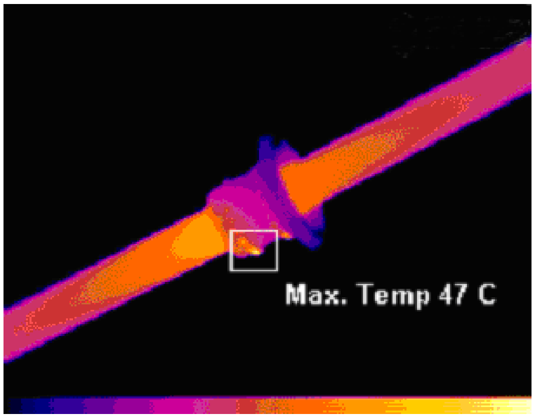


Figure 4-6
Target too Small

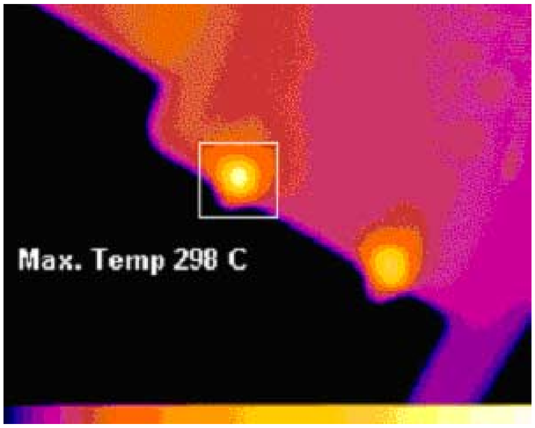


Figure 4-7
Correct Target

Thermal Focusing

Once the image is in optical focus, it is important to thermally focus the infrared image to perform a proper analysis. Failure to perform this can severely limit the operator's efficacy in detecting thermal anomalies.

Thermal focusing is a technique of adjusting the temperature span (contrast) and thermal level (brightness) of the infrared image in order to extract subtle details to aid diagnosis. Using this technique, one can pinpoint the areas of greatest temperature and uncover thermal condition clues to help determine the root cause of a thermal anomaly.

To demonstrate the value of the proper temperature span, Figure 4-8 is an example of a high tension pole assembly where all details are obscured. Figure 4-9 shows distinct elevated temperatures on the C-phase switch when the proper temperature span is set. Temperature span can be perceived as 'fine-tuning' the temperature range.

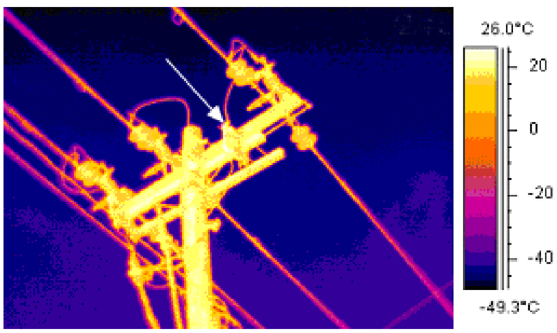


Figure 4-8
Improper Temperature Span

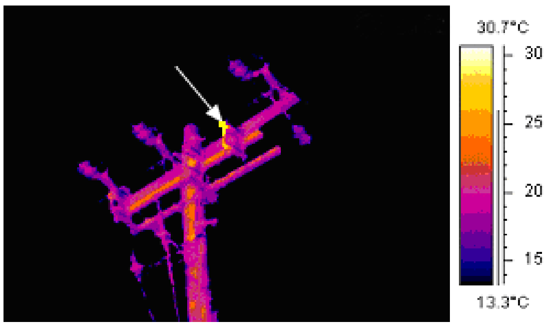


Figure 4-9
Proper Temperature Span

Spot Size

Ensure that distance-to-spot size ratio is known. For example, a distance to spot size ratio of 250 to 1 means that for a distance of 250 inches the spot size must be a minimum of 1 inch. If necessary, move in closer or use a telephoto lens. Remember to focus, ensure that the temperature range exceeds the temperature being taken, and know the distance-to-spot size ratio for a particular camera.

Additional Factors

There are also additional factors that can cause inaccurate temperature measurements; however, many times these factors can be corrected during post-processing. Some of the most critical factors are emissivity, background (reflected) temperature, equipment load, direct or indirect measurements, and the environment.

Knowing the target's emissivity and background (reflected) temperature is essential in obtaining an accurate temperature to within a few percent. Additional discussions on these factors are described in Appendix B: Heat Transfer. If an objects emissivity is less than 0.5, the factor for errors becomes much greater; therefore, if possible, use an emissivity enhancer such as electrical tape, paint, etc. Equipment load is generally associated with electrical applications, the higher the load the higher the temperature. The increase in load, however, is not linear with temperature, but the load increase affects on temperature can be calculated within reason. Indirect and direct measurements are discussed under Analysis. Environmental affects can also cause temperature changes, especially objects that are exposed to the wind. Extreme caution is necessary when wind is present, as wind can decrease an object's temperature by a significant margin, depending on the velocity.

The IR thermographer should become familiar with the camera. The thermographer should know what adjustments cannot be corrected for during post-processing, and those factors that are critical to taking a proper image with accurate temperature measurements.

Common Misconceptions

When learning how to apply IRT accurately and effectively by incorporating all of the above procedures, it is normal that misconceptions are encountered along the way. Several of the most common misconceptions are described in Appendix D: Common Misconceptions.

Analysis

For IRT, problem severity is often categorized using temperature alone as the main criterion. Temperature is quite significant for most electrical system surveys, but it's not the only thing to consider. Most PDM programs evaluate the criticality of the equipment, which is normally based on replacement value and affect on power generation, and assign one or more diagnostic technologies where they make sense to protect that equipment.

Temperature by itself can be misleading. Variables affecting the temperature reading of an electrical problem include: load, hot spot size to working distance ratio, wind speed, emissivity, ambient and background temperatures, solar effects and how 'direct' the reading is. The last parameter considers the amount of thermal insulation between the actual problem spot and what the IR camera 'sees.' Often, this is categorized as a direct reading for bare connections, or connections with thin layers of insulation, and indirect reading for heavily insulated components. Remember, good electrical insulation is good thermal insulation. Indirect examples include: Oil circuit breaker contacts, load tap changer contacts, insulated 4160 switchgear connections, internal connections in bus ducts (including iso-phase bus ducts), pad mount transformer connections, underground elbows, and so on. All of these items need a separate temperature severity criteria from that of direct readings.

Severity Criteria

Ranking an anomaly by its severity is a fair request for any diagnostic technology. In many cases it's obvious, especially with mature Predictive Maintenance (PDM) teams where everyone has agreed to specific criteria and procedures. In other cases it is extremely difficult. For the latter, bringing in other diagnostics is often fruitful.

Few severity criteria address the direct/indirect issue. Some utilities have separate criteria for overhead and underground electrical distribution facilities. Their criteria state that for overhead lines, a 61ºC temperature rise is a critical problem, for underground lines an 11ºC rise is critical. Corrective measures are required for 21ºC rise for overhead and 5ºC rise for underground.

Any published severity criteria that does not address direct/indirect ought to be revised. It is known that a 5ºC rise on an OCB often indicates a critical problem. Similar temperature rises on the above-mentioned indirect targets can also be critical in nature. There is just too large a difference between directly read and indirectly read targets to ignore. Research should be ongoing in this area to specify severity criteria for the various types of indirect targets. Failure of these devices can be extremely costly in both dollars and human life.

Attempting to correct for load variations has resulted in simple equations that are incorrect. As shown by Perch-Nielsen and B. R. Lyon, et al, temperature rise does not follow the simple square-of-load-change rule that is widely disseminated. Similarly, for wind effects it has been shown that the wind speed correction factors historically used by thermographers are suspect.

These other variables are even more crucial for indirect targets. Small temperature rises that indicate big problems can be significantly influenced by other factors, such as wind and solar insolation, because they are small.

All of these variables can appear daunting to the PDM team responsible for establishing severity criteria. But it is possible to write reasonable severity guidelines with caveats for the variables, letting the thermographer have some leeway in establishing the criteria. It is strongly recommended that written severity criteria with temperature rise as one of the key parameters be established, and it is also suggested that direct criteria be separated from indirect criteria.

There are several published Guidelines for the severity criteria. EPRI, the U.S. Military, and European Standards should be consulted for further references.

The Severity Criteria can take two forms; (1) they can be organized into general categories that identify temperature levels, or zones, versus levels of criticality; and, (2) they can be applied to specific machines or components, or to like groups of machines or components. In either case, the levels are established through experience and the accumulation of data. Since Severity Criteria is unique, each organization should set up a program that best suits its equipment and operation.

One generally accepted Severity Criteria based on categories and temperature rises above established references is as follows:

ADVISORY:	1 to 15°F rise above a reference (0.5°C – 8°C)
INTERMEDIATE:	16 to 50°F rise above a reference (9°C – 28°C)
SERIOUS:	51 to 100°F rise above a reference (29°C - 56°C)
CRITICAL:	in excess of 100°F rise above a reference (56°C)

Another Severity Criteria developed by the U.S. Military, included in U.S. Military Standard MIL-STD-2194 (1988), is based on temperature rise above the surrounding ambient and is as follows:

DESIRABLE: component is 10°C (18°F) to 24°C (44°F) above ambient

IMPORTANT: component is 25°C (45°F) to 39°C (71°F) above ambient

MANDATORY: component is 40°C (72°F) to 69°C (125°F) above ambient

IMMEDIATE: component is 70°C (126°F) or more above ambient

In addition to the above approaches, Severity Criteria can be established on individual machines or components. This method is based on many factors, including: temperature rise versus historical data that establishes rate of deterioration and time to failure; criticality of the machine or component to the overall process; location with respect to other materials/equipment should a fire result; safety of personnel; etc. Applications could include temperature rises of critical machines; mechanical components, bearing temperature rises, electrical supply or connection rises, fluid leakage losses, or even the number of tubes clogged in fluid type heat transfer equipment.

Report Generation

Generating a comprehensive IRT report is extremely important. Most IRT software products provide the capabilities to generate an ‘exception’ page for each finding. An exception page generally provides an area on which to paste a visual image and thermal image (thermogram) alongside a text section that includes a description of the finding, recommended action, and some other details, i.e. temperature rise, load, location, etc. This information is critical in identifying the problems; however, it does not provide the plant with a lot of other information that was gathered during the survey, such as those components that are operating properly. In addition, if the IRT Report only identifies the anomalies found then it is always the bearer of bad news. For years this was how the majority of reports were generated, and many are still being generated in this manner. Predictive Maintenance (PDM) programs have changed how data is converted into action and also how the information is provided to the customer.

PDM is also a process that is intended to provide the condition of all plant components; whether the **‘health’** of a component is good or bad. Knowing what is operating correctly is as important as knowing what is not operating at its optimum condition. It is important for an Operator to know that if the spare motor is needed, it is available and is operating properly. It is also important to know that when the last time that an IRT survey was performed, the 1C BFP Motor was not on-line; therefore, it was not surveyed and the recent failure may have shown signs during the last survey instead of diagnosing it as a catastrophic failure. The purpose of keeping track of all components being surveyed is to better understand the operating conditions of the components so improvements can be made regarding how data should be taken to ensure that the data being collected defines the component’s condition. If 500 plant components are being observed, and only 10 show signs of deterioration, why not provide an IRT report that lists 490 healthy components and 10 exceptions. Your maintenance department would welcome the praise for doing a great job. The need to communicate the IR activities and results cannot be emphasized enough. The thermographers need to call attention to the findings that they discover, and management has to be aware of these findings in order to obtain their continued support of the technology.

The following are examples of suggested items to be included in a comprehensive IRT Report.

An appropriate cover page, as shown in Figure 4-10 should be prepared which not only includes the company's name and date; but, the major supporters of the IR survey, a list of key individuals participating and supporting the activities, and those key individuals performing and attending the exit interviews.

Infrared Thermography Survey

for

NAME OF COMPANY
NAME OF LOCATION
City, State

Accompanied by:
A. Jones, Co. ACRONYM, Engineering
B. Johnsone, Co. ACRONYM, Operations
C. Brown, Co. ACRONYM, Shift Manager
D. Smith, Co. ACRONYM, Maintenance Foreman

Exit Interview with:
A. Jones

Performed by:
Name, Company
Name, Company
Name, Company

Survey Date: mm/dd/yy

Figure 4-10
Sample Report Format – Title Page

Figure 4-11 shows a sample Table of Contents that includes all of the key ingredients of a typical report. Other items can be added as appropriate.

Infrared Thermography Survey

Table of Contents

Figure 4-11
Sample Report Format – Table of Contents

Figure 4-12 is a description of the definitions that are naturally applied and a reminder sheet of this type helps the uninitiated understand what particular pieces of information actually mean.

Definitions

1. Item Number:	Each object scanned is listed and referenced by number.
2. Not-in-Service:	Periodic surveys monitor the same equipment on a specified schedule. If the equipment is not in service during the scheduled survey it is listed and identified as being "not-in-service".
3. Thermal/Visual Photo:	Each finding has two photographs taken of the object. A visual photo is taken for equipment identification, along with a thermal photo (thermogram). Findings are summarized in order of observation not in order of importance or classification of serverity.
4. Thermogram:	A thermogram is a color or black & white photograph of the thermal image appearing on the infrared display monitor.
5. Temperature Rise:	The temperature rise shown for each finding is the temperature difference in Celsius (°C) between the object and a reference temperature. When available, a piece of equipment similar to that being scanned is used as the reference. This could be one phase of a three phase system. If a comparison like this cannot be made, the reference temperature is the ambient air temperature. This could be done for a motor, gear set, etc. In cases when a comparison is not necessary, the actual temperature is shown (such as a kiln, boiler, etc.).

Figure 4-12
Sample Report Format - Definitions

Figure 4-13 contains the description of the severity criteria that is used for evaluating the component's condition. The severity criteria assigned to the component determines the time that can be allotted before maintenance is performed.

Severity Criteria

Electrical Equipment Severity Criteria

Classification	Symbol*	Temp. Rise	Comments
MINOR PROBLEM	*	1° - 10°C	Repair as a part of regular maintenance; little probability of physical damage.
INTERMEDIATE PROBLEM	**	10.1° - 35°C	Repair in the near future (2-4 weeks). Watch load and change accordingly. Inspect for physical damage. There is probability of damage in the component, but not in surrounding components.
SERIOUS PROBLEM	***	35.1° - 75°C	Repair in the immediate future (1-2 days). Inspect the surrounding components for probable damage.
CRITICAL PROBLEM	****	75.1°C or greater	Repair immediately. Inspect surrounding components. Repair while IR camera is still available to inspect after correction.

* SEVERITY IS INDICATED BY THE NUMBER OF ASTERISKS ASSIGNED. These classifications are based on observed temperature rise only. The importance of the item involved to the operation must be considered when determining timing of corrective action. In addition, the temperature rise is dependent on the load on the equipment; a minor finding on lightly loaded equipment could be more serious when the equipment is fully loaded.

Mechanical and Other Equipment Severity Criteria

Mechanical findings such as bearing temperatures, motor casing temperatures, temperature variations in heat transfer or cooling equipment, etc., are classified according to normal versus abnormal temperature with respect to baseline data and/or similar components, or according to the severity of the problems found and how important that piece of equipment is to production.

Figure 4-13
Sample Report Format – Severity Criteria

The next item in the report is a list of the equipment included in the survey. Figure 4-14 is a spreadsheet that lists the item number and the number of both the thermal and visual images, and these numbers are the references for the data related to the equipment. The temperature rise is recorded in degrees Centigrade and is an indication of the severity of the problem. If the equipment ID number is available it should be recorded along with the equipment description and location.

Load Center	Item #	Not in Service	Thermal Photo	Visual Photo	Temp Rise	Equipment ID Number	Equipment Description	Location
N/A	1		1	2	40		Generator disconnect	Unit 22, Switchyard
N/A	2		3	4	63		20 Transformer	Unit 32, Switchyard

Figure 4-14
Sample Report Format – Equipment List

Figure 4-15 is the summary of the images presented in a spreadsheet format and relates directly to the equipment list spreadsheet. This gives an overall view of the condition of the equipment that was surveyed, whether it had an anomaly or if the thermogram represents baseline data.

Thermogram #/ Item #	Equipment ID Number	Equipment Description	Severity	Location
1 / 1		Generator disconnects	***	Unit 22, Switchyard
3 / 2		20 Transformer	**	Unit 32, Switchyard

Figure 4-15
Sample Report Format – Summary of Images

Finally, the report should provide a data/image sheet for each equipment/component that was surveyed. Each page has both the thermal and visual images of the component, the equipment location, ID number, description, and the specific item involved. A data/image sheet is included whether the captured image detects an anomaly or is baseline data.

Figure 4-16 is an example of a data/image sheet where an anomaly was detected. In this case, a transformer connection indicated a 63ºC temperature rise: therefore, the probable cause and recommendation items were completed.

Infrared Thermography Survey

for

Company, XX Plant

Thermogram No.	Survey Date	Temperature	
		Rise °C	Severity
3	mm/dd/yy	63	**

Location:	Switchyard	Thermal Image
Equipment ID No.:		
Equipment Description:	20 Transformer	
Specific Item:	'A' Phase connection/disconnect side	
Probable Cause:	Loose/Corroded connection	Visual Image
Recommendation:	Inspect for looseness and corrosion	
Comments:	Amps 2500, MW 58	

Figure 4-16
Sample Report Format – Data/Image Sheet

Follow-up

As with any technology or maintenance strategy, feedback of the actions taken when a fault is identified is of vital importance. It is good historical information when like or similar events occur, it helps improve the application of the technology each time, and it is very effective when requesting additional management support, especially benefits feedback.

Post-Survey Plant Status Feedback

Communication is a very important element of an IR thermographer's job. Being able to communicate the findings properly is also essential to getting the repair work done and at the right time. Therefore, if there was a pre-survey meeting, or impromptu discussions with various plant staff, or communications sent out recording troublesome equipment, it is important that the report provide feedback to those individuals as to what was found during the survey. The individuals that took their time to enlighten everyone as to their concerns deserve a response. This follow-up will open up good lines of communication now and in the future. A recommended approach to convey the information to all concerned parties is to conduct a post-survey meeting.

Repair Feedback

When repairs are finally made it is essential to know if the thermal signature was accurately diagnosed. Being able to get feedback on the ‘as-found / as-left’ condition is valuable information that can help define or enhance existing severity criteria. Identify a means for maintenance to easily record the pertinent information. Possibly have a notification on the Work Order that prompts the maintenance personnel to record desired information, and then have the information routed to the IR thermographer for review.

Post-Maintenance Survey

When a repair is completed, it is recommended that a post-maintenance IR thermography check be made to ensure that the detected anomaly has been corrected. Ensuring that the repair was performed satisfactorily, and that the root cause was corrected and not the effect, it is important to conduct the post-maintenance survey. The post-maintenance survey has additional benefits in that it provides new ‘baseline’ data.

5
TRAINING/CERTIFICATION

Infrared Training and Certification

Infrared Thermography (IRT) has grown considerably since its introduction in the 1970's to the present. The numbers of users have also grown considerably during this period, and with the increase of users came the increase of private training companies. However, the capabilities of these private training companies, and the material being taught, varied from one company to another. As a result, it became obvious that there was a need to standardize the training being provided by the various private companies, in order to confidently validate the capabilities of an IR thermographer. These efforts led to more uniform training requirements which then lead to IR thermography certification processes.

Presently, there are several private companies that provide IRT certification processes. The organization that has played a key role in standardizing certification training programs is the American Society for Non-Destructive Testing (ASNT), which is an internationally recognized organization. The ASNT has developed a document (SNT-TC-1A) intended as a guideline for employers to establish their own written practice for the qualification and certification of their nondestructive testing personnel. The certification process requires that in order for a person to achieve a Level III Infrared status, that they not only have to pass an infrared exams but they also have to have knowledge of several other non-destructive testing (NDT) practices. Since the ASNT is an internationally recognized organization, many of the private companies state that their infrared certification process meets or exceeds the ASNT 'infrared' recommendations.

A careful review of these various programs showed that many aspects of each program have merit, but none of them address all of the concerns for application within the electric power industry. As a result, EPRI provides its own IR thermography training and certification process. The EPRI training and certification program was created to satisfy the express interests of the EPRI members to have a more utility focused IR certification process.

Regardless of which company or organization provides the training and certification, if desired, it is important to learn the science and the proper application of infrared thermography. It is of the utmost importance to have the required skills necessary to provide a safe, thorough, and accurate IR thermography inspection; and, to develop the capabilities to perform a proper analysis.

Infrared Hands-on Training

Certification-training courses are typically conducted in classrooms and primarily focus on the physics of the infrared technology, the operation of the equipment, and typical applications. The hands-on training that is provided in the classroom is generally being conducted around classroom experiments. Classroom training cannot be overstated; it is necessary to fully understand how to properly utilize infrared; however, using the equipment in the field is much different than in a classroom. Hands-on training allows the user to experience, first-hand, the methods and techniques a qualified IR thermographer uses for various applications. A novice IR thermographer over time will be able to teach himself the methods that identifies the various types of anomalies on the multiple types of components; but, as stated, it is accomplished over time and not without going through a learning curve. If available, it is important to take advantage of an experienced IR thermographer. Ensure that the person selected works in the utility industry and understands the types of applications of interest.

6
SAFETY

Safety can never be overstated. It may only take one unsafe action to cripple someone or even cause death. Many of us become complacent in the work place without considering the consequences. Safety is every individual's responsibility. There are many pieces of equipment that can present a risk for an accident. Some of these dangers include electrically energize equipment, high pressure, high temperature, rotating, loud, chemically or radiological contaminated, etc. Just about everything in a power plant can cause an injury. It is very important that anyone who works within the plant boundaries realizes the dangers, especially an infrared thermographer that is observing most of the equipment in the plant through a camera eyepiece or 4-inch screen that can distort the field-of- view and distract from concentration.

The following are guidelines concerning personal protective equipment, infrared equipment, and plant equipment operation awareness.

Personal Protective Equipment

The National Fire Protection Association (NFPA) article 70E, Part II, Chapter 3 and the Occupational Safety and Health Standards (OSHA) 1910 are two examples that contain safety issues that provide guidelines for personal protective equipment. The following are recommendations from the NFPA 70E guideline in regards to personal protective equipment:

- Head, Face, Neck, and Chin Protection – Employees shall wear nonconductive flame-resistant head protection wherever there is a danger of head injury form electrical shock or burns due to contact with exposed, energized electrical conductors or circuit parts, or from falling objects. Where there is potential exposure to arc flash burns, or to flying objects, the head protection shall be supplemented by a cape, scarf, and full-face shield or hood with a viewing window.
- Eye Protection – Face shields, windows, and safety glasses shall be used to protect the eyes from potentially flying of falling objects. Where there is potential exposure to arc flash conditions, they shall protect the eyes from the resulting thermal and luminous energy.
- Body Protection – Employees shall wear clothing resistant to flash flame wherever there is possible exposure to an electric arc flash.
- Hand and Arm Protection – Insulating rubber gloves with leather protectors and insulating rubber sleeves shall be used as required where there is danger of hand and arm injury from electric shock or burns due to contact with exposed, energized electrical conductors or circuit parts. Appropriate hand and arm protection shall be worn where there is possible exposure to arc flash burns.

Completely review NFPA 70E, OSHA 1910, and your company safety procedure manual for the applicable safety standards for your type of work.

Infrared Equipment Operation

Infrared equipment is usually not considered to be a hazard. However, there are several points that should be taken into consideration. The following describes these conditions:

- IR Camera eyepiece – Viewing objects through the camera eyepiece can affect the field-of-view. Normally, the infrared thermographer is focused on what is being viewed through the eyepiece; therefore, the attention to the surroundings becomes secondary. Not being aware of the surroundings can cause an accident by stepping into a hazard or moving too close to a piece of equipment that is rotating, electrically energized, hot, chemically contaminated, etc., just to name a few. There are many components in the field that can present a danger if not given the proper attention. To reduce these risks of danger ensure that when using the IR camera eyepiece that it is done from a standstill position. **Stop and Look —** Identify the piece of equipment of interest, look around for any hazards, and then proceed.
- Safe distance – It is very important to know what is a safe distance for observing the various field components; particularly, when dealing with electrically energized components such as: breaker compartments; electrical ductwork; isophase buses; high voltage switchyard components, etc. The locations of some of these electrical components do not provide the minimum safe distance for observation with an IR camera. Do not compromise safety to get the job done. **Freeze and Leave —** The correct action is to save or freeze the IR image and leave the area immediately.
- Follow company rules. Most plants have established safety rules and thermographers should understand and follow these requirements in all cases. If anything, the thermographer must not only follow the company rules, but incorporate any other safety issues relative to the incorporation of this unique technology.
- Review the pertinent electrical safety information as discussed in OSHA 1910, NFPA 70E, and the Canada Occupational Safety and Health Regulations, Part VIII.

In addition to electrical safety there are many other components that can pose a risk of injury or death if not taken seriously. It is important that the thermographer be familiar with the operational characteristics of the plant equipment that will be observed, or request assistance from someone who does.

7
CONTINUOUS IMPROVEMENT

Providing a comprehensive IRT Program requires a defined approach that is designed to meet specific IRT goals. These IRT goals should be driven by the specific plant goals such as Commercial Availability, Equivalent Forced Outage Rate (EFOR), Performance (heat rate), etc. Over time, these goals may change due to the operating mode of the plant, as well as technology advancements that may allow for new applications not previously possible. Therefore, it is important to continuously monitor a program's direction to ensure that it is current with existing plant goals and the technological advancements.

Over the years EPRI has designed a method to monitor a plant's current condition for various programs, as compared to the industry's best practices. This method was first started to gage the effectiveness of a Predictive Maintenance (PDM) Program. The success of the PDM model has inspired new models to include Plant Maintenance Optimization (PMO) and several technology models (Vibration, IRT, Lube Oil, and Motor Monitoring). Each model uses industry experts to define the categories and sub-categories to determine what activity is required to achieve a best practice or 'World Class' ranking. The results are tabulated and displayed in the form of a 'spider chart'. The spider chart's best practice grade is considered 'World Class' and is numerically graded as an eight (8) for each of the respective categories.

Using the spider chart concept to monitor a comprehensive IRT program is shown in Figure 7-1. This chart helps define the requirements of a good IRT program as determined by the industry experts. Therefore, whether a novice or expert, the spider chart provides a means to continuously evaluate the IRT program by identifying the strengths and weaknesses; and, provides guidelines for continuous improvement. The IRT Spider Chart includes an example of an IRT program assessment (shaded) followed by the defined categories. These key IRT categories, their subcategories, and samples of their ratings are listed in detail in Table 7-1.

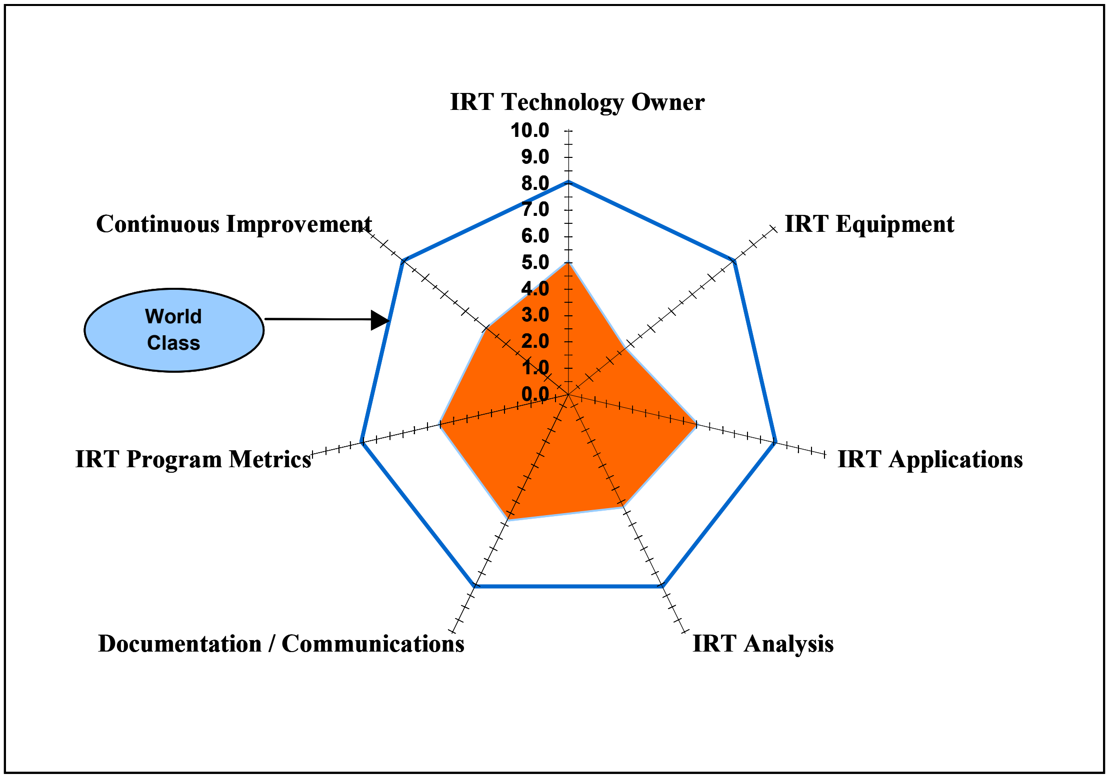


Figure 7-1
Infrared Thermography Program Assessment

Table 7-1
Key Element Category

Key Element: IRT Technology Owner	***Point Value***
Full Time – adequate time to support expectations	2.00
High School Education	0.50
College, Trade School, or Other	0.50
Level I Certification	1.00
Level II Certification	1.00
Level III Certification	1.00
Safety Training	1.00
Continued Education (conferences, Users Group, writes technical papers, etc.)	1.00
IRT Technology Owner - Roles and Responsibilities defined and understood	2.00
Total	*10.00*

Table 7-1
Key Element Category (cont.)

Key Element: IRT Equipment	***Point Value***
Has use of camera that is adequate to perform job effectively and is available as needed	1.00
Has report generation software with capabilities of producing:	
• Equipment List	1.00
• Severity Guidelines	1.00
• Equipment Status (i.e. In or Out of Service)	1.00
• Exception Page	1.00
Has access to computer, as needed, to produce report, view images, etc.	1.00
Has means to archive report/images effectively	1.00
Effective camera operation techniques utilized	1.00
Access to visual camera, as needed	0.50
Has and follows Corporate Standards	1.00
Follows suggested Camera Calibrations Frequency	0.50
Total	*10.00*
Key Element: Applications	***Point Value***
Initial IRT Program (just starting)	1.00
Other Plant disciplines involved with and support IRT Program (i.e. performance engineering, operations, maintenance, etc.)	1.00
Effective use with the following applications:	
• Electrical	1.00
• Rotating/Mechanical Equipment	1.00
• Performance	1.00
• Switchyard	1.00
• Other advanced applications	1.00
Appropriate selection methodology for equipment list and route development	1.00
Effective follow-up (post-maintenance testing, PAM, etc.)	1.00
Field survey periodicity maintained	1.00
Reviews previous reports to ensure previously OOS equipment is In Service for next field survey	1.00
Total	*10.00*

Table 7-1
Key Element Category (cont.)

Key Element: Analysis	***Point Value***
Understands "Basic Severity Guidelines" for all applications	2.00
Performs IR diagnosis adequately	2.00
Effective Analysis Process	1.00
Ability/wiliness to influence maintenance decisions	1.00
Confers with other plant personnel and utilizes other condition indicators to better determine components condition	1.00
Transfers component condition to appropriate plant personnel effectively	1.00
Uses experience to assist in evaluating a condition on a 'component' and how it will effect plant production	2.00
Total	*10.00*
Key Element: Documentation/Communication	***Point Value***
Documented program procedures and guidelines (i.e. TAD, MAG)	1.00
E&CI Matrix developed and used	1.00
Generates report with:	
• Equipment List	1.00
• Severity Guidelines	1.00
• Images	1.00
• Recommendations	1.00
• Equipment Status (i.e. In or Out of Service)	1.00
Maintains records to provide component history to assist with continued program improvement process (PAM, etc.)	1.00
Updates Condition Status Report or other communication mechanisms regularly	2.00
Total	*10.00*
Key Element: Metrics	***Point Value***
IRT Program cost calculated	2.00
Performs Cost Benefit Analysis effectively	2.00
Metrics selected to identify program effectiveness	2.00
Performs Return On Investment (ROI) calculations effectively	2.00
IRT Program Metrics are tracked effectively	2.00
Total	*10.00*

Table 7-1
Key Element Category (cont.)

Key Element: Continuous Improvement	***Point Value***
Root Cause Analysis is performed effectively on appropriate components	2.00
E&CI Matrix is maintained	1.00
Additional applications are added effectively	1.00
Program is evaluated effectively for enhancements (i.e. Self Assessment)	1.00
Attends conferences and user group meetings	1.00
Takes advanced technology training	1.00
Continuous Maintenance Department feedback	2.00
Use of Industry Operating Experiences	1.00
Total	*10.00*

8
BENEFITS

A benefit is a term that can be expressed in many different ways and for many different reasons. A benefit can be expressed as a qualitative or quantitative measure to distinguish the success of a process or to define the dollars saved by avoiding a catastrophic equipment failure. A benefit indicator can be as simple as ensuring that the quarterly IRT electrical component surveys are being accomplished every quarter. Although at times it may seem unnecessary and time consuming, the end product justifies to management and others that IRT is one of the most versatile and effective diagnostic tools in the utility industry. Some of the benefit methods to consider are as follows:

- Cost Benefit Analysis (CBA) – CBA is a method that calculates the avoided costs associated with correcting a component's problem prior to having a failure. EPRI has published several documents regarding the methods used to perform this type of calculation, which has been accepted throughout the utility industry. For examples on how to calculate a cost benefit refer to EPRI report TR-111916, Infrared Thermography Anomaly Assessment.
- Continuous Improvement IRT Program Spider Chart – The IRT Program Spider Chart (Section 7: Continuous Improvement) identifies several IRT program goals that are driven by specific plant goals. Using the spider chart concept helps define the requirements of a good IRT Program.
- Metrics – There are many indicators that can be used to define the success of a power plant. Many of these indicators are the result of several tools, techniques, and processes that contribute to the overall success of the plant. The following is a list of some of the measures that can assist in defining the plant's condition:
  - ✓ Commercial Availability
  - ✓ Equivalent Forced Outage Rate (EFOR)
  - ✓ Heat Rate (BTUs per Kwhr.)
  - ✓ Corrective Work Ratio is the Number of Corrective Maintenance (CMs) Work Orders divided by Total Number of Work Orders (WOs).
  - ✓ Emergency Work is the Number of WOs written with P1 or P2 status (critical and non-critical components).

Whether used as a troubleshooting or pre-outage tool, or as part of an aggressive PDM program, it has been demonstrated many times over that thermography has been very instrumental in reducing maintenance costs and increasing plant availability. The dollar benefits realized to date by EPRI member utilities incorporating a good IRT program are well documented.

9 REFERENCES

1. Wolfe, William L. Radiation Theory. In The Infrared Handbook; Wolfe, William L., Zissis, George J., Eds.; Infrared Information and Analysis Center, Environmental Research Institute of Michigan for Department of the Navy: Washington D. C.; 1978.

2. Madding Robert P.; 'Indirect infrared thermography measurements—some experiments and insight;' Thermal Solutions Conference Proceedings; January, 2001; Orlando, Florida.

3. Bjornson R.; 'Generator step-up transformer, low voltage bushing overheating event;' pp. 21-23; Proc. Inframation Conference; Volume 1, Infrared Training Center and FLIR Systems; September, 2000.

4. Perch-Nielsen T.P., Sorensen J.C.; 'Guidelines to thermographic inspection of electrical installations:' pp. 2-12: Thermosense XVI; SPIE; Vol 2245; April, 1994.

5. Lyon B.R., Orlove G.L., Peters D.L.; 'The relationship between current load and temperature for quasi-steady state and transient conditions;' pp. 62-70; Thermosense XXII; Proc. SPIE; Volume 4020, April, 2000.

6. Madding Robert P. and Lyon Bernard L; Wind effects of electrical hot spots—some experimental IR data; pp80-84; Thermosense XXII; Proc. SPIE; Vol 4020, April, 2000.

7. Infrared Thermography Anomalies Manual, EPRI Final Report TR-108935, EPRI M&D Center, August, 1997.

8. Infrared Thermography Anomaly Assessment, EPRI Final Report TR-111916, EPRI M&D Center, December, 1998.

9. Infrared Thermography for Plant Thermal Loss Management, EPRI Technical Review, TE-114093, November, 1999.

10. Infrared Thermography Guide NP-6973-R2, NMAC Final Report, December, 1994.

11. Electric Motor Predictive Maintenance (EMPM) Program TR-108773-V2, EPRI M&D Center, August, 1999.

12. Electric Motor Predictive and Preventive Maintenance Guide NP-7502, NMAC Final Report, July, 1992.

13. Infrared Thermography Developments for Boiler, Condenser, and Steam Cycle, EPRI Final Report TR-109529, EPRI M&D Center,

A
GLOSSARY OF THERMOGRAPHY TERMS

Absolute Temperature Scale: Temperature scales that are measured from absolute zero. Rankin and Kelvin scales are both absolute.

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

Ambient temperature: The temperature of the surroundings, typically taken as the air temperature.

Aperture: The term used by some IR manufacturers referring to dynamic range, as with the Agema 400 series. Also used by PEV imagers and some other thermal detector based imagers to refer to the variable opening size of the lens.

Area: A software tool that allows for measurement of an area in the radiometric image. The area can often be defined as a box, circle or other shape within which the measured radiometric temperature can be displayed as the average, maximum or minimum.

Attenuation: The effect a material has to reduce radiometric transmission; most commonly used to describe the filtering effect of the atmosphere.

Background: The source of radiation that reflects off of the target the IR instrument is viewing.

Background temperature: The temperature of the source of radiation that reflects off of the target the IR instrument is viewing.

Band pass filter: A filter which restricts transmission from a surface to a specific band of wavelengths. The term narrow band pass filter describes a filter allowing only a very small band of wavelengths to pass.

Blackbody: An object that absorbs 100% of the radiant energy striking it. The absorption and emission of a blackbody are both equal to 1.

Black body reference source: A traceable, calibrated high emissivity device, the temperature of which can be adjusted. A black body reference source is used to calibrate or check the calibration of a radiometer.

Boundary layer: A thin layer of fluid next to a surface. This layer of fluid has a velocity less than the main stream of fluid, becoming stationary next to the surface. The thickness of the fluid layer is related to the velocity of the fluid. In thermography the fluid is most always air, or some other transmissive gas.

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

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

Calibration: The rather complex process, typically performed by the equipment manufacturer, during which the response of a radiometric system is characterized or compared to a series of known temperature references.

Calibration check: The simple process used in the field to check the performance of a radiometric system by comparing it to a known temperature reference, often the tear duct of a person, an ice water bath, a boiling water bath, or a calibrated black body reference source.

Cavity radiator: A hole, crack, scratch, or cavity which will have a higher emissivity that the surrounding surface because reflectivity is reduced. A cavity seven times deeper than wide will have an emissivity approaching .98.

Celsius scale: A temperature scale where water boils at 100° and freezes at 0° (both at standard pressure). Formerly called the centigrade scale.

Characterize: To understand. Specifically to understand the response of an infrared system, or the spectral characteristics of a radiating surface, or the heat flow characteristics of an object.

Coefficient of Thermal Conductivity: See Thermal Conductivity

Composition: The way in which the image is composed; that is, what details are included in the image. Also called framing.

Conduction: Heat transfer from molecule to molecule or atom to atom, not requiring the movement of the substance. This is the only way heat is transferred in solids. Heat transfer by conduction is also present in fluids (liquids and gasses) when atoms or molecules of different energy levels come in contact with each other.

Conductor: A material or substance that conducts heat well when compared with materials that don't conduct well (insulators). Most metals are good heat conductors.

Convection: The transfer of energy caused by the movement of fluids either liquid or gas.

Convective heat transfer coefficient: A value that represents the relative efficiency with which an object transfers heat between a surface and a fluid. Often determined by experimentation.

Conservation of Energy Law: Another name for the First Law of Thermodynamics. For radiometry it refers to the fact that the sum of the reflected, absorbed and transmitted radiation striking a surface will equal the total radiation striking the surface
(R + A + T = 1).

Data: The thermal information gathered by the infrared system, stored either in an analog or digital format.

Data capture rate: The rate at which the thermal data or information can be gathered by the infrared system and stored either in an analog or digital format. Data has typically been captured at a rate of thirty or sixty frames per second, new high speed systems are capable of capture rates over 500Hz.

Density: The mass of a substance per unit volume. Units in the United States are pounds per cubic foot.

Dew Point Temperature: The temperature at which a gas condenses into its liquid state at a given temperature and humidity .

Diffuse reflector: A rough surface that randomly scatters the radiation it reflects.

Distance to object or target: The distance from the thermal radiometric system to the target; the value may be used by the system software, especially on short wave sensing systems, to correct for atmospheric attenuation.

Dynamic range: The amount of radiometric data in a single stored image. Data stored as an 8-bit image has 256 thermal levels and cannot be adjusted after it is stored. Data stored as either a 12- or 14-bit image can be adjusted after it is stored, although only 8-bits can be viewed as an image at any one time.

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

Electromagnetic spectrum: The range of electromagnetic radiation of varying wavelengths from gamma rays to radio waves.

Emissivity: A property of a material that describes its ability to radiate energy in comparison to a blackbody at the same temperature. Emissivity values range from zero to one.

Emittance: The property of a material *in situ* or in place describing its ability to radiate energy in comparison to a blackbody at the same temperature. Emittance values range from zero to one but can change with angle of view and other factors.

Energy: A measure of the ability to do work. Energy can take various forms; thermal energy is most often measured in British Thermal Units (Btu) or calories (c).

Exponentially: Changing at a rate determined by an exponent; energy radiating from a surface is proportional to the temperature of the surface to the fourth power (T4).

Fahrenheit scale: A temperature scale where water boils at 212° and freezes at 32° (both at standard pressure). Used primarily in the United States.

Focal Plane Array (FPA): In infrared imaging system that uses a matrix type detector such as 240x320 pixels; can be either radiometric or qualitative.

Forced convection: Convection occurring due to outside forces such as wind, pumps, or fans.

Foreground: The area beyond the target.

Film coefficient: See Boundary Layer.

Filter: A semi-transparent covering that is installed over the lens or detector to provide for either protection of the primary lens or selective transmission of various wavelengths.

First Law of Thermodynamics: Energy in a closed system is constant, it can't be created or destroyed.

Flame filter: A filter used to restrict wavelengths to those transmitted through a flame so that you can see through it; the exact spectral characteristics of the flame must be defined.

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

Fourier's Law: The equation that describes conductive heat transfer through a material, where energy transfer equals the product of thermal conductivity, area, and temperature difference.

Framing: The way in which the image is composed; that is, what details are included in the image. Also called composition.

Fusion: See Latent Heat of Fusion

Glass filter: A filter used to restrict wavelengths to those emitted by or transmitted by glass.

Graybody: An object that radiates energy proportional to but less than a blackbody at the same temperature.

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

Hertz: The SI unit of frequency defined as one cycle per second.

High Band pass filter: A filter which restricts transmission of wavelengths below a certain point, while permitting those above that point to be transmitted.

High temperature filter: A filter used to restrict overall radiation allowing you to view or measure higher temperatures.

IFOV: Instantaneous field of view or spatial resolution; the specification of a system detailing the smallest area that can be accurately seen at a given instant.

IFOVmeas: Instantaneous field of view measurement or measurement resolution; the specification of a system detailing the smallest area that can be accurately measured at a given instant.

Instantaneous field of view measurement: See IFOVmeas

Instantaneous field of view: See IFOV

Isotherm: A software tool that allows for measurement of all areas of similar apparent temperature, or radiosity, in the radiometric image. Typically the isotherm level and span can be adjusted to display the information in a false color overlaying the thermal image.

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

Joules: The SI unit of energy and work.

Kelvin scale: A metric, absolute temperature scale commonly used in scientific work.

Kilocalories: One thousand calories. Commonly used for expressing the energy value of foods. Symbol is *Kcal* or *C*.

Kirchhoff's Law: For an opaque object radiant energy absorbed equals radiant energy emitted.

Latent energy: Energy used to make or break the bonds of the state (solid, liquid, gas) of a material.

Latent heat of fusion: The energy that used to create or break the bonds in the solid state of a material.

Latent heat of vaporization: The energy that used to create or break the bonds in the gaseous state of a material.

Level: The term used to describe the thermal level setting of the IR imager; level can generally be adjusted higher or lower to improve or highlight a thermal image. Contrast with the terms span and range.

Linearly: Changing at a rate determined by a simple multiplier; radiant energy changes at a linear rate determined by the multiplying effect of the emissivity of the surface.

Long wave: Thermal radiation generally accepted to have wavelengths between 8-15$m\mu$.

Low Band pass filter: A filter which restricts transmission of wavelengths above a certain point, while permitting those below that point to be transmitted

Minimum resolvable temperature difference: The smallest temperature difference that can be distinguished by an operator of an infrared system. Also known as MRTD.

Micron: A millionth of a meter; also known as micrometer and represented by the symbol μm.

Micrometer: A millionth of a meter; also known as micron and represented by the symbol μm.

MRTD: The smallest temperature difference that can be distinguished by an operator of an infrared system. Also known as Minimum Resolvable Temperature Difference.

Narcissus: The situation in which an infrared system sees its own detector in a reflective surface, usually dramatically affecting the temperatures being viewed or displayed.

Natural convection: Convection occurring only due to changes in fluid density.

Newton's Law of Cooling: The rate of heat transfer for a cooling object is proportional to the temperature difference between the object and its surroundings.

Palette: The arrangement of colors or gray shades used to display the thermal levels. See Saturation Palette and Stepped Palette.

Phase: The state of a material, either liquid, solid or gas.

Phase change: The process matter goes through when it changes from a solid to a liquid to a gas.

Pixel: Picture element; the smallest detail of a picture.

Planck's Curves: A set of curves that describe the relationships among the temperature of a blackbody and the amount of energy it radiates as well as the distribution of the wavelengths of that energy.

Plastic filter: A filter used to restrict wavelengths to those emitted by thin film plastic.

Psychometric Chart: A graph showing the relationships among, dew point, relative humidity, and temperature for air.

Quasi-steady state heat flow: A thermal condition that is assumed to be steady state for the purpose of analysis.

Qualitative: Thermal imaging without radiometric temperature measurement.

Quantitative: Radiometric temperature measurement.

Radiation: Particles or waves emitted from a material. In thermography radiation relates to heat emitted from a surface.

Radiometric: Non-contact temperature measurement based on the thermal radiation emitted by a surface.

Radiosity: All radiation coming from a surface including that which is emitted, reflected, or transmitted.

Rankin scale: An non-metric, absolute temperature scale with degrees equivalent to the Fahrenheit scale.

Range: The term used with many IR systems that describes the preset range of temperatures that can be viewed and or measured; generally most systems offer several ranges allowing the user to select the proper temperature range for the scene being viewed.

RAT Law: See <u>Conservation of Energy Law</u>**.**

Realbody: An object that radiates less energy than a blackbody at the same temperature but emitted energy varies with wave length.

Relative scale: A temperature scale that compares temperatures to something other than absolute zero, typically the boiling and freezing points of water. Fahrenheit and Celsius scales are both relative.

Relative humidity: The amount of water vapor in a volume of air compared to that which it would contain at the same temperature when saturated. For short wave sensing systems this parameter is important so that atmospheric attenuation can be accounted for.

R-value: The measure of a materials thermal resistance. It is defined as the inverse of thermal conductivity.

Saturated: Thermal data that is outside of the measurement span or range.

Saturation palette: A display palette that clearly shows when data is saturated, or out of the active measurement span or range, by displaying it as a different color. The palette can thus be easily used to show data that is above or below a certain threshold.

Second Law of Thermodynamics: Heat cannot flow from a cooler object to a warmer one unless additional work or energy is added. Also stated as heat cannot be totally changed into mechanical work.

Secondary Lens Transmission Rate: A factor used to correct for a reduction in transmission when a filter or other semi-transparent covering is added to the primary lens.

Short wave: Thermal radiation generally accepted to have wavelengths between 2-6$m\mu$.

Slit Response Function (SRF): A test used to determine spatial and measurement resolution for infrared systems.

Solar filter: A filter used to reduce the effects of the short wavelengths emitted by the sun which cause solar glint or reflections.

Span: The term used to describe the adjustable band of temperatures being viewed or measured. Contrast with the terms Level or Range.

Spatial resolution: A measure of the ability of an infrared system to see detail, usually specified by its IFOV or instantaneous field of view.

Specific heat: The amount of heat required to raise a unit mass of a given substance by a unit temperature.

Specular reflector: A surface that reflects radiation at an angle equal to the angle of incidence; a 'mirror' image.

Spot: A software tool that allows for measurement of a spot in the radiometric image. Usually the temperature of this spot represents the average temperature of a very small number of pixels.

Stack effect: The phenomenon, related to natural convection, in which air moves in response to changes in building height.

State change: See Phase Change.

Steady State Heat Flow: A hypothetical thermal condition where temperature difference across a material or system are unchanging.

Stefan-Boltzmann constant: 0.1714 x 10-8 Btu/hr • ft2 (5.7 x 10 -8 watt meter -1 kelvin -4).

Stefan-Boltzmann Law: Total energy radiated by a blackbody surface is proportional to its absolute temperature to the fourth power.

Stepped palette: A display palette that has clear delineations between colors or shades of gray as opposed to a continuous palette. When using a stepped palettes each separate color or shade of gray represents a discrete temperature band.

System parameters: Corrections that can be made in the system software, such as distance to object and relative humidity, that improve the accuracy of the radiometric measurement.

Temperature: The relative measure of hotness or coldness of a material or substance.

Thermal background: See Background.

Thermal Capacitance: The ability of a material to store thermal energy. It is defined as the amount to heat required to raise the temperature of one cubic foot of material one degree Fahrenheit. It is arrived at by multiplying a materials specific heat times its density.

Thermal Conductivity: The symbol for thermal conductivity is 'k'. It is the measure of a materials ability to conduct thermal energy. It is defined as the rate at which heat flows through a material of unit area and thickness, with a temperature gradient over a unit of time. In U.S. units it is the amount of heat that flows through one square foot of material that is one inch thick, induced by a 1°F temperature difference in one hour.

Thermal Diffusivity: The rate at which heat energy moves *throughout* the volume of an object. It is the ratio of the thermal conductivity to the thermal capacitance of the material.

Thermal Foreground: The area beyond the target, particularly those objects that transmit energy to the system through a semi-transparent target. See Foreground.

Thermal Resistance: The inverse of thermal conductivity. It is the measure of a materials ability to resist the flow of thermal energy. See R-value.

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

Transient heat flow: A thermal condition where the heat flow through a material or system is changing over time.

Transparent filter: A highly transparent filter used to protect the primary lens from damage.

Vaporization: See Latent Heat of Vaporization.

Wien's Displacement Law: The law that describes the relationship between the temperature of a black body and the peak wavelength of radiation it gives off. At higher temperatures there is a displacement to shorter wavelengths. The Law is stated as
$b/T = \mu m$ where b is Wien's Constant (5215.6), T is the blackbody absolute temperature (R) and μm is the peak wavelength. SI value is 2897 for K.

Wien's Displacement Constant: The value, 5215.6 (2897), determined by Wien to quantify the relationship between the temperature of a black body and the peak wavelength of radiation it gives off.

8-bit system: An infrared system capable of storing data that can be divided into 256 thermal levels.

12-bit system: An infrared system capable of storing data that can be divided into 4096 thermal levels.

14-bit system: An infrared system capable of storing data that can be divided into 16,384 thermal levels.

B
HEAT TRANSFER

Heat is a form of energy and is properly thought of as energy in transit. Heat flows from objects at higher temperature to objects at lower temperature. An object that gains heat increases its internal energy. Alternately, an object that loses heat decreases its internal energy.

Temperature is defined as the degree of molecular and atomic activity of an object. The higher the temperature, the higher the molecular and atomic activity. Temperature difference is the driving force for heat flow, just like pressure difference is the driving force for fluid flow and voltage difference is the driving force for electrical current flow.

There are three fundamental modes of heat transfer: Conduction, Convection and Radiation. Though in many cases these three modes are discussed separately, it must always be remembered they act together in many cases. The total heat flow is the sum of the heat flow due to each of these three modes.

Figure B-1 gives a real-world example of the three heat transfer modes in a domestic setting. It is useful to discuss in some detail how various objects are heated by the fire in the stove. The fire heats the internal surfaces of the stove walls and its top by radiation and convection. Heat conducts through the walls of the stove and warms the outer surface. The outer surface radiates to the environment, and the air around the stove convects heat away from the surface into the environment. Though air and other gases have a finite conduction coefficient, it is quite small compared to the other two modes.

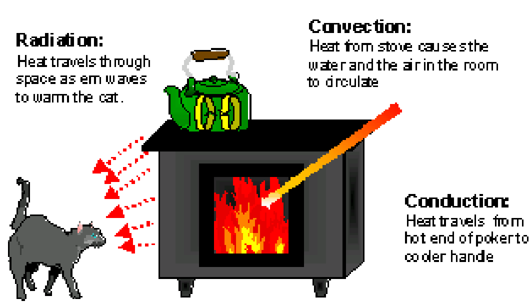


Figure B-1
Illustration of Modes of Heat Transfer

In steady-state conditions, the environment around the stove comes into thermal balance with the stove, primarily through radiation and convection, which is true for most cases. Temperatures and heat flow are constant over time. If the stove is in a room, the steady-state room temperature will depend on the type of structure, where the stove is placed, and environmental conditions affecting that structure. On a cold winter night, it is hoped that the stove can keep the ambient room temperature near 70º F. But the air temperature near the floor will be cooler than that near the ceiling, due to the nature of convective heat flow. In addition, radiant heating will warm the region near the stove more than the areas further from the stove.

The important thing to remember is that 'steady-state' is defined as a condition where heat flow and temperatures are constant over time. It doesn't mean that nothing is happening; however, it does mean that what is happening isn't changing. If a thermometer is placed anywhere in the space, the reading will stay the same over time for a particular location. But, it can change dramatically from location to location.

Transient heat flow causes the temperature at a given point to change over time. As the fire 'burns down', less energy is supplied to the stove and it starts to cool off. The temperature of the stove surface drops, upsetting the balance in the room.

In an industrial environment, similar events can occur that are caused by serious problems that can be diagnosed through infrared thermography (IRT). For example, an Oil-filled Circuit Breaker (OCB) with bad contacts will generate heat through resistive heating of the contacts. The amount of heat generated is directly related to the power (I^2R - current squared times the electrical resistance) dissipated in the bad connection. This can raise the temperature of the contacts to a level that will break down the oil, eventually causing catastrophic failure of the OCB.

In steady-state conditions, the outside surface of the OCB will come to a thermal balance with the surrounding environment, just like the stove in the living room. Heat will radiate from the surface, and the outside air will transfer heat by convection off the surface of the OCB. Heat will also conduct through the current carrying conductors to some degree, and perhaps through the base of the OCB into the concrete pad. But most of the heat leaves the surface through radiation and convection.

There is considerable thermal resistance between the hot contacts and the outside surface of an OCB. In general, good electrical insulators such as oil are also good thermal insulators. The outside surface temperature can be hundreds of degrees cooler than the internal hot spot. When using IRT, the thermographer must be aware of such situations, often called 'indirect readings'. Therefore, understanding heat transfer basics is key to grasping whether a target is a direct reading or an indirect reading.

Knowledge of steady-state heat transfer equations allows the calculation of the amount of heat lost from the OCB surface. If solar loading, and other external possibilities for heating the surface are excluded, the only thing left that can create heat loss is from an internal problem. Therefore, the heat lost from the OCB surface can be equated to the heat generated within the OCB, with a high degree of confidence. (*Note, it is not a concern how the heat got from the bad contacts deep within the OCB to the outside surface).* This is a good thing, as the heat transfer mechanisms will otherwise be quite complex, having to include convection by the oil and conduction through the oil. Suffice to say, the thermal patterns on the surface of the OCB may not be a good indicator of where within the OCB the problem lies, but they can be an excellent indicator of how serious the problem is.

The thermal heat losses in equation form are:

$$I^2R = Q_{rad} + Q_{conv}$$

Q_{rad} and Q_{conv} represent the heat transferred by radiation and convection, respectively. If the electrical current, I, is known, the electrical resistance, R, of the problem connection can be calculated. If the heat loss is not accounted for, a resistance lower than the actual value can be calculated. Therefore, this is a conservative estimate of the magnitude of the problem. The key is that the equation is valid only in steady-state conditions. If the load changes, if the ambient air temperature changes, if the wind speed changes, and so on, the equation won't work.

As 'time' is the key element in steady-state conditions, the question occurs as to how fast changes will occur. Suppose the load doubled at 10:00 a.m. This would cause the heat generated at the resistive contacts to increase by a factor of four since it is a square function (2^2=4). Would this show up on the surface of the OCB as an immediate temperature increase? Common sense says it would not, and so do the equations. For transient heat flow, the heat capacity or thermal mass of an object is quite important. The heat capacity of an OCB, for example, is quite large; therefore, it can take many minutes if not hours for new steady-state conditions to be reached. If a thermographer performs a survey of this component at 10:15 a.m., what load should be logged?

If an IR thermography did a survey of an OCB and spotted a temperature rise, it would be important to know the load for at least an hour or two prior to the survey. If the load just doubled, and the results are based on the new load, the seriousness of the problem will be underestimated. The surface temperature that would be seen with IRT would be due to the earlier lower load. Waiting for new steady-state conditions for the higher load will result in higher surface temperatures.

Some have used the equation to propose corrections in temperature rise for fractional loads. It was assumed, incorrectly, that the temperature rise would follow a square law. That is, if the load doubles, temperature rise increases by a factor of four. But heat transfer by radiation, due to its temperature dependent nature, keeps this from happening.

The skilled thermographer recognizes the importance of load and load variations. Accounting for them, at least qualitatively, will result in better diagnostics. For problem conditions, waiting for steady state or near steady-state conditions is recommended.

So, for many IRT applications, transient conditions are problematic. But for some, such as roof moisture surveys, transient conditions are preferred. This will be illustrated in the section on transient heat flow. With this introduction to heat transfer, the modes can now be discussed in more detail.

Conduction

Heat transfer by conduction is the only mode that works in solid materials. For a solid rod, the heat flow through the rod is governed by 4 variables: the thermal conductivity, cross-sectional area and length of the rod, and the temperature difference along the rod (see Figure B-2).

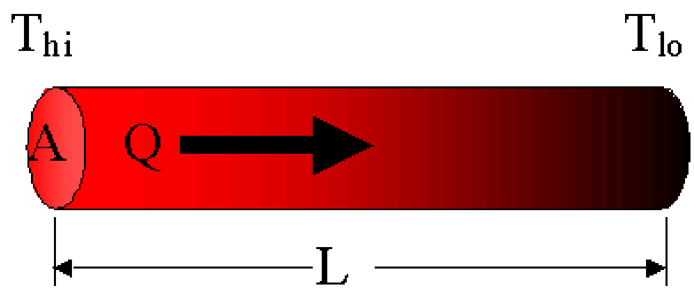


Figure B-2
Conductive Heat Transfer

The rate of heat flow, Q, is measured in Watts (metric) or BTU/hr (English). In equation form, steady-state heat transfer by conduction in one-dimension is give by:

$$Q_{cond} = \frac{kA\left(T_{hi} - T_{lo}\right)}{L}$$

Where the Heat Rate, Q, is directly proportional to the temperature difference, the cross-sectional area, A, and the thermal conductivity, k, of the object. It is inversely proportional to the length, L, of the rod.

Convection

Heat transfer by convection occurs when a fluid (liquid or gas) moves from a higher temperature area to a lower temperature area, cooling in the process. The fluid leaving the higher temperature area is replaced by cooler fluid that warms up and the process continues. Convection can be forced or natural. Natural convection results from the movement of fluids caused by buoyant forces resulting from density differences between hot and cold fluids. In a nutshell, hot air rises.

In rare cases, a warmer fluid can be denser than a cooler fluid. Water at 39º F, for example, is denser than water at 38º F and therefore will sink. This is true all the way down to 32º F. As a result, ice floats, and the coldest temperature of the bottom of a lake that is not frozen solid will usually be 39º F. But for most IRT applications, natural convection will take heat from a lower altitude to a higher one. Thermal patterns on bus ducts, have been observed where the hot spot is on top, but the problem is actually near the bottom. The thermographer needs to be careful in interpreting thermograms where natural convection plays a strong role.

Forced convection results from the movement of fluids caused by a fan, pump or blower. Though convection is usually thought of as occurring in air, many other fluids are likewise utilized. In the electric utility industry, oil is a primary fluid used both for insulation and convective heat transfer and the fins on a transformer are a good example of this phenomenon. Oil heated by the workings of the transformer is cooled by flowing through the fins. Air convects between and around the fins thereby removing heat. The fins also transfer heat by radiation. They are called radiators, but the difference between convection and radiation is nominal. The warm oil gets to the fins by one of two methods depending on transformer design: Forced convection with electric pumps, or natural convection exploiting the density dependence of oil on temperature. In both cases the oil is removed from the top and inserted into the bottom of the transformer. Thermograms of properly operating fins show them to be warmer at the top and cooler at the bottom.

The thermogram (Figure B-3) shows two sets of cooling fins improperly functioning, whilst the third set on the right is properly operating. This is a natural convection setup; the transformer has tilted slightly on the pad over the years and the oil level is a little bit low. This combination was enough to cause the problem. But the thermographer must exercise caution. There are cooling fin setups that rely on the thermal expansion of oil to activate another set of cooling fins with a slightly higher entry point when the weather becomes hot. Good training is key to good thermography.

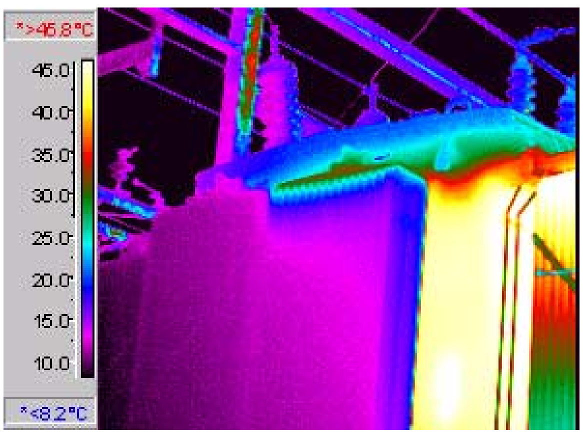


Figure B-3
Thermogram

Heat transfer by convection depends on many variables: temperature difference, surface area and extent, orientation of the surface, type of fluid and velocity of the fluid. The equation for convective heat transfer under steady state conditions is deceptively simple:

$$Q_{conv} = h_c A \left(T_{hi} - T_{lo} \right)$$

Where, the Heat Rate, Q, is directly proportional to the Convective Coefficient, h_c, the Surface Area, A, and the Temperature Differential.

The difficulty lies in the Convective Coefficient, h_c. The variables noted in the above equation: orientation of the surface; type of fluid; velocity of the fluid; and, are all included in h_c. This coefficient also depends on whether the flow is laminar or turbulent. Significant amounts of empirical data and years of research have been consumed to understand convective heat transfer. In most cases, calculations that are within 20% of the true value are quite acceptable for convective heat transfer. For the user, the simpler the structure, the more likely that good results can be obtained.

Radiation

In the field, all modes of heat transfer are usually present. Conduction works best in solids, convection in fluids and radiation in a vacuum. Fortunately for thermographers, radiative heat transfer also works well in air. IR cameras detect and image thermal radiant energy. It is often incorrectly stated that radiative heat transfer becomes important only at high temperatures.

Contrary to this, thermal radiation can dominate the heat loss from the surface of an OCB. For example, a 24” diameter by 48” tall OCB at 95º F (35º C), with the ambient and background at 86º F (30º C), loses 28 watts by convection and 90 watts by radiation in a no-wind condition. If the load (current) on this OCB phase is 370 amps, the electrical resistance required to generate this heat would be 863 micro-ohms, indicating a serious problem.

Radiative heat transfer from an object with emissivity, ε, and surface area, A, depends on these variables: surface area, object emissivity, orientation of the object and the temperature difference with a twist. The twist is that the absolute temperatures must first be raised to the fourth power (squared twice), then the difference taken. In equation form:

$$Q_{rad} = \varepsilon \sigma A F_{12} \left(T_{hi}^4 - T_{lo}^4 \right)$$

Where the Heat Rate, Q, is directly proportional to the Emissivity, •, the constant σ, the Surface Area, A, the View Factor, F, and the Temperature (to the 4th power) differential.

The emissivity can be thought of as the efficiency of the object as a radiator. The constant, σ, is called the Stefan-Boltzman constant. The view factor, F_{12}, is one when the surrounding environment is uniform in radiance with an apparent temperature, T_{lo}. If the surroundings vary in radiance due to temperature or emissivity factors, the view factor must be implemented for accurate results. This complicates the calculation significantly and is beyond the scope of this work. The radiation equation also assumes the object is a graybody; which means that the emissivity is spectrally constant. For non-graybodies, the calculation gets considerably more complicated.

When calculating heat transfer by conduction or convection, using the Celsius or Fahrenheit scales is exactly the same as using the Kelvin or Rankine scales. This is illustrated in the following section on temperature scales. But when raising the temperature to the fourth power, the differences are not the same. The absolute temperature scale *must* be used when calculating radiative heat transfer.

Temperature Scales

Temperature is measured in metric units in degrees Celsius and, for absolute temperature, Kelvin. In English units temperature is measured in degrees Fahrenheit and, for absolute temperature, Rankine. The following equations show the relationships:

$$T_C = T_K + 273.16$$

$$T_F = T_R + 459.67$$

$$T_F = \frac{9}{5} T_C + 32$$

$$T_C = \frac{5}{9} \left(T_F - 32 \right)$$

Subscripts: C, Celsius; K, Kelvin; F, Fahrenheit; R, Rankine. Temperature difference equations can be readily calculated from the above set.

$$\Delta T_C = \Delta T_K$$

$$\Delta T_F = \Delta T_R$$

$$\Delta T_F = \frac{9}{5} \Delta T_C$$

$$\Delta T_C = \frac{5}{9} \Delta T_F$$

The Greek letter delta, Δ, is used to indicate temperature difference. In fact, experienced thermographers usually refer to the temperature difference as 'Delta T'. When taking temperature differences, the offset constants, such as 273.16, cancel. Therefore, a Celsius degree is the same *size* as a Kelvin degree.

Thermographers probably do not need to memorize these equations as modern IR cameras can do the conversions for them. But it is useful to be able to mentally compute ΔT. The 9/5 factor comes from the size difference between Celsius and Fahrenheit degrees. There are 180 Fahrenheit and 100 Celsius degrees between freezing and boiling. The ratio of 180/100 equals 9/5. A Fahrenheit degree is almost half the size of a Celsius degree. It takes 180 of them to span the same range as is spanned by 100 Celsius degrees. Remember 9/5, and that the same ΔT in Fahrenheit will always be a larger number than the Celsius ΔT.

Transient Heat Flow

Heat transfer under non-steady-state conditions is called transient heat flow. Frequently, this is problematic as discussed above. Often transient heat flow is preferred, primarily to extract surface thermal signature variations due to thermal mass variations. Roof moisture surveys fall into this category.

Figure B-4 shows temperature versus time for two areas of the same roof. The dry area has less thermal mass, or thermal capacitance, and exhibits larger swings in temperature throughout the diurnal cycle. Thermal behavior is analogous to electrical behavior when it comes to capacitance. In electrical systems, a capacitor is an open circuit under dc current conditions. It takes an ac current to show the effects of a capacitor, which is to dampen the voltage and current swings. So, for roof moisture IR surveys, a large diurnal thermal swing is desired. This means that a nice hot sunny day followed by a clear dry night, creates a large radiant transfer to the sky. At mid-day the dry area is warmer and at mid-night the wet area is warmer; and, early in the morning and evening there is a crossover point where both areas are the same. Clearly this is not the time to begin the IR survey! It appears that the ΔT is greater in the daytime than at night; but, virtually all roof moisture surveys are done at night. This is due to several factors. One is that the temperature on the roof during the day can be uncomfortable, even dangerously hot, for the IR team. Also, it is easier to damage a hot roof by walking on it. In addition, solar effects can cause anomalies. As a result, more uniform thermal signatures are found at night.

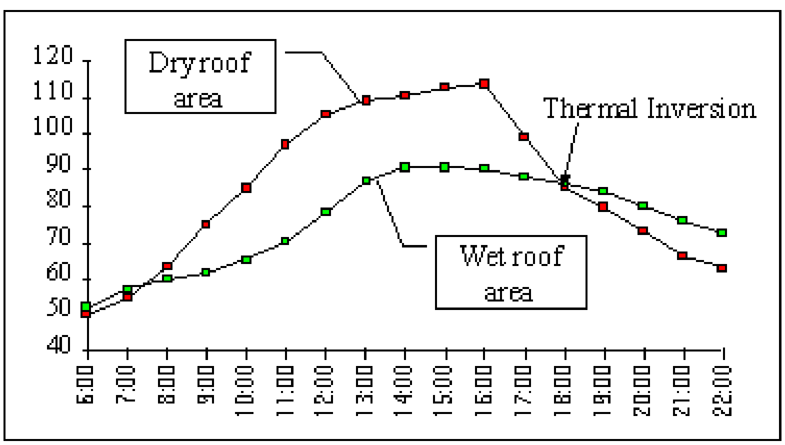


Figure B-4
Temperature versus Time Graph

View factor effects must be qualitatively considered. Parapets, penthouse areas such as for elevators will usually have warmer roof regions near them as they block part of the sky as compared to totally exposed areas. Performing roof moisture surveys requires an intimate knowledge of the roof construction. Safety issues cannot be overemphasized. Roof integrity and clearing the roof of debris should be done prior to the survey. Care must be taken to not walk off the roof; and, there are many other operational procedures to consider that are beyond the scope of this work. But the basics of transient heat flow are one important piece of the IR survey for roof moisture.

Many other IRT applications rely on transient heat flow. They include, concrete block building envelope structural integrity, liquid levels in tanks, buried land mine detection, de-laminations in roadways and detection of buried bodies. Though temperature measurement is less important for these applications than for industrial predictive maintenance diagnostics, a solid understanding of heat transfer basics is imperative.

C
CHECKLIST FOR ELECTRICAL MAINTENANCE INSPECTIONS

Tips For Better Electrical Maintenance Inspections

☑ Always attempt, whenever possible, to inspect electrical systems when loading exceeds 50%. Try to do IR surveys when the load has stayed constant for at least an hour to several hours. Surface temperatures on indirectly viewed equipment such as load tap changers, oil circuit breakers and so on will significantly lag a load change. If the load has dropped in the last few minutes before your measurement, you may over-assess the problem. If the load has increased, you may under-assess the problem. Thermal mass or heat capacity becomes very important when the load changes.

☑ Compare components from one phase to those of another phase. There are several reasons for this:

1. Usually the emissivity is the same. But remember, emissivity must always be considered. It doesn't cancel when measuring temperature differences.
2. The surface area remains the same (heat generation and dissipation effects are equal).
3. All phases are the same distance from the infrared camera.
4. All phases will have the same loading (hopefully).

☑ Unbalanced loads will account for some differences between conductors. Use metering devices already installed on the system or clamp - on ammeters to check the differences to help discriminate between problem types.

☑ The type of load will have something to do with whether the load is balanced. Three-phase motor loads should be balanced, but lighting and single-phase loads may be unbalanced.

☑ Bear in mind that a temperature rise between phases of, say, 10% may be a minor problem when occurring in a system near full load, but that it may pose a serious threat when occurring in a system that is lightly loaded. The reason is that if the latter system is ever loaded to near capacity, the temperature could become high enough to melt the components and cause a catastrophic failure.

☑ Use high emissivity areas for measurements and comparisons: cracks, bolt holes, conductor insulation. The temperature measurements you get will be more accurate.

☑ Be careful when looking at low emissivity materials – you can't see small delta T's well. Your ability to distinguish temperature difference decreases rapidly with decreasing emissivity. Don't attempt temperature measurement for targets with emissivity values less than 0.5.

☑ The enclosure, insulation and the number of conductors in the equipment can reduce the current-carrying capacity. During a system survey, make comparisons between phases and between conductors and connectors.

☑ Whenever you find heat on the surface of an enclosure, check to see if a resistor, heater or transformer is mounted on the other side. Though a resistor will look hot, heating should be even over the energized portion.

☑ Have well-defined severity criteria for both direct and indirect targets. We recommend re-shooting IR after the part is repaired and safely re-energized. This gives a baseline IR image, and verifies the repair. Get agreement from engineering, operations, maintenance and management on these criteria and their recommended actions. If you do this up front, when the big problems hit, it will be easier to get your job done. You cannot force them to shut it off and fix it immediately. But you can point out that they agreed to this as a recommended action for a critical problem. At the end of the day, the financial risk must be managed by management. Your personal safety, however, must be managed by you.

D
COMMON MISCONCEPTIONS

The information contained in this Appendix was contributed by the Infrared Training Center (ITC) of the FLIR Corporation.

Do Emissivity Effects Cancel When Doing Relative (Temperature Difference) Measurements? No!

Many thermographers have been taught incorrectly that they do not need to correct for emissivity effects when measuring temperature differences between two objects having the same emissivity. Implicit in this assumption is that the background reflections off the two objects are equal. This causes the background effects to cancel each other when the difference is taken. But does that get rid of emissivity effects? Absolutely not!

Here is a simple experiment to do with your IR camera. Get two containers of low emissivity. Any bare metal can will do, such as used Sterno cans, metal paint cans, etc. Fill one can with hot water, leave the other can at room temperature. View these two cans with the IR camera and get a temperature difference with the camera emissivity set to one. Now put a piece of high emissivity material such as Scotch Super 88 vinyl electrical tape (054007-06143), ε =0.95, on each can where you measured the temperature difference. Repeat the measurement with the emissivity still set to one. Are both sets of readings the same? If emissivity effects cancel, they should be the same. But they are, in fact, very different.

Figure D-1 shows the results in a side-by-side comparison. Two cans, one filled with hot water, the other at room temperature, have a small strip of Scotch 88 electrical tape attached to the front surface. The temperature of the tape equals the temperature of the can for each case. But the IR camera shows very different results when measuring both temperatures and temperature differences. The same emissivity, 1.0, is used for both to illustrate the importance of using the proper emissivity value. When using proper emissivity settings, 0.28 for the cans and 0.95 for the tape, the actual temperature differences are the same at 56.8ºF. Note the error introduced by using an emissivity setting of 1.0, which is small for the tape but quite large for the cans.

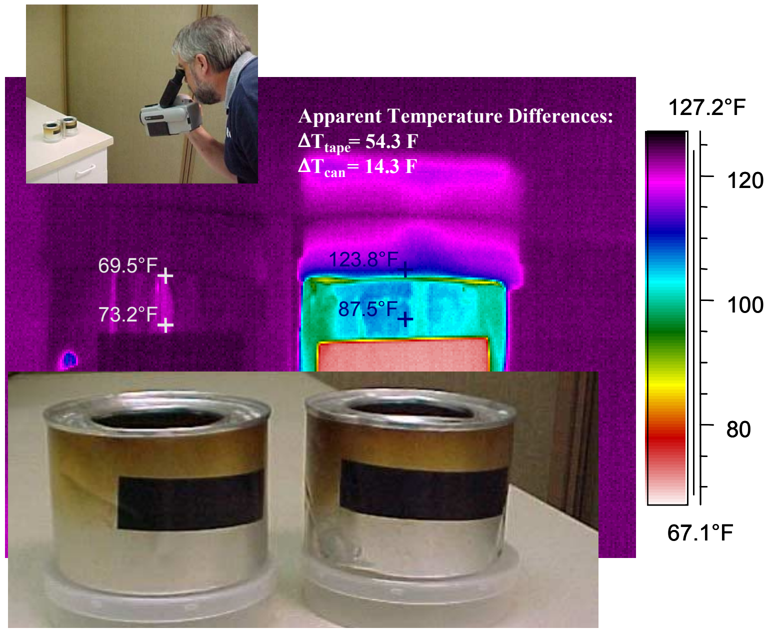


Figure D-1
Apparent (uncompensated) temperature differences for equal temperature targets with different emissivities. Top, IR image. Bottom, visual image. Inset shows setup.

For the mathematically inclined, the following shows how emissivity does not cancel for relative (temperature difference) measurements. The radiant energy received by an IR camera from an opaque object can be written as the sum of emitted plus reflected energy coming from the target[1]:

$$L_m = \varepsilon L(T_t) + \rho L(T_b) \qquad \text{Equation D-1}$$

L_m is the measured radiance, $\varepsilon L(T_t)$ is the radiance emitted by the target with emissivity ε and temperature T_t, and $\rho L(T_b)$ is the energy reflected off the target with reflectivity ρ and background temperature T_b.

For two objects with the same emissivity and same background but different temperatures, the equation for the measurement difference can be written as:

$$L_{m1} - L_{m2} = \varepsilon L(T_{t1}) - \varepsilon L(T_{t2}) \qquad \text{Equation D-2}$$

The reflectivity for opaque objects with the same emissivity is the same, and with the same background radiance the background term cancels out. The radiance difference is then:

$$L(T_{t1}) - L(T_{t2}) = \frac{L_{m1} - L_{m2}}{\varepsilon} \qquad \text{Equation D-3}$$

Equation D-3 shows the radiance difference is equal to the measured difference divided by the emissivity. The temperature difference is found by the camera firmware through a calibration lookup table. The camera finds the temperature corresponding to a radiance value equal to the measured value divided by the emissivity, then takes the difference. This derivation confirms our experiment: Emissivity makes a big difference even for relative, or difference, measurements.

Can You Measure Emissivity of Targets at the Same Temperature as the Background? No!

An opaque object is emitting and reflecting energy to the IR camera. It emits according to its emissivity and its temperature. It reflects according to its reflectivity and the temperature of the background. For opaque objects, $\rho = 1-\varepsilon$. This means that emissivity and reflectivity are complementary. An opaque object with emissivity of 0.8 has a reflectivity of 0.2. If the object and background temperatures are equal, the camera will see the same result no matter what the emissivity.

Using equation D-1 making the target temperature equal the background temperature, recognizing $\rho = 1-\varepsilon$ and rearranging terms we can write:

$$L_m = \varepsilon L(T_t) - \varepsilon L(T_t) + L(T_t) \qquad \text{Equation D-4}$$

Further simplifying:

$$L_m = L(T_t) \qquad \text{Equation D-5}$$

If the target temperature equals the background temperature, the IR camera will read this value no matter what you set for emissivity!

Can You Get Rid of All Reflections Just By Moving? No!

You see what seems to be a hot spot on a target. You move and the hot spot moves. You determine this to be a reflection. You change to a location where the hot spot is no longer reflecting. Good move. Is the target still reflecting? You bet it is. It is just not reflecting a hot spot. You still have to compensate for the background reflection to get a good temperature reading.

Do Distance Effects Cancel when Comparing the Same Size Target at the Same Distance? No!

This is of the same ilk as trying to ignore emissivity effects by measuring temperature differences. We all know you can be too far away to get a good temperature reading. Suppose we are looking at a fuse cutout. Behind it is a hill. The lower end is normal and has about the same temperature as the hill behind it. The top is hotter than the hill behind it. For the first we would get a correct temperature no matter what the distance. For the second, the further away we get, the lower the reading (refer to Figure D-2). Clearly, the distance effects would not cancel as the hot spot starts looking cooler as we get further away and the ambient spot doesn't change. What is going on?

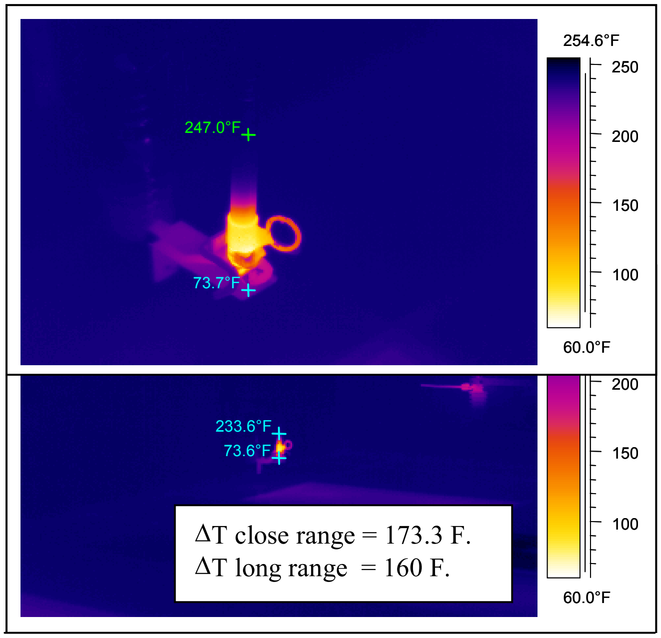


Figure D-2
Effect of distance on temperature difference measurements

To understand this, we need to understand how the camera optics work at a very basic level. The lenses are not perfect. When we get 'too far' away from a target, the effect is that in the IR camera, energy from around the target starts mixing into the target, and energy from within the target starts to 'spread' outside the target. This dilutes the temperature of the hot spot due to the cool surroundings. But the fuse cutout portion that is the same temperature as the hill behind it is mixing energies of the same value. So, its temperature does not appear to change, even though we are too far away.

This is not unlike being out of focus. So, another way to look at the effect of distance is there is never a really perfect focus. Which brings us to the next misconception.

Do I Need to be Concerned About Focus for Temperature or Temperature Difference Measurement? Yes!

Focusing 'unscrambles' the photons (heat energy) coming from an object and its surroundings to create a sharp image in the IR camera. Unfocused targets will look fuzzy. What fuzzy means is that photons from outside the target get scrambled with photons from within the target, and photons from within a target get scattered outside the target. The overall effect is to dilute the true target temperature with whatever is around it. Figure D-3 gives an example of this. The simulated hot spot on the fuse cutout has over 170ºF temperature rise when focused. When out of focus at the same distance, the temperature rise drops to just over 120ºF. For smaller targets, this effect is much worse.

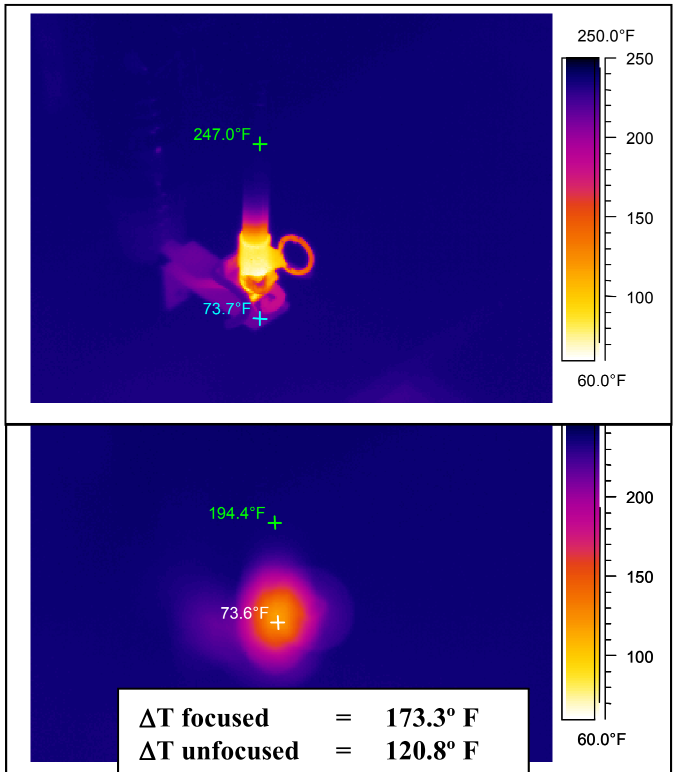


Figure D-3
Effect of focus on temperature difference measurements

Carrying this logic a step further, it is more important to focus on small targets than on large ones. And the effect of defocusing is increased if the target is much different in temperature than the surroundings. You really want to be careful with such items as switchgear viewed against a clear sky in a low humidity environment. Such a sky condition is quite cold. Switchgear targets tend to be somewhat small and are usually not very close due to safety and other concerns. These factors combine to make good focus and proper working distance quite important. For most substation, switchyard, transmission and distribution line applications, a good telescope with your IR camera is mandatory equipment. Also recommend is good pair of binoculars for visual inspection.

Do You Need to be Concerned About Wind Effects? Yes!

We use fans and blowers for cooling all the time. We should not be surprised that the wind can be an effective cooler. But we often ignore these effects. Experiments with wind blowing on a hot fuse disconnect show that even small breezes can influence temperature rise. These experiments show that a three mph wind can cut the temperature rise of a hot spot in half[2]. Many thermographers feel that they only need to be concerned about wind outside. But air conditioning systems can blow cold air inside and also cool hot targets.

An automotive company thermographer discovered this on opening an electrical cabinet. A hot connection seen in the initial scan of the interior of the opened cabinet slowly disappeared. In a few minutes it was virtually gone. What happened? When the cabinet was opened, conditioned air was able to blow inside.

It is recommended that IR thermography surveys be performed in low wind conditions, under 10 mph. The thermographer should definitely consider wind effects when evaluating a thermal anomaly.

Can I Use the Same Severity Criteria on Indirect Measurements as I Use on Direct Measurements? No!

A direct measurement is one where there is little or no thermal insulation between the IR camera and the target of interest. An indirect measurement is where there is considerable thermal insulation between the target and the surface seen by the IR camera.

Examples of indirect measurements for electrical applications include: Oil filled circuit breakers, bus ducts, load tap changers, internal connections on transformers, underground switchgear, heavily insulated switchgear and other connections hidden from direct view due to inaccessibility.

The temperature rise indicating serious to critical problems for these indirectly view items is usually just a few degrees. An experiment we performed on a bus duct section indicated the internal temperature rise was about 25 times the bus duct surface temperature rise. As shown in Figure D-4, for this bus duct, a 22º F rise seen on the duct would indicate about a 550ºF rise on the internal bus! This multiplier should not be universally applied, but it is indicative of the serious nature of indirectly viewed targets.

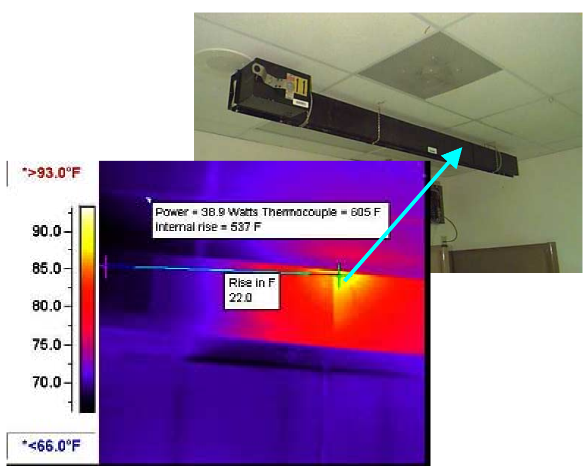


Figure D-4
IR image (bottom) of bus duct with a simulated critical problem

Another potential problem with indirect targets is environmental effects[3]. Solar loading of previously shaded underground switchgear, exposed to the sun when the access cover is opened, can rapidly mask problems. Wind effects can also hide indirectly viewed problems. In general, environmental and other external influences can more readily mask the low temperature differences associated with indirect measurement, making them even more challenging to diagnose.

One large organization thought they were being extremely conservative with their severity criteria by using a 10ºC rise as the level to report any problem. They did not discriminate direct from indirect readings. Until an 8ºC rise went unreported and a serious fire resulted three weeks later. Their severity criteria now incorporate direct and indirect readings.

For Electrical Problems How Do I Deal with the Load?

Certainly load is crucial to proper diagnosis of electrical problems, most of which are seen by IR thermography due to heat caused by electrical current flowing through an abnormally high resistance. As the power dissipated, as heat by a resistor equals the current squared times the resistance, load (current) is crucial.

Thermographers should make every effort to determine the load on an electrical circuit where they have found a problem. Due to the heat capacity of electrical systems, the load should have been constant for a time prior to measurement. How long this is depends on the heat capacity of the equipment and other factors. In some cases as much as an hour is needed for the temperature of a problem area to reach its maximum value after a load increase.

Correcting for load is not simple. Some have promoted using a square law, as the power increases as the square of the current. If heat transfer were linear with temperature rise, this would work. But heat transfer by radiation varies as the fourth power of the temperature. This non-linearity causes the square law to be incorrect. The actual temperature rise normalized to 100% load can be expressed as the ratio of full power to percent power at measurement raised to an exponent, n, where n is a value between about 0.6 and 1.8. Perch-Nielsen et al and Lyon et al and have investigated these effects[4, 5]

So, what to do about compensating for less than 100% load conditions. Many thermographers will not perform an IR survey on equipment at less than 40% to 50% load. Recognizing the difficulties associated with attempting to normalize partial load IR data to full load conditions, many thermographers also employ a variety of decision criteria to make a good recommendation. These other criteria include environmental effects, criticality of the equipment, down time for failure, cost of down time and so on. The skilled thermographer knows the target will not have a full load equivalent temperature rise equal to a current squared calculation. That would be the maximum. The minimum corrected temperature rise would probably be a value calculated per the results shown in the above references. Typically, the full load condition will bump the problem severity one, two or even three categories for direct measurements. For indirect measurements, a problem seen at partial load is probably already in the critical category. The risk of performing IR surveys on indirect targets under partial load is one may not see a temperature rise.

Summary

Often, these errors will go completely unnoticed, as there is usually no other means to verify findings. But these misconceptions can easily cause the thermographer to underestimate the severity of a problem with potentially dire consequences. Ultimately, this can result in failure of a thermography program, as these "bad calls" will call into question the reliability of the technology.

A well-trained thermographer will avoid the pitfalls caused by the common misconceptions discussed in this paper. IR cameras have evolved into a very useful diagnostic tool. In the hands of a skilled thermographer, millions of dollars in cost of equipment repair and downtime can be avoided with proper application of IR thermography principles and practice.

References

1. "Emissivity measurement and temperature correction accuracy considerations"; Robert P. Madding; Inframetrics, Inc.; North Billerica, MA; Thermosense XXI; Proc. SPIE; Vol. 3700; pp 393-401; April, 1999.

2. "Wind effects on electrical hot spots—some experimental IR data"; Robert P. Madding and Bernard R. Lyon Jr.; Infrared Training Center; North Billerica, MA; Thermosense XXII; Proc. SPIE; Vol. 4020; pp 80-84; April, 2000.

3. "Environmental influences on IR thermography surveys"; Robert P. Madding and Bernard R. Lyon Jr.; Maintenance Technology; pp 36-41; December, 1999.

4. "Guidelines to thermographic inspection of electrical problems"; Thomas Perch-Nielsen and J.C. Sorensen; Danish Technological Institute; Department of Energy Technology; Taastrup, Denmark; Thermosense XVI; Proc. SPIE; Vol. 2245; pp 2-13; April, 1994.

5. "The relationship between current load and temperature for quasi-steady state and transient conditions"; Bernard R. Lyon Jr., Gary L. Orlove and Donna L. Peters; Infrared Training Center; North Billerica, MA; Thermosense XXII; Proc. SPIE; Vol. 4020; pp 62-70; April, 2000.

Target:

Predictive Maintenance Program Development and Diagnostic Tools

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Printed on recycled paper in the United States of America

1004019

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com