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Managing Water in the West

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Volume 4-13

Thermal Analysis

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Thermography allows for nonintrusive measurement of temperature and thermal characteristics or thermal patterns of plant equipment. The intent is to detect abnormal temperatures or changes in temperature that may indicate problems in their incipient stages. Serious failures and outages may be avoided when problems can be identified and remedied early. Early detection permits more effective maintenance planning and scheduled outages. Thermography can be used to troubleshoot, perform pre- and postoutage measurements, verify successful installation or repair, and predict problems.

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Disclaimer

Acronyms and Abbreviations

ASNT	American Society of Nondestructive Testing
Btu	British thermal unit
C	Celsius
CARMA	Capital Asset and Resource Management Application
CO_2	carbon dioxide
EPRI	Electric Power Research Institute
F	Fahrenheit
FIST	Facilities Instructions, Standards, and Techniques
FPA	Focal Plane Array
HVAC	Heating, ventilating, and air conditioning
Hz	hertz
IFOV	Instantaneous field of view
IFOVmeas	Instantaneous field of view measurement
IMFOV	Instantaneous measurement field of view
I^2R	current squared multiplied by the resistance of the system
IR	infrared
JHA	job hazard analysis
K	Kelvin
LTC	load tap changers
LWIR	long-wave infrared
MDT	Minimum detectable temperature
mm	millimeter
mph	miles per hour
MRT	minimum resolvable temperature difference (also MRDT)
MWIR	midwave infrared
NETA	InterNational Electrical Testing Association
NFPA	National Fire Protection Association
O&M	operation and maintenance
PdM	predictive maintenance
PEV	pyroelectric vidicon
PM	preventive maintenance
PPE	personal protective equipment
R	Rankine
Reclamation	Bureau of Reclamation
RSHS	*Reclamation Safety and Health Standards*
SI	International System of Units
SWIR	short-wave infrared
TSC	Technical Service Center
UL	Underwriters Laboratories
°	degree

>	greater than
<	less than
µm	micrometers

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1.0 Introduction

1.1 What Thermal Analysis Does

Thermal analysis allows for nonintrusive analysis of temperature and thermal characteristics or thermal patterns of plant equipment and structures. The intent is to describe different methods used to dynamically detect abnormal thermal conditions or changes in temperature that may indicate problems in their incipient stages. Using different technologies will be discussed to detect dynamic changes in heating; however, using thermal imaging cameras is preferred. Identifying and remedying problems early may avoid serious failures and outages. Early detection permits more effective maintenance planning and scheduled outages. Thermal analysis can be used to troubleshoot, perform pre- and postoutage thermal comparisons, verify successful installation or repair, and predict problems with equipment.

1.2 How Reclamation Benefits

The Bureau of Reclamation (Reclamation), as the Nation's second largest hydropower producer and the eighth largest power generating utility (based on installed capacity), has many opportunities to benefit from thermal analysis. Reclamation's power facilities—powerplants and pumping plants—comprise much electrical and mechanical equipment, housed in civil structures such as dams, buildings, and switchyards. Much of this equipment lends itself to thermal inspection. Thermal analysis using thermography has been conducted on a limited basis within Reclamation, and potential failures have been successfully avoided.

A thermal inspection (often called "scanning" or "surveying") takes place with equipment in service and under load; thus, production is not disrupted, and outages are often not needed. This is important in Reclamation facilities, which support public power systems where continuity of service is paramount.

Two examples of imminent failures, located and avoided using thermography, are shown in figures 1 and 2.

Throughout Reclamation, thermal inspections have proven the effectiveness of this technique in solving problems and reducing outages. Each power facility should have a well-planned, defined, and carefully executed thermal maintenance process. Thermal analysis, using infrared (IR) thermography, has proven very successful in improving maintenance effectiveness and reducing maintenance costs in many industries. IR thermography is economically justified by returning approximately $4 in savings to every $1 spent on IR thermography.[1] As the price of thermal analysis equipment decreases, the effective savings will increase. Savings result from:

- Avoiding forced outages, resulting in loss of revenue
- Reducing severe damage caused by equipment failing catastrophically

[1] Maintenance Technology Magazine, June 2001, May 2004, and May 2005.

- Reducing costly, time-based preventive maintenance by predictive analysis of equipment condition

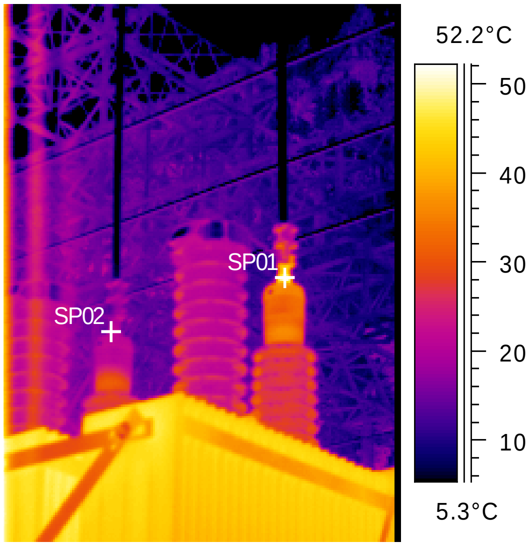

Figure 1. Transformer bushing with incorrect washer that does not allow correct connection. Connection spot 1 (52.4 degrees Celsius [°C]), is greater than (>) 30 °C hotter than spot 2 (22.2 °C) on similar bushing under same load.

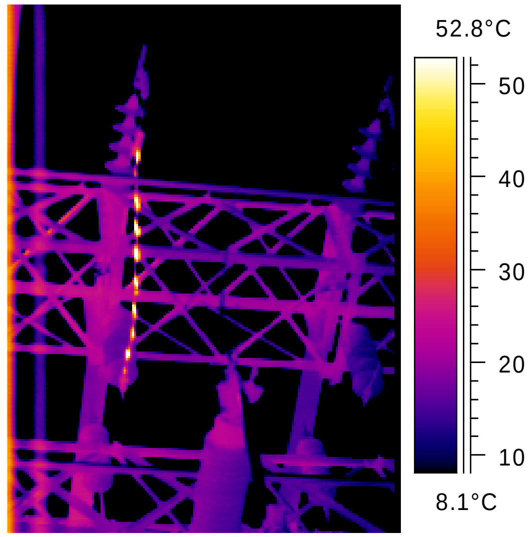

Figure 2. High-side connection from transformer, illustrating a "barber pole" effect where only part of the cable strands carry the current. This qualitative image prompted immediate remedial action.

2.0 Scope

Thermal analysis instruments and processes described in this Facilities Instruction, Standards, and Techniques (FIST) volume apply to all maintenance programs at Reclamation power facilities. All appropriate electrical and mechanical features of the facility should be considered for thermal analysis.

This FIST volume outlines thermal analyses processes and recommends equipment to monitor and monitoring schedules that may be adopted locally. When discussing thermal analysis, several forms of technology can be used. These technologies include:

- Tapes and paints that change color based on operating temperature
- Noncontact IR spot measuring devices, including hand-held radiation thermometers that provide a digital readout of the approximate operating temperature
- Thermal imaging cameras that provide both qualitative and quantitative temperature values

This FIST will guide managers and maintenance staff in thermal analysis technology development and use. Establishing a thermal analysis process using these guidelines and executing thermal inspections and analysis on a regular basis will help ensure that Reclamation's expectations are in accordance with industry standards and that equipment is in sound condition. Although thermal analysis is extremely useful as a standalone maintenance technique in a predictive maintenance (PdM) program, it is not a substitute for other appropriate testing and maintenance techniques, including visual inspections.

This FIST volume is intentionally broad and does not intend to cover all technical aspects of thermal analysis theory or use. While the use of a thermal imaging camera is highly recommended, alternative means of conducting thermal analysis are discussed in a general sense to aid in establishing a more comprehensive program. Many comprehensive sources of technical information, existing in the marketplace, are referenced in this volume.

This volume provides some basic thermal analysis concepts and principles to ground the reader who is developing a thermal analysis process. Sufficient information is provided to help the process developer make reasonable decisions. Technical thermal analysis content in this document focuses on:

- Suggested use of thermography and other technologies used for typical Reclamation power facility equipment and structures
- Experience and lessons learned from ongoing thermal analysis, focusing on thermographic work in Reclamation facilities
- Relationship of thermal analysis maintenance to the Capital Asset and Resource Management Application (CARMA)
- Analysis, recordkeeping, and reporting specific to Reclamation's needs
- Advice on specific thermal analysis issues needed to define a local process

3.0 Standards and Resources

National Fire Protection Association (NFPA) Standard 70B, Recommended Practice for Electrical Equipment Maintenance, lists suggested practices. NFPA 70B, section 11.17.5 states:

> "Routine infrared inspections of energized electrical systems should be performed annually. . . More frequent inspections, for example, quarterly or semiannually, should be performed where warranted by loss experience, installation of new equipment, or changes in environmental, operational, or load conditions."

NFPA 70B also indicates that the inspection should be performed using instruments that use a scanning technique to produce an image of the equipment being inspected; however, this FIST discusses other equipment that can be used to perform thermal analysis of equipment.

NOTE: Other technologies used to perform thermal inspections often will yield less reliable results and only should be used when the use of thermal imaging equipment is not feasible, typically due to safety issues.

Mechanical equipment also should be inspected periodically. These recommended practices are identified in this FIST volume.

Additional features may be desirable or necessary.

See appendix A for a glossary of thermal analysis terms.

3.1 Standards

NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance, National Fire Protection Association*, 2010.

InterNational Electrical Testing Association (NETA), *Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems*.

3.2 Books, Manuals, Reports, and Papers

Common Sense Approach to Thermal Imaging, 2000, Gerald C. Holst, JCD Publishing.

"Common Misconceptions in Infrared Thermography Condition Based Maintenance Applications," 2001, Robert P. Madding, Infrared Training Center, North Billerica, Massachusetts.

Electrical Safety Handbook, 1994, John Cadick, P.E., McGraw-Hill, Inc, 1994.

"Emissivity Measurement and Temperature Correction Accuracy Considerations," 2001, Robert P. Madding, Infrared Training Center, North Billerica, Massachusetts.

"Environmental Influences on IR Thermography Surveys," 2002, Robert P. Madding and Bernard R. Lyon, Jr., Infrared Training Center, North Billerica, Massachusetts.

"Important Measurements That Support IR Surveys in Substations," 2002, Madding et al., InfraMetrics.

Infrared Inspection Application Guide 1000496, Final Report, December 2000, Electric Power Research Institute (EPRI), Palo Alto, California.

"Infrared Nondestructive Testing: Help, Hindrance, or Hype?" December 2002, Richard Becker, Bureau of Reclamation Power Operation and Maintenance (O&M) Workshop, Laughlin, Nevada.

Guideline for Developing and Managing an Infrared Thermographic (IR) Program, Technical Report 1004019, EPRI, Palo Alto, California.

Nondestructive Testing Handbook, Volume 3, "Infrared and Thermal Testing," American Society for Nondestructive Testing (ASNT), 2001.

Practical Applications of Infrared Thermal Sensing and Imaging Equipment, Volume TT34, 1999, Hebert Kaplan, Tutorial Texts in Optical Engineering, SPIE Press.

"The Relationship Between Current Load and Temperature for Quasi-Steady State and Transient Conditions," 2002, Bernard R. Lyon, Jr. et al., Infrared Training Center, North Billerica, Massachusetts.

"Wind Effects on Electrical Hot Spots – Some Experimental IR Data," 2002, Robert P. Madding and Bernard R. Lyon, Jr., Infrared Training Center, North Billerica, Massachusetts.

3.3 Magazines and Web Sites

Academy of Infrared Training, http://www.InfraredTraining.NET

Infrared Training Center, http://www.infraredtraining.com/

IR Cameras, Infrared Imaging Systems, http://www.IRcameras.com

IR Information for the Real World, http://www.irinfo.org

Infraspection Institute, http://www.infraspection.com

Maintenance Technology magazine, http://www.mt-online.com

Reliabilityweb.com Network, http://www.reliabilityweb.com/

4.0 Initiating a Thermal Analysis Process

Each power facility should have a thermal analysis process. The process should be developed, implemented, and documented locally using guidance provided in this volume. Figure 3 provides an overview of a thermal analysis process with references to applicable sections of this document.

4.1 Goals

Thermal analysis should be an integrated part of the overall maintenance program and not considered as a replacement for visual inspection.[2] However, it is recognized that there are cases where thermal imaging cameras alone will not be adequate to perform thermal analysis on the entire system based on the ability to gain access to equipment while the system is operational. In these cases, other technologies will be used to document the temperature rise of the equipment.

An effective thermal analysis process can use equipment including state-of-the-art thermographic imaging equipment, hand-held noncontact thermometers, one-time application products such as heat dots or heat tape, or thermal paint to monitor operating equipment temperature. There should be a process in place to evaluate the collected data, make maintenance decisions based on the analysis, and document the results that could include reporting by exception.

Thermal analysis can be used as a suitable predictive maintenance tool as well as a tool to augment Reclamation's preventive maintenance (PM) practices. When used in Reclamation's PM practices, the following steps should be considered:[3]

- Conduct a qualitative inspection to determine if any problems exist.
- If a problem is found, develop a followup action work order for a more indepth assessment, which may include a quantitative inspection using a thermal imaging camera to determine the magnitude of the problem (i.e., the temperature difference taking into account the wind and circuit loading).
- Apply the appropriate severity criteria to determine what corrective action to take.

4.2 Contracting

When establishing a thermal analysis process, it is important to decide whether to perform thermal analysis inspection using in-house expertise or to contract it out. The analysis should be based on the criticality of the equipment to the facility mission, accessibility of the equipment, the overall benefits associated with maintenance savings from an enhanced PM practice or benefit from a predictive maintenance practice based

[2] NFPA 70B, section 11.17.1.4.

[3] Refer to FIST 6-2 for work order management.

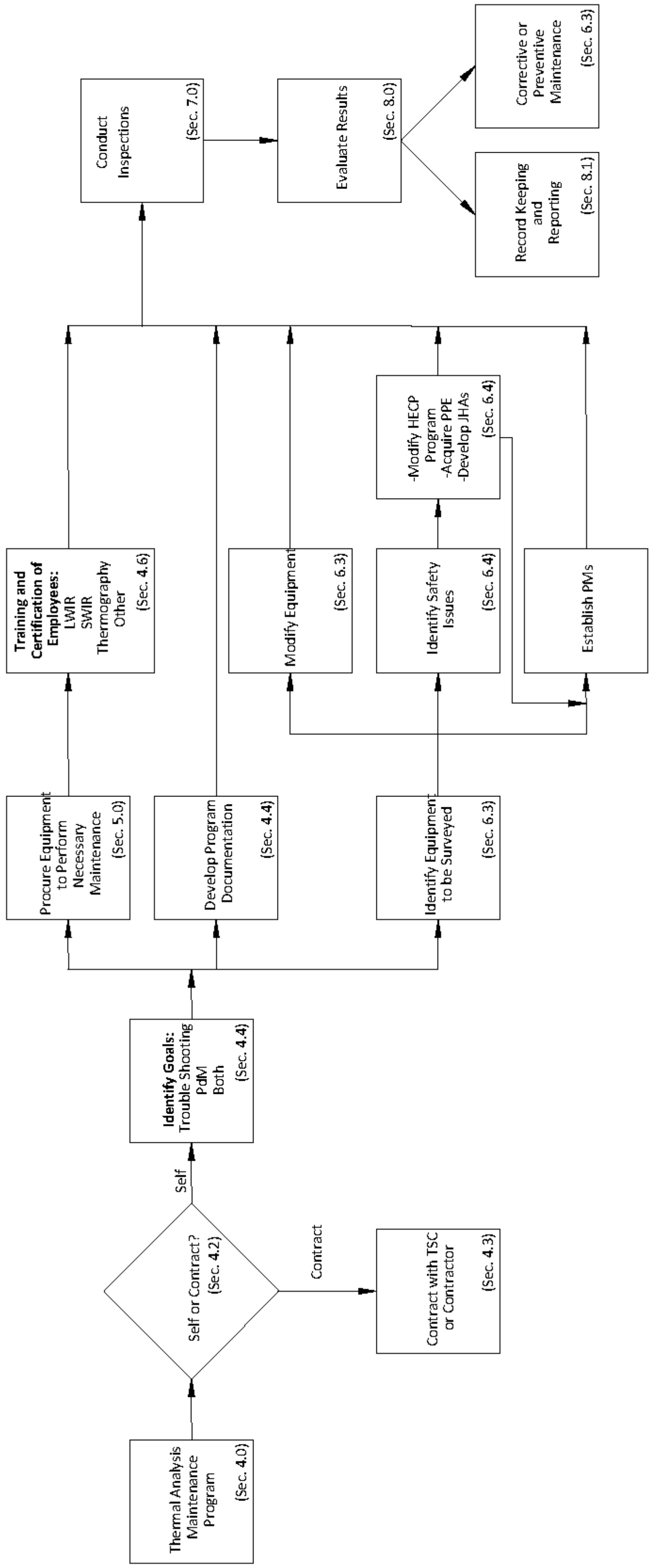

Figure 3. Thermographic maintenance process.

on thermal analysis, and type of analysis to be performed. Contracting the work out only should be considered if a full thermographic analysis (using a thermal imaging camera) is being performed.

The economics and effectiveness of contracting or in-house expertise should be carefully weighed, with emphasis placed on consistent, accurate results.[4] All subsequent thermal analysis activities depend on the decision to contract or use in-house expertise. When it is determined that the thermal analysis program is to be performed in-house, several methods and tools are available to perform the work. If the thermal analysis will rely on quantitative analysis through using state-of-the-art thermographic cameras and software, the systems can be expensive; one should consider renting or borrowing equipment if the in-house option is chosen. A thermographic camera may be borrowed from the Technical Service Center (TSC) Hydropower Technical Services Group.[5]

Contracting might include:

- Qualified private sector contractors
- Power marketing administrations or other utilities
- Other Reclamation offices
- TSC equipment and/or thermographers[6]

In-house and contracting alternatives each have their advantages and disadvantages:

	In-house	**Contracting**
Advantages	• Equipment and expertise always available. • Consistent results. • Familiarity with equipment being inspected.	• Others own and maintain thermographic equipment. • More extensive and recent experience. • May be more cost effective. • No need to maintain in-house expertise for scanning.[7]
Disadvantages	• Costly to procure and maintain thermal analysis equipment. • Equipment may be infrequently used and will become outdated. • Operators will not have as frequent experience as contractors. • Certification or annual training costs.	• Equipment and expertise not as readily available. • Results may not be consistent with different thermographers and thermography equipment. • Contractor may not be familiar with facility and plant equipment.

[4] NFPA 70B, section 11.17.1.3.

[5] Contact the Hydropower Technical Services Group, 86-68440, at 303-445-2300 for more information.

[6] Contact the Hydropower Technical Services Group, 86-68440, at 303-445-2300 for more information.

[7] In-house expertise in interpreting results is still advised.

4.3 Consultation and Resources

Thermographic inspection and analysis is an ever-changing technology with new products and techniques emerging constantly. It is important for thermographers to stay informed and have resources to assist with special circumstances. Consultation with other qualified thermographers is important to an effective thermography process. Some ways to stay abreast include:

- Periodically attending thermography training courses and/or conferences
- Reading related trade journals and visiting Web sites
- Consulting with thermographers at the TSC

4.4 Documentation

The local thermal analysis process should be documented for clarity and continuity. Documentation should define:

- Goals of the local thermal analysis process.
- Responsible employees and their roles.
- Consultation resources.
- Contracting issues, if any.
- Thermal analysis equipment to be used (owned, borrowed, etc.).
- Thermal analysis equipment calibration requirements and records.
- Plant equipment to be inspected (detailed listing recommended).
- Inspection tools and processes (should provide consistency when performing thermal analysis).
    - Devices to be used for the thermal analysis for various locations or equipment to be monitored.
- Analysis guidance.
- Recordkeeping practices (including report generation requirements).
- Training strategies.
- Safety considerations.
    - A job hazard analysis should be performed prior to performing a thermal analysis inspection.

A sample IR report is included in appendix D. When compiling a report, it is important to include as much data as necessary to be able to recreate the IR survey. While the sample report only includes two possible problems, oftentimes, the reports will include thermal images of normally operating equipment. Past images of normally operating equipment may be used to compare with new images to help identify problem areas. These reports should be made available to the thermographer prior to performing a thermal analysis scan to allow them to become familiar with previous test results, equipment, camera settings, and the distance from the equipment to the thermal imaging equipment. Copies of the previous job hazard analysis' (JHA) also should be made available to personnel performing thermal analysis inspections to ensure that all appropriate information is on the present JHA.

4.5 Preventive Maintenance Program

Thermal analysis inspections can be integrated into the local PM program. Once the plant equipment is identified where thermal analysis would be beneficial, a separate PM for the thermal analysis should be created. The job plan for the thermal analysis should identify the devices used in the thermal analysis measurements, the technical application of the devices, and the site specific issues to be aware of (such as location for the camera, heat tape, or noncontact spot measuring device). The thermal analysis PM and job plan will allow some adjustments to the job plan and/or PM frequency of the monitored equipment. Many offices conduct thermal analysis inspections throughout the plant (or on a given generating unit) under one PM. For example, an annual PM is issued to conduct thermal analysis inspection on all equipment throughout the plant and switchyard when all equipment is operational. This usually makes more sense than performing thermal analysis inspections on equipment in a piecemeal fashion for PM purposes. Recordkeeping, as described below, is an important part of the PM program, since a comparison to past inspections is essential. A benchmarking procedure should be developed along with how subsequent inspections will be documented.

Benchmarking should include:

- Equipment to be inspected.
- Loading equipment when inspected. Ideally, the benchmark should be performed when the equipment is carrying full load.
- Location of thermal analysis instrumentation in relation to the target equipment. Sometimes, there is only one place for setting the instrumentation to monitor the equipment. If multiple locations, angles, or distances are thermally analyzed, they should be documented; or the best position for conducting the survey should be identified in the benchmark records.
- Thermal analysis equipment used.
    - There are differences between cameras, long-wave (LWIR) versus mid-wave IR (MWIR),[8] angle of the lens, etc.
    - Make, model, and emissivity value used for hand-held radiation thermometer used to collect data.
    - Manufacturer and expiration date, if applicable, of tapes and paints used to determine temperatures.
    - If paints are used, a copy of the material safety data sheet must be located onsite.

[8] Short wave infrared (SWIR) equipment is now classified as MWIR (mid-wave infrared).

- Type of record kept.
  - Does it include a thermographic image and visible photograph?
  - Is a written description of the component temperature sufficient?
  - Does data include distance from target, noting abnormal conditions at the facility, and recommendations?
- Equipment temperature. Determine if the equipment temperature should be included in a trending program.

Once the benchmarks are completed, ensure these records are available for comparison to all subsequent thermal analysis surveys conducted. Significant temperature variations from the benchmarked temperatures should trigger further investigation. This should include a thermographic survey, if hand-held radiation thermometers are used to collect data.

4.6 Training and Certification

Training on using the thermal inspection equipment depends on its complexity and the desired result. When using a hand-held radiation thermometer, such as an IR temperature gun, the emissivity and distance from the target can greatly skew the accuracy of the resulting measurement. At the same time, many cameras are very basic and need very little training to ensure good, qualitative analysis. This training may be in the form of reading the camera manual and other technical resources, on-the-job training from a skilled operator, or attending classroom training. Using thermal analysis equipment for qualitative analysis by plant staff does not require certification. The complexity of the imaging system must be weighed against the desired result and ease of use. These will have a direct bearing on the use within the plant. The easier the system is to use, the more likely it will be used; however, overly simplified thermal analysis instruments can yield incorrect data if the employee is not properly trained.

When problem areas are discovered during an inspection performed by an individual who has not completed certification, it is important to have a certified operator perform a quantitative review of the problem. This inspection should be performed prior to making decisions on outages and repair strategies. Certification is critical when the results are used for official records pertaining to contract performance, such as performing a core loop test during a rewind. The credibility of the operator is enhanced by certification. When contractors are used, certification of their thermographers should be required.

Basic training in thermal analysis, including functionality and inspection techniques, may be acquired from contractors or by contacting thermographers at the TSC. Training in the science of thermography also is provided by vendors such as:

- Academy of Infrared Thermography, http://www.infraredtraining.net
- American Infrared, http://www.americaninfrared.com
- FLIR Systems, http://www.flirthermography.com
- Infrared Training Center, http://www.infraredtraining.com
- Infraspection Institute, http://www.infraspection.com

- Jersey Infrared Consultants, http://www.jerseyir.com
- Snell Infrared, http://www.snellinfrared.com

For specific temperature measurements and analyses, the thermographer must have knowledge of the material being imaged, the limitations of the thermographic equipment, inspection techniques, and the analysis software, if applicable. For consistency and accuracy, thermography inspections should be performed by personnel who have an understanding of thermographic technology, electrical and mechanical equipment maintenance, and the safety issues involved.[9] If circumstances require certification, the thermographer will be certified at least to an ASNT Level II thermographer, or equivalent. Level II certification is defined as:

> "An individual with Level II certification is qualified to set up and calibrate equipment. He/she can interpret and evaluate results with respect to applicable codes and standards. He/she is thoroughly familiar with the scope and limitations of the method for which he/she is qualified. The Level II individual provides on-the-job training for Level I personnel."[10]

Following the initial certification, the thermographer should be recertified on a 3- to 5-year basis.[11]

[9] NFPA 70B, section 11.17.1.1.

[10] American Society of Nondestructive Testing, Columbus, Ohio.

[11] ASNT, SNT-TC-1A recommended recertification intervals are 3 years for Level I and Level II and 5 years for Level III. Certifications from vendors, such as the Infrared Training Center, have recertification set at 5 years.

5.0 Selection and Maintenance of Hardware and Software

The choice of thermal analysis instrumentation and software depends on local goals. For most facilities, measuring relative temperatures using qualitative or comparison of thermograms is sufficient for annual inspection purposes. This will highlight most anomalies—loose connections, hot phases, etc.—to the degree necessary to initiate further investigation and correction. Hardware capable of this level of inspection is less expensive and easier to use than hardware for quantitative inspection. For most IR thermographic equipment or systems, periodic calibration of the imager or radiometer is needed to ensure valid results. The calibration requirements should be considered when purchasing thermography equipment. It may be possible to obtain an extended warranty and calibration plan at a reduced cost when purchasing thermal imaging cameras.

In some cases, it may be necessary to accurately measure temperatures to truly diagnose a problem without incurring a maintenance outage. For example, an electrical connection may appear hot, but the question is: Is the connection deteriorating, is it hotter than allowable, or will it fail? This level of analysis requires more expensive and complicated equipment as well as more knowledge and skill on the part of the thermographer.

Proper selection of the equipment is needed for the diagnostics. Often, the terms “thermal imager” and “IR camera” are used interchangeably without distinguishing whether the equipment can calculate temperatures quantitatively; and these terms also include the term “radiometer.” IR thermographic cameras, called “thermal imagers,” are capable of showing temperature gradients of the target and, therefore, identify hot spots but do not have the capability of calculating temperature quantitatively. “Radiometers” calculate quantitative temperatures. Hand-held radiation thermometers display temperature values but do not display a thermal image of the equipment being surveyed. Thermal imaging cameras display a two-dimensional image, where as hand-held radiation thermometers only display point temperatures. Since the hand-held radiation thermometers are only point measurement devices, it is critical to understand how the distance from the target can affect the measurement. When determining if a hand-held radiation thermometer will be adequate to perform thermal analysis on a given piece of equipment, the user must determine the distance between the instrument and the target. The greater the distance between instrument and the target, the measurement area becomes larger, thus increasing the error in the measurements. Refer to section 7.3.1 and figure 8 (shown later within this document) for additional information on spot size.

NOTE: Realize that the temperature values provided by hand-held radiation thermometers devices are approximate and are typically the average of a large area.

Hand-held radiation thermometers also do not allow the user to adjust for reflected or transmitted radiation, increasing the likelihood of obtaining incorrect data.

It is important to understand that noncontact thermal analysis equipment measures IR radiation emitted from an object under test as well as the reflected radiation from other objects in proximity with the object under test. IR radiation is electromagnetic radiation with properties similar to visible light. The speed of IR radiation is equal to visible light. The major difference between IR and visible light is the wavelength, λ, measured in micrometers (µm). Figure 4 shows the relationship of the visible light spectrum to the IR spectrum.

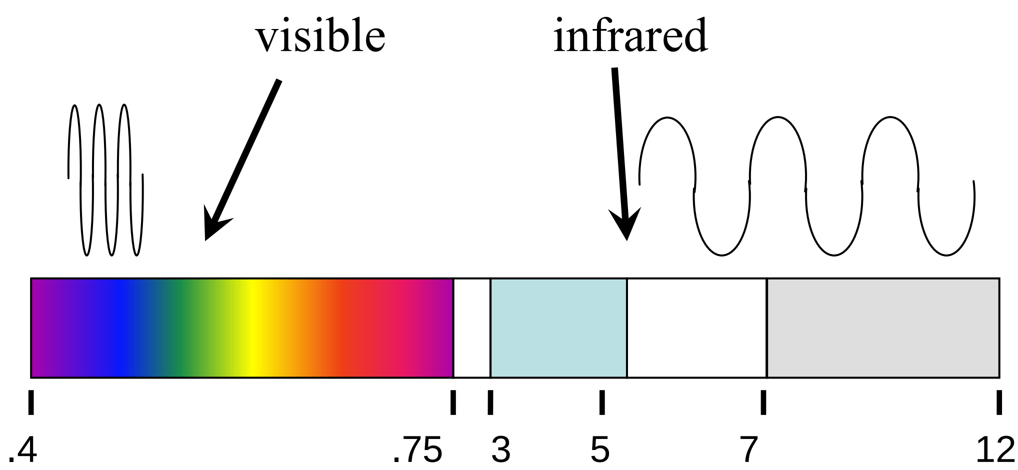

Figure 4. Visible and IR spectrum.

IR cameras of the MWIR type with a wavelength range of 3.0–5.5 µm and of the LWIR type with wavelength range of 7.0 –15.0 µm are acceptable for Reclamation work. The LWIR type camera is preferred because the MWIR type camera typically uses an intercooler that takes several minutes to cool the detector before the camera can be used to acquire images or perform scanning. Also, LWIR is not affected by sun glints (momentary flashes), although it is affected by continuous solar reflections. The LWIR equipment is better suited for outdoor IR work, such as in substations and switchyards.

When procuring an IR camera system, many factors should be considered. Appendix B provides a list of objective and subjective considerations and a comparison tool.

The *price* of IR thermal analysis systems can be quite high, especially thermal imaging equipment; however, the *cost* of misdiagnosing problems also should be considered. When choosing a system, considerations should include the value of being able to accurately determine a quantitative temperature, thus reducing investigation and repair time, and the financial impact of a forced outage should a faulty component fail to be recognized. A "pricier" system may be the most cost effective in the long run. Regardless of the type of camera selected, the system used is no better than the training provided to the operator or thermographer. Do not skimp on training.

Many thermal imaging cameras offer similar specifications that meet the needs of a thermal analysis program. It is recommended to use the equipment to perform a thermal imaging survey of your facility to determine if the hardware is ergonomically designed and easy to use before you purchase the equipment. Typically, a manufacturer will send out a representative or the hardware for your demonstration prior to purchase.

Once the survey is complete, have the vender demonstrate the software package that is used to create reports and manipulate images. Once the demonstration is over, ask to use the software package to determine if the software is intuitive and easy to use. Ensure that the options within the software perform as expected and that the program operates without errors on the operating system you plan to use. Open images and attempt to make changes to the image, changing parameters such as emissivity, palette colors, and other options that are available. If additional data is stored with the image, such as audio or text notes, ensure that this information is easy to access.

6.0 IR Thermography Concepts and Principles[12]

6.1 General[13]

IR energy is part of the electromagnetic spectrum and behaves similarly to visible light. IR can be reflected, refracted, absorbed, and emitted. All objects emit IR radiation as a function of their temperature. The warmer an object, the more IR radiation (light) is emitted. An object at absolute zero (-273.16 °C) emits almost no IR radiation. Since IR radiation is invisible to the human eye, the technology used in thermography measures IR radiation and produces a visible image of IR light emitted by objects because of their temperature. The image, called a thermogram, is developed by using false color images that, in turn, make interpretation of the thermal patterns easier.

6.2 Thermograms

Thermograms are thermal maps of surfaces where color hues represent the distribution of thermal energy. The image captured represents the total IR energy coming from the object or target, consisting of emitted, reflected, and transmitted IR energy, and modulated by the intervening atmosphere.

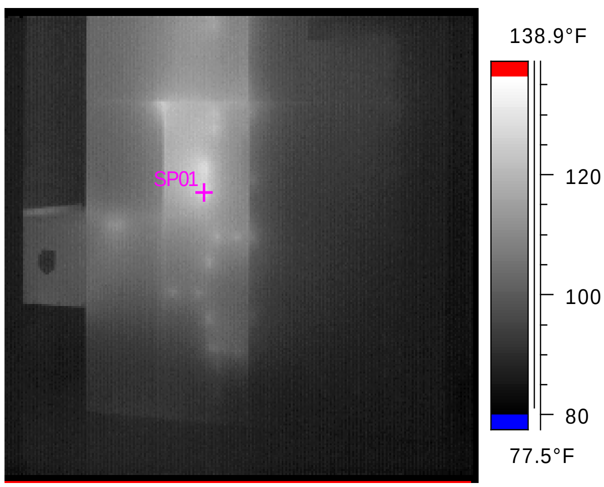

Figure 5. Qualitative IR image of a main circuit breaker enclosure illustrating indirect imaging. The copper bus within the enclosure is extremely hot. The temperature recorded at SP01 is 128 degrees Fahrenheit (°F). The actual bus temperature would be in the magnitude of three or more times this temperature. Repairs were extensive, including re-insulation of the bus.

The thermogram's purpose is to identify the temperature difference, or delta, of the target compared to a reference temperature. The reference temperature might be ambient temperature, temperature of similarly loaded equipment or phases, or the baseline temperature measured under normal conditions.

It should be remembered that temperature recorded by the camera is not necessarily the actual temperature of the component being measured. Often, the camera is seeing the indirect or transmitted temperature on the surface of a panel or enclosure (figure 5) rather than the heat-generating component enclosed within.

Thermograms may be "qualitative" in that they represent the thermal energy without correction for variables—thus, giving an approximate surface temperature. Qualitative

[12] IR Thermography — Level I Curriculum, EPRI.

[13] Adapted from Guideline for Developing and Managing an Infrared Thermography Program, EPRI (1004019).

thermograms are highly beneficial and can provide a wealth of information, even without knowing the actual temperature values. Thermograms also may be “quantitative” in that they correct for all variables, providing a nearly true surface temperature using numerical values in addition to thermal imaging. In short, a qualitative inspection does not produce numerical data; however, these inspections can yield highly valuable information.

Qualitative thermograms take less time and, in most cases, require simpler equipment. Qualitative thermograms may provide sufficient information for comparison purposes (e.g., comparing phases) and often can find the root cause of a problem.

Interpretation is somewhat subjective and may not provide sufficient detail to really understand a complex problem; however, the purpose of qualitative analysis is to alert employees of a problem that will require further investigation.

For many PM purposes, qualitative thermograms are sufficient, since comparison to similar equipment is all that is needed to detect an anomaly. Equipment and training for qualitative inspections will be reasonably priced and can provide valuable information pertaining to the condition of the equipment being surveyed.

Quantitative thermograms provide more accurate temperature data and are needed for identifying trends or determining the severity of the problem. However, they require more sophisticated equipment, increased thermographer training and experience, take more time, and may confuse the thermographer with too much information. A hand-held radiation thermometer is not to be used to obtain high-accuracy quantitative temperature measurements because they cannot account for the necessary parameters to adjust for background radiation and other variables necessary to determine an accurate temperature value.

Depending on the equipment used, the actual temperature of the component may be two, three, or even more times higher than the temperature being recorded by the noncontact IR measuring equipment.[14] This depends on the physical construction and material of the object being surveyed.

Apparent temperatures seen in the thermogram include all temperatures—both the direct temperature of the target and temperatures from ambient air and reflected radiation. To obtain accurate temperature values, it is recommended that the thermographer obtain Level II thermography training. Level II training provides the information and guidance needed to correctly use the thermal imaging device, accounting for all variables, to obtain accurate temperature measurements.

[14] Electrical Applications, InfraMation 2004 IR Clinic, Las Vegas, Nevada.

The following strategy is recommended for thermograms at Reclamation facilities:

Activity	Strategy
Annual PM IR inspections	Use qualitative thermal analysis to compare to similar equipment, to compare phases of three-phase systems, and to detect simple anomalies.
Troubleshooting suspected or known problems	Use qualitative thermal analysis to identify a problem or quantitative thermograms to determine the severity of the problem.
Evaluate repair work and proof test new installations	Use qualitative thermal analysis to determine if a problem exists and quantitative thermograms to define the problem
Evaluate condition for condition-based maintenance program	

6.2.1 Targets and Target Signatures

A target is an object that is to be detected, located, recognized, or identified. Target signatures are the spatial (size), spectral (wave band), and intensity (temperature) features that distinguish the target from the background.[15] Thermographic systems exploit the intensity differences, and the signatures are the characteristic patterns that the thermographer must learn to identify. Signatures are created by the apparent differential between the target and its background. The radiation that appears to emanate from the target depends upon its emissivity.

6.2.2 Detecting Thermal Anomalies [16]

Thermal analysis does not measure temperature directly. Instead, it measures the radiation that appears to emanate from the target. This measured radiation includes the target's self-emission, path radiance, transmitted radiation, and reflections. Reflectivity and emissivity both depend on the surface quality and surface shape (geometric properties).

Detecting the difference between normal and abnormal temperatures may be accomplished by either comparison to an object of known emissivity and operating characteristics or by symmetry when using a thermal imaging camera.

Comparison of the temperature or thermal pattern of one object to a similar object that is known to be operating properly is one way of detecting irregularities. The similar object must be subjected to the same conditions as the target object—for example, same manufacturer, same load, same emissivity, and same environmental conditions.

[15] Common Sense Approach to Thermal Imaging, Holst, chapter 11.

[16] Common Sense Approach to Thermal Imaging, Holst, chapter 11.

Symmetry or asymmetry patterns are another way of detecting irregularities. Many objects operating under normal conditions will exhibit a symmetrical pattern. An asymmetrical pattern indicates a problem. For example, unequal heating of phases of a three-phase circuit demonstrates possible problems with the system and load unbalance.

6.2.3 Radiation

Thermal analysis equipment detects radiated heat energy of the types shown in figure 6:

- Emitted
- Reflected
- Transmitted

Each of these radiated energy types plays a role in thermal analysis and should be understood. The IR equipment receives all three types of energy, but not all indicate the true temperature of the target. These energy types generate three of the four apparent sources of temperature difference (emittance, reflectivity, geometric, and transmittance differences). Geometric difference refers to the variations in shape of the target, the surface texture of the target, and if there are natural cavities created due to the shape of the target. All four temperature differences must be recognized and factored into the inspection so that accurate measurement and comparison of emitted radiation is determined.

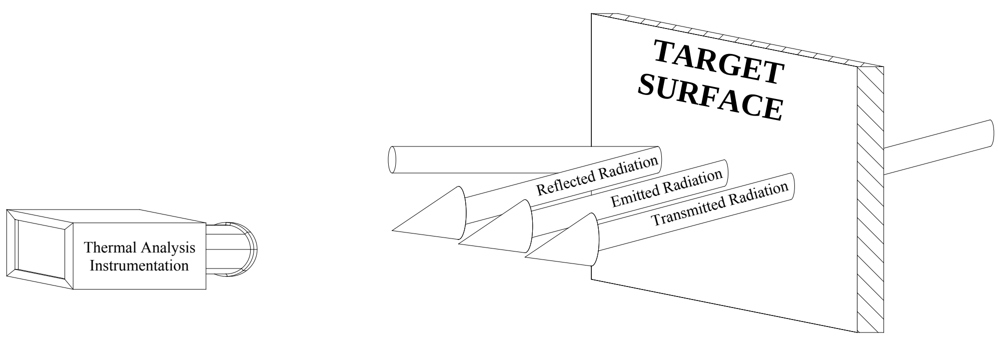

Figure 6. Radiation sources.

6.2.4 Path Radiance and Atmospheric Transmittance

Path radiance refers to radiant energy that emanates from the medium (air) that the target energy passes through to get to the IR measuring device. This generally can be considered small where the distance to the target is short and the atmosphere is transparent to the wavelength of the IR measuring device.

The atmosphere is composed of many different gasses, particles, etc., which can absorb, reflect, or otherwise redirect the radiation from the target to the measuring equipment, imager, or radiometer. The resulting reduction in the target radiation reaching the IR measuring device is attributed to atmospheric transmittance.

If viewing a target from a long distance, the atmospheric transmittance must be included in the target temperature calculation.[17] However, for most IR inspections performed in the relatively close distances of powerplants and switchyards, atmospheric conditions (weather) can be ignored unless the weather is really bad— in which case, the inspection should be postponed.

6.2.5 Atmospheric Absorption

Atmospheric absorption of IR energy is possible over long distances and typically is caused by attenuation of the infrared signal. The greater the distance between the thermal imaging instrumentation from the target surface, the more likely the signal can be attenuated. The level of attenuation or atmospheric absorption is dependent on weather conditions. Increased humidity, snow, rain, dust, and other airborne contaminates can increase the attenuation. It is important to record atmospheric conditions when performing thermal analysis outdoors; typically, indoor measurements or relatively short-distance inspections in switchyards are not affected.

6.2.6 Blackbody

A blackbody is an ideal body that completely absorbs all radiant energy striking it and, therefore, appears perfectly "black" at all wavelengths. The radiation "emitted" by a blackbody is "blackbody radiation." A perfect blackbody has an emissivity of unity (i.e., 1.0) and a reflectivity of zero at all wavelengths. Blackbodies are used to calibrate IR measurement devices.

6.2.7 Emissivity

Emissivity is a property of a material that describes its ability to radiate energy compared to a blackbody at the same temperature. High emissivity indicates an increased efficiency of the object to act as a heat radiator. See appendix E for methods to determine or enhance emissivity of a target and appendix F for a table of material emissivity. Most experienced thermographers will not rely on emissivity tables when conducting quantitative temperature measurements; instead, the thermographer will perform various checks to determine the emissivity for each target. The tables are approximate and can lead to errors if not used correctly.

Emissivity values range from zero to one and are affected by surface characteristics such as age, paint, dust, dirt, dew, frost, chips, scratches, and weathering effects. Generally, smooth surfaces produce low emissivity while rough surfaces produce high emissivity. For accurate IR readings, ideally, the emissivity of the target should be as high as possible so that most of the energy measured is emitted from the target itself rather than being reflected.

Emissivity also is affected by viewing angle and temperature. Care should be taken to point the IR measuring device as close to perpendicular to the target surface as possible. When taking temperature measurements of objects with low emissivity, it is important to ensure that the recorded temperature is the temperature of the object and is not affected by the reflection of the thermographer or other equipment in the area.

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[17] Common Sense Approach to Thermal Imaging, Holst, chapter 12.

The emissivity of the target and surrounding environment are impossible to know exactly and can be time consuming and difficult to determine. Therefore, it is very difficult to determine accurate temperatures, and inspections tend to be mostly qualitative.[18] If quantitative values are required, the thermographer should determine the emissivity of the target object experimentally by comparing an object of known emissivity to the target object and adjusting the emissivity accordingly.

6.2.8 Reflectivity

Reflectivity is a property of a material that describes its ability to reflect energy from a source other than the target but on the same side of the target as the IR measuring device (see figure 6). Reflected energy usually is added to the radiated energy from the target. Therefore, reflected energy will be detected by the IR measuring device, and the temperature displayed by the device will not indicate the true temperature of the target. Reflectivity typically is a problem when attempting to perform IR thermal analysis on objects with a smooth surface and a low emissivity. Materials that have a low emissivity are reflective to IR radiation.

6.2.9 Transmissivity

Transmissivity is a property of a material that describes its ability to transmit energy from a source other than the target but on the opposite side of the target from the IR measuring device (see figure 6). Transmitted energy will be detected by the IR measuring device. Transmitted energy results in a false or inaccurate target temperature. This is important where targets are transparent to IR energy but is rarely a problem in powerplant applications. Opaque objects do not transmit IR energy. It must be pointed out that, although glass and many plastics are transmissive to visible light, they are opaque to IR and will appear black in an IR camera viewfinder.

Transmissivity characteristics are important when discussing IR windows in electrical cabinets or housings. IR windows will act as filters and attenuate the IR energy.

The thermographer must be aware of the effects of these apparent differences and make provisions to eliminate their effects to arrive at true temperatures. Techniques for accomplishing this include:

Apparent Difference	Remedial Action
Emittance difference	Use testing techniques to determine the emissivity for each target or change the emittance with paint, tape, or other coating with a known emissivity value.
Reflective difference	Avoid highly reflective scenes. In many cases, moving around the target, while trying to maintain a nearly perpendicular angle with the target, can reduce or eliminate the reflections radiated from the target.

[18] Common Sense Approach to Thermal Imaging, Holst, chapter 12.

Apparent Difference	Remedial Action
Transmittal difference	Compensate for the transmittance of thermal radiation when using IR windows. Many good windows used for viewing the internals of electrical cabinets or equipment(i.e., motor controllers) have a transmittance of only 0.5. This will reduce the overall temperature of the target and, therefore, must be accounted for in the camera software settings.
Geometric difference	Make every effort to view the target perpendicularly. Additionally, geometric shapes can contribute to reflections. Finding cavities or plane intersection to focus on will provide better temperature measurements results.

6.3 Plant Equipment Selection and Modification

Electrical and mechanical equipment radiate thermal energy as a byproduct of normal operation. IR inspections are very useful in identifying abnormal temperatures that indicate potential problems. Inspections also can find problems in structural systems.

6.3.1 Electrical Equipment

Electrical equipment generates heat through the current squared multiplied by the resistance of the system (I^2R) heating effects of electrical losses.[19] Some heating is normal, but excessive heating may indicate a problem. *Quantitative* temperature measurements may help identify where temperature ratings are being exceeded, and *qualitative* temperature measurements will indicate where individual components or phases of similar devices in electrical circuits may be heating abnormally. All observations should be documented and trended over the life of the equipment.

For PM purposes, it is recommended that a thermal analysis survey be performed annually. More frequent inspections should be performed where warranted by loss experience, installation of new equipment, or changes in environmental, operational, or load conditions. When developing the test procedures for each facility, the following electrical equipment should be surveyed:

- Arresters
- Batteries and connections and battery chargers
- Buswork, ducts, enclosures, insulators
- Bushings
- Cables, potheads, and stress cones

[19] Note that temperature is not proportional to I^2R; the relationship between current and temperature is more complex.

- Circuit breakers
- Coupling capacitors
- Current transformers
- Distribution panels
- Electrical connections
- Exciters and voltage regulators
- Fuses
- Generator components, as needed
- Lighting
- Motors and lead boxes
- Potential transformers
- Switches (disconnect)
- Switchgear
- Power transformers
- Transmission lines

It is recognized that some of the equipment listed above may not be accessible while the equipment is energized to perform an IR thermal analysis survey. In these cases, other technology, including labels and paints that change color based on operating temperature, should be used to monitor operating temperatures. The paint or label should be applied while the equipment is under clearance and then periodically monitored, typically during annual maintenance, from a safe distance. When using labels or paints, it is critical that those individuals tracking the temperatures of this equipment understand what the maximum temperature is or how the paint or label appears when the maximum temperature is reached. If paints or labels are used to document the operating temperatures of the equipment, it is essential that the paints or tapes be irreversible. Irreversible temperature recording labels and paints are available from numerous manufacturers and can be found easily online.

6.3.1.1 Conditions Detected[20]

If abnormal conditions are discovered, these conditions should be noted and further investigated. Some examples of abnormal conditions that typically are found are listed in the following tabulation.

Component	Conditions Detected
Bus duct surfaces	Unbalanced loads and high resistance in joints, bus plug-ins, and connections
Batteries, chargers, emergency power system	Poor connections, defective contacts, or standby (transfer) switches

[20] Adapted from Academy of Infrared Thermography.

Component	Conditions Detected
Motors/generators	Unbalanced loads, shorted or open windings, blocked cooling passages, and overheating of brushes, slip rings, and commutators
Switches, load centers, motor control centers, power factor capacitors, bus bar connections, fuses, circuit breakers	Loose or corroded connections, poor contacts, unbalanced loads, or overloading
Power transformers (critical to the operation of the facility)	Loose/deteriorated connections, bushings, blocked/restricted cooling fins or tubes, low fluid level, and bad pothead connections
Transmission lines, lightning arrestors, circuit breakers, conductors, splices, disconnects, compression clamps, cables, potheads, stress cones	Loose/corroded/improper connections and splices, inoperative capacitors, failed lightning arrestors, overloading, and broken conductor strands

6.3.1.2 Equipment Modifications

Current-carrying components of electrical equipment generally are shielded from direct view by panels that protect personnel from risks of the energized components. This indirect viewing of the actual current-carrying components makes it difficult to conduct a meaningful IR inspection. Although removing the panels is possible, this raises safety concerns and may upset the thermal equilibrium, resulting in a measurement that may not accurately represent normal operating conditions. Other means of thermal analysis may be more appropriate in these conditions, such as using heat tape or heat paint.[21]

A better alternative is to install viewing ports or IR windows[22] so that IR inspections and visual inspections can take place without removing the panels. Ports can be installed in existing equipment, and consideration should be given to specifying new equipment with such ports. Glass covers and some plastics are not transparent to IR radiation.[23] Thus, only ports and windows that are Underwriters Laboratories (UL) Listed, UL Certified, and that meet the Institute of Electrical and Electronics Engineers specifications for viewing panes should be used.

6.3.2 Mechanical Equipment

Mechanical equipment generates heat, generally through friction. In addition, mechanical systems such as heat exchangers, piping, and ventilation may be transferring heat from other sources. Friction losses are costly, and reducing them will improve efficiency. Mechanical systems such as coolers are good subjects for inspection since hot spots may indicate heat transfer problems, blocked cooling passages, nonfunctional pumps, and even inadvertently closed valves. Carbon dioxide (CO_2) and oil storage tank levels can be assessed by IR inspections. Heat radiation in mechanical systems is normal,

[21] Common Sense Approach to Thermal Imaging, Holst, chapter 11.

[22] Ports are openings with covers, and windows are openings with lens materials transparent to IR energy.

[23] NFPA 70B, section 11.17.5.3.

but excessive heating may be an indication of a problem. For PM purposes, mechanical equipment that should be inspected annually includes:

- Air compressors
- Bearings and seals
- Brakes
- CO_2 systems
- Cooling system heat exchangers
- Engines, gasoline and diesel
- Gear boxes
- Heat exchangers
- Motor bearing housings
- Piping
- Pivot pins, hinges, and linkages
- Pumps
- Servomotors
- Valves
- Vessels and tanks

6.3.2.1 Conditions Detected[24]

Component	Conditions Detected
Drives and pillow blocks	Overloaded bearings or rollers and misalignment of shafts or pulleys
Heavy-duty equipment: tires, bearings, brakes, pulleys, gears	Overheating brakes, tires, bearings, pulleys, gears, gear or pulley misalignment, and transmission/gearbox overheating
Hydraulics	Defective seals, overheating lines, and unequal flow
Heating, ventilating, and air conditioning (HVAC) systems	Air leaks, energy loss, clogged condenser/heat exchanger tubes, and refrigerator and air conditioner efficiency
Internal combustion engines	Valve or injector malfunction, blocked radiator tubes, and oil coolers
Mechanical drive turbines and small turbine generator units	High lube oil temperature, high bearing temperatures, drain valve blockage, steam trap blockage, faulty stop/control valve operation, and leaking shaft seals

[24] Academy of Infrared Thermography, with modifications.

Component	Conditions Detected
Pumps, compressors, fans, and blowers	Overheated bearings, high compressor discharge temperature, high oil temperature, broken or effective valves or rings, and misalignment of drive belts and gears
Vessels and tanks	Liquid or gas levels

6.3.2.2 Modifications

Most mechanical equipment has safety shrouds or enclosures, which can limit the view of moving parts. Solid shrouds and covers must be removed to conduct an inspection. This poses a safety problem and may disrupt the thermal equilibrium, giving a measurement that may not accurately represent normal operating conditions. Inspection ports similar to those described for electrical equipment can be installed to allow the use of thermal imaging tools, or using heat sensitive tapes and paints on nonexposed surfaces also will allow monitoring of equipment temperatures.

6.4 Safety

As with any O&M activity, personnel safety is of utmost importance when conducting thermal analysis surveys. Since inspections are performed while the equipment is in operation and under load, risk always exists in the form of electrical and mechanical energy, as well as physical hazards, when attempting the inspection.

Thermal inspections are intended to be a noncontact routine analysis of easily accessible equipment or components. It is not intended that panels exposing the thermographer to hazardous energy would be opened. When analysis of equipment behind protective panels is needed, other thermal analysis techniques should be employed such as heat tape or heat paint. While thermal tapes and paints may not yield precise temperature values, the results of analysis still can provide valuable information and indicate if additional maintenance should be performed.

If the inspection does include exposing the thermographer to hazardous energy sources, it must be conducted in accordance with FIST Volume 1-1, Hazardous Energy Control Program, including the Facility Supplement, Reclamation Safety and Health Standards (RSHS), and arc-flash protection procedures (NFPA 70E).

Safety concerns include:

- Exposure to arc flash hazards since performing inspections may include times when protective barriers on electrical equipment are removed. Thermographers must comply with facility-specific and Reclamation arc flash protection processes, including wearing all appropriate personal protective equipment (PPE). Assessing the exposure risk requires an arc flash energy study, and the JHA must clearly state the need for arc flash protection. To enhance safety, the thermographer should adopt a **Freeze and Leave** practice of capturing the image and immediately leaving the area. This will reduce the amount of time the thermographer is exposed to hazardous energy. When possible, telephoto lenses should be used to maximize the distance between the employee and possible hazards.

- Exposure to electric shock hazard in the vicinity of exposed energized electrical equipment. Care must be taken to observe minimum approach distances as defined in RSHS, table 12-1 (NFPA 70E, table 130.2(C)). Again, a **Freeze and Leave** practice is recommended to enhance safety.

- Heavy and cumbersome cameras and accessories pose risk, and precautions should be used to ensure safety. Care must be exercised when climbing with thermographic equipment or maneuvering through tight spaces.

- The thermographer's attention is very focused on the camera, the image, and target being inspected, and this may make them oblivious to risks around them. The thermographer must be protected from a variety of hazards involving loss of footing, head and body obstructions, energized parts, and mechanical energy. It is recommended that the thermographer be accompanied by an assistant who helps protect the thermographer from these hazards and that the thermographer adopt a **Stop and Look** practice and not be in motion when making a measurement.

7.0 Conducting Inspections

The following items are advice and guidance, the "do's and don'ts"of thermographic inspections that will yield better results.

7.1 Basics

Thermographers should do several things before conducting inspections.[25]

- Read the instruction manuals and understand all the features of the device.
- Make certain the batteries are charged.
- Confirm the device calibration is current.
- Learn the default values for device settings.
- Learn the specifics for the thermal analysis equipment used.
- Learn the device's functions:
    - Estimates of distance and emittance of targets and magnitude of background sources.
    - Pointing, aiming, and ambient reflections.
    - Device calibration.
    - Field of view settings.
    - Gain and level settings.
    - Spatial resolution of the device/camera (spot size ratio).
- Practice taking pictures with the camera to ensure that pictures taken are in focus.
    - If a picture is not in focus, no useful information can be obtained from the image.
- Become familiar with the software package used in conjunction with the IR measuring devices.
    - Some software packages will allow the user to adjust range, span, and emissivity of images from the software.
    - While several variables may be changed in the software, the thermographer should rely on the hardware to take good measurements and not rely on the software to fix shortcomings in thermal images.

[25] IR Thermography – Level I Curriculum, EPRI.

7.2 Equipment Selection

Before a thermal inspection can be completed, the way in which the temperatures will be collected needs to be examined. Thermal analysis at the facility can be performed using a thermal imaging camera, a hand-held radiation thermometer, heat sensitive stickers and paints, or any combination of the above.

Of the listed technologies, the thermal imaging camera provides the best information and greatest accuracy. Using thermal imaging, one image contains information of thousands of points allowing the thermographer to better monitor equipment. Inexpensive cameras have a thermal sensitivity of less than 0.2 °C with an accuracy of 2 °C providing quality information that is easy to trend. Typically, as the price of the camera increases, so does the quality of the image and accuracy of the readings; but in most maintenance applications, inexpensive cameras are adequate for capturing data. When a thermal imaging camera is not available, a hand-held radiation thermometer can be used.

Hand-held radiation thermometers provide an average temperature of an object using infrared technology. This equipment is very inexpensive to purchase, but with these devices the user has no way to determine the exact location or location size of the measurement area. Most hand-held radiation thermometers do not allow the user to adjust emissivity, introducing additional errors into the measurements. Great care should be taken anytime a hand-held radiation thermometer is used.

In instances when the thermographer would be exposed to arc flash or other dangerous conditions while conducting inspections, IR viewing panes, inspection grills, or inspection ports can be installed on exiting equipment. Typically, IR viewing panes are used in electrical applications to create a sealed barrier between the thermographer and a potential arc flash hazard. When thermal analysis on mechanical equipment is to be performed, without removing shields or barriers that would typically block the view of the thermographer, inspection grills can be used to allow safe visual access to the equipment.

The IR windows allow a portion of the thermal radiation to be transmitted to the camera, but it is important to compensate for the attenuation of the image through the viewing panes. The view pane characteristics need to be investigated to determine the amount of attenuation of the infrared signal if performing quantitative measurements. This will include examining a known target without the IR viewing pane in place and then comparing the measurement of the target when viewing through the viewing pane. After the test has been performed, the transmissivity can be calculated and programmed into the camera.

Thermography should be used whenever possible, however there are instances where it is not possible to use the thermal imaging camera typically due to the safety of the employee. For example, there may not be a location that an IR viewing pane can be installed to allow employees to safely monitor the temperature of electrical equipment while it is operating. In this case, the use of non-reversible temperature labels can provide information regarding the operating temperature of the equipment. The labels can be configured and purchased in several form factors providing 1–10 different temperature readings. The labels are typically accurate to within 3 °F over a temperature range of between 105–500 °F.

The labels should be stored in a cool, dry area until they are installed. The labels use an adhesive backing to stick to equipment. If the indicated temperature is reached, the indicator will turn black. Employees can monitor the labels during routine inspections to determine operating temperature of the equipment. Labels should be ordered based on the maximum allowable operating temperature of the equipment. If a label has changed color, the label should be replaced at the time of visual inspection, and additional maintenance will need to be performed on the equipment based on the operating temperature. For example, an unmanned IR camera can be set up to monitor the actual operating temperature of the equipment if necessary. The old label can be placed in a maintenance log book as a record of the operating temperature. Labels that have not changed color should be replaced at least every 5 years to ensure that they are in proper working order.

7.2.1 Camera Settings

The thermographer should ensure that the following settings on the camera are correct before and/or during inspection:

- Date and time
- Atmospheric temperature (ambient air temperature)
- Relative humidity (use portable hydrometer or use plant's hydrometer)
- Distance to target
- Emissivity of target
- Temperature of objects that are reflecting radiation off the target (background temperature)
- Desired temperature range (from camera optional ranges)
- Normal or telephoto lens (e.g., 12- or 24-inch)
- Focus

Although the distance measurement may not be critical for qualitative inspections, a value will need to be assigned in most cameras. The distance to the target should be measured or approximated, and the value programmed into the camera. Using a valid approximation for distance will allow the data to be trended over the life of the equipment. If quantitative measurements are warranted, then a more accurate value for distance will need to be measured. The distance to the object is important because the camera will use this value to approximate the attenuation of the IR signal based on environmental conditions.

Camera settings are important to get an accurate inspection because some things cannot be manipulated in the thermogram after the fact. Typically, focus, temperature range, and distance to target cannot be manipulated in the software.

Emissivity, relative humidity, ambient temperature, and reflected temperature may be manipulated after the fact, depending on the thermographic equipment and software. The thermographer should set the values in the camera prior to performing an IR survey. This will allow the thermographer to spot problems quickly and to make recommendations immediately following the survey. Depending on the software package used to analyze data and create reports, the above parameters within the thermograms can be modified to improve the quality of the image. Modifying these parameters allows the user to create similar images that can be trended over time or compared to similar equipment. Refer to the software instruction manual for additional information for your specific software package and version.

7.3 Image Quality

Image quality is affected by many factors, as shown in figure 7.

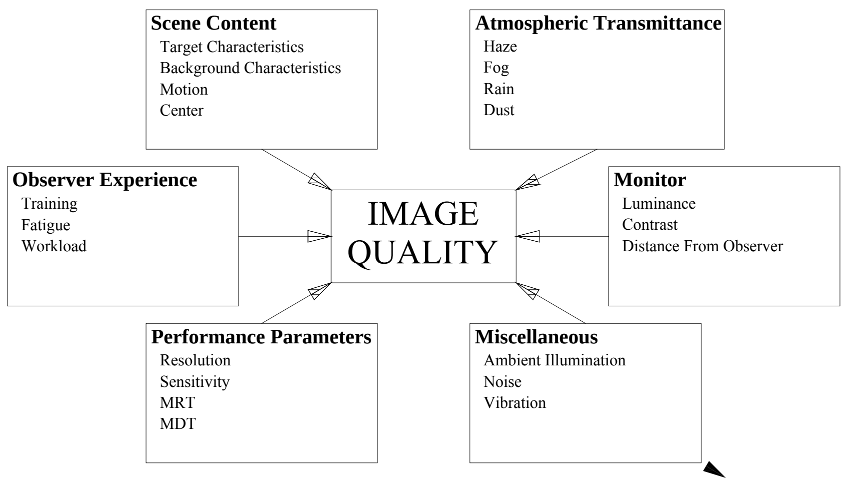

Figure 7. Image quality contributors.

Source: Holst, Common Sense Approach to Thermal Imaging, figure 7-1.

7.3.1 Spot Size

The thermal analysis equipment will record the temperature of a "spot" in the image and display this temperature. The size of the spot is critical since the temperature recorded is the average of the temperatures of the pixels within the spot. If the spot is too large, the average may "water down" a hot spot pixel, giving the false impression that the temperature is lower (or higher) than the pixel centered on the hot spot. Ideally, the spot size will be as small as possible, but there are practical limits. The spot size is partially determined by how close the device is to the target; and, in some cases, the approach distance must be relatively large for safety or physical obstructions or because the target is in the air. Using a telephoto lens on IR cameras will reduce the spot size of distant targets. Even though these can be expensive, they should be used where quantitative measurement is needed.

When using hand-held radiation thermometers, it is critical to understand and take into account the spot size for your specific equipment. Hand-held radiation thermometers typically have a spot size ratio ranging from 6:1 to 110:1. For comparison, thermal imaging cameras have a spot size ratio ranging from 63:1 to 889:1 with the typical spot size being approximately 250:1. The spot size of a thermal imaging camera can be changed depending on work to be performed by using different lenses. Figure 8 is an example of how the actual spot size changes based on spot size ratio and the distance from the target. Assuming the employee is 6 feet from the equipment under test, the actual spot size can vary from 0.65 inch to 12 inches. If the actual target size is 0.5 inch, then with a spot size ratio of 110:1, the employee would need to be within 55 inches of the target to only measure the temperature of the target. If the spot size ratio was 12:1, then the employee would need to be within 6 inches of the target to only measure the temperature of the target.

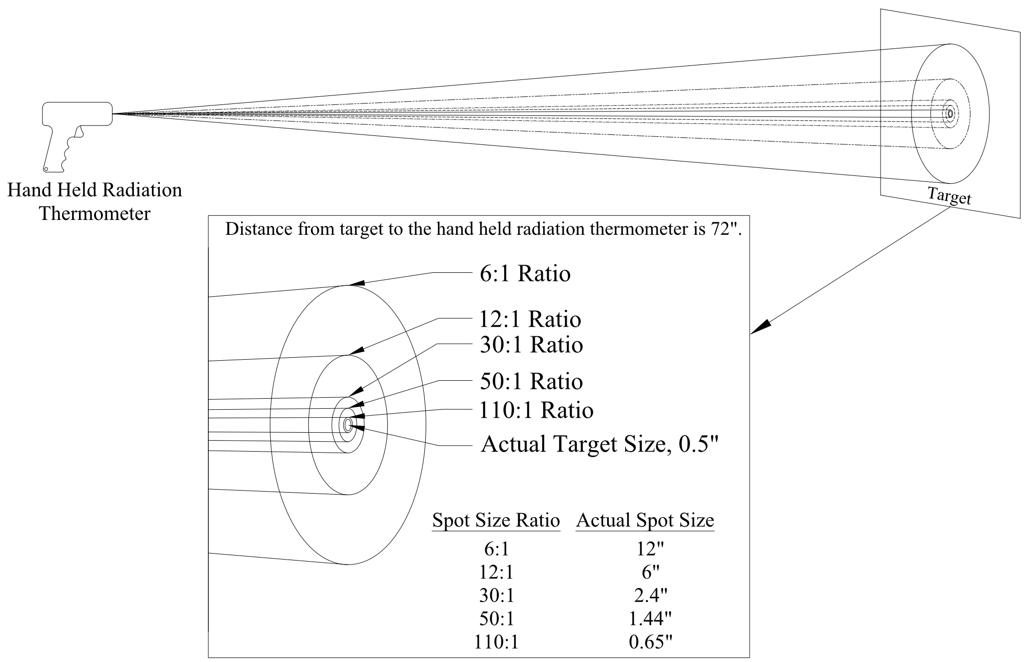

Figure 8. Spot size of hand-held radiation thermometer.

It is important to understand the device's spot size ratio, sometimes called the distance-to-spot ratio or instantaneous measurement field of view (IMFOV), which determines the maximum distance the thermographer can be from the target and still get a good reading. For example, a spot size ratio of 250 to 1 means that, at 250 inches (about 21 feet), the spot size to be measured must be a minimum of 1 inch. If the thermographer cannot get within 21 feet, a telephoto lens should be used. If the spot size or target is less than 1 inch (for example, ½ inch), the device would need to be closer than approximately 10½ feet for accurate temperature readings, or a telephoto lens would be required. For ¼ inch, the device would need to be closer still. The target should be larger than the spot size to ensure accurate data.

7.3.2 Distance

The physical distance of the IR thermal equipment to the target is one parameter that cannot be corrected after the image is taken and saved. The distance to the target is an important variable in determining apparent temperatures. The distance should be measured or estimated and entered into the camera. Using a laser distance device is an easy way to measure the distances between the thermographer and equipment. Never use a metal tape measure to determine the distance between the thermographer and equipment when working near energized equipment. The discussion above on spot size shows that the correct distance is very important to obtain quality IR images and proper analysis. The distance from the IR thermal equipment to the target needs to be reported on the PM forms. To simplify the process, it is possible to mark the floor in front of the equipment so the thermographer always maintains the same distance from the target, allowing for repeatable measurements.

7.3.3 Field of View and Instantaneous Field of View

The definition of field of view depends on the type of instrument used. For a hand-held radiation thermometer, the field of view (or instantaneous field of view [IFOV]) is the target spot size. In a scanner, imager, or radiometer, the field of view is the scan angle, picture size, or total field of view.[26] This can be related to a regular 35-millimeter (mm) camera; a 50-mm lens will provide a certain picture size. If the lens size is doubled to 100 mm (a basic telephoto lens), at the same distance, the overall field of view is reduced, but the items in the picture appear closer and clearer in detail. In IR thermography, the lenses are designated using angular notations. As the lens angle increases, so does the field of view. A "standard" 24-degree lens will have a larger field of view than a 12-degree telephoto lens.

IFOV relates directly to spatial resolution of the instrument used. IFOV is the smallest area that can be accurately seen at a given instance.

Figure 9 illustrates the field of view and the relation to the instantaneous field of view when using a thermal imaging camera.

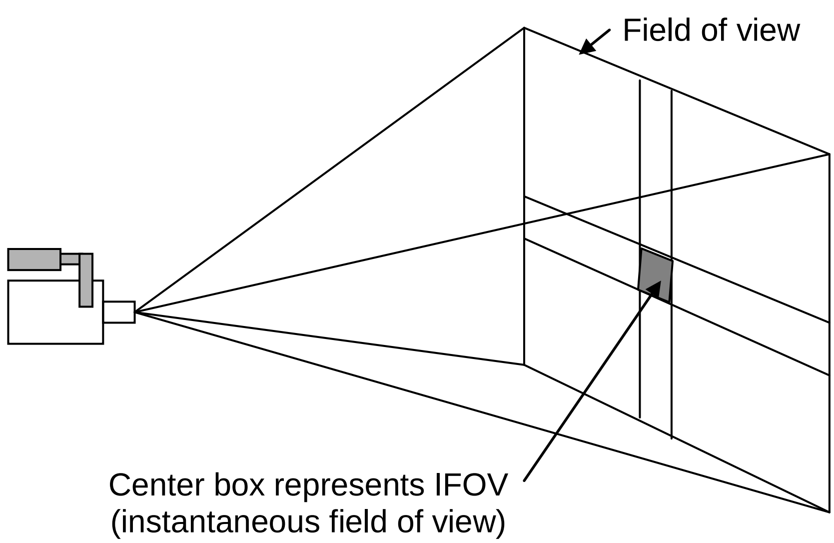

Figure 9. Field of view of an IR camera.

7.3.4 Estimating Emissivity

Before inspection of any component, it is essential that the emissivity of that component be estimated and set in the IR thermal inspection equipment. Otherwise, inaccurate temperatures will be recorded. For qualitative inspections, the starting emissivity may be estimated at 0.9–0.95. It is a good practice for a facility to establish a uniform starting emissivity for consistent results. Hand-held radiation thermometers may or may not allow the user to change the emissivity of the instrument. If the instrument does not

[26] Nondestructive Testing Handbook, Third Edition, ASNT.

allow the user to change the emissivity, then it will only provide accurate results for objects with the preprogrammed emissivity. Coatings may be added to equipment included in the thermal analysis program that will change the emissivity of the object.

Some cameras and the associated analyzing software programs can adjust emissivity after the image is saved. However, if the emissivity is set prior to imaging, quicker analysis may be made in the field as to the severity of any anomalies found. Emissivity tables are provided in many publications and also can be found in appendix F. These tables should be used sparingly and with caution. The best emissivity value for a given target is established in the field using accepted practices for determining the target's emissivity. See appendix E.

7.3.5 Background Sources

Heat energy from sources of radiation other than the target must be estimated and entered into the camera for a more accurate temperature measurement. There are specific procedures for using the camera to determine the background temperature. Once obtained, these values should be inputted into the camera.

7.3.6 Pointing, Aiming, and Ambient Reflections

Viewing angles can affect the amount of IR radiation gathered by the thermal analysis instrumentation. The optimum angle of the instrument to the target is 90° (perpendicular) to the plane of the target. Effort should be made to ensure the best possible viewing of the target. The optimum angle cannot always be achieved or maintained. Therefore, the temperature recorded from a target on an angle other than 90° may not be as accurate.

Generally, shiny surfaces do not emit radiation energy efficiently and can be hot while appearing cool in an IR thermographic image or on the readout of the hand-held radiation thermometer. Likewise, direct reflections of sun rays from shiny surfaces into the camera can be misread as hot spots. One method of determining if the spot observed in a camera is an anomaly or is the result of a reflection is to move around the target when possible. Usually, when conducting outdoor inspections, if the "hot" spot goes away or diminishes significantly, then the "hot" spot was probably a reflection. If the hot spot remains, measure it.

Do not rely on this technique for all targets. Targets may be large or shaped so that hot spots on the front side may be completely obscured when viewed from the back side. The technique of moving around then will not accurately locate all anomalies. The thermographer must be aware of unusual conditions that may influence the IR radiation measured by the test instrument. This points out the need for training and experience. It also emphasizes the need to have the thermographer familiar with the workings of the equipment being inspected.

7.3.7 Calibration

Have the thermal analysis instrumentation calibrated periodically, according to the manufacturer's recommendations. This will help ensure the instruments are working properly and recording accurate thermograms and/or temperatures.

7.3.8 Reference Photos

It is very helpful when analyzing thermograms to have a visual reference photo taken with a standard camera of the equipment at the same time and point of view as the thermogram. The reference photo will make it easier to identify components that might not be obvious in the thermogram. When using hand-held radiation thermometers, reference photos are critical to identify locations of hot spots. Since hand-held radiation thermometers do not capture data, extensive notes and reference photos are the only way to document the location of temperature data for future reference.

7.4 Environmental

7.4.1 Weather

Weather significantly affects timing and techniques of IR inspections.[27] Measures must be taken to reduce the effects of weather, particularly where *quantitative* temperatures are desired.

Wind in particular must be considered. Wind is equivalent to forced convective cooling and dramatically affects building, roof, electrical, and mechanical thermographic inspections. Even indoors, wind effects from air conditioning and ventilation will rapidly cool a hot spot.

Currently, *there are no recognized standard wind correction factors*. For *qualitative* measurements, wind speed of less than 15 miles per hour (mph) is probably adequate for inspection. For quantitative measurements, wind speed must be even lower—less than 10 mph and preferably less than 5 mph.[28]

The following is an example of the cooling effect of wind:[29]

With a sustained 3–5 mph wind:
- Measured spot temperature = 70 °C
- Ambient air temperature = 20 °C
- Delta (temperature over ambient) = 50 °C

With no wind:
- Measured spot temperature = 120 °C
- Ambient air temperature = 20 °C
- Delta (temperature over ambient) = 100 °C

Even though wind effects generally are found outdoors, IR inspections inside buildings also may be affected by air movement. Ventilation fans, air conditioning, and even natural ventilation can reduce the apparent temperature. As many of these factors as possible should be removed, especially when conducting quantitative inspections.

Commercial devices (anemometers) are available for measuring wind, and they should be used for outdoor inspection to determine if it is possible to quantitatively determine temperature. Wind speed may be estimated using the following scale:

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[27] NFPA 70B, section 21.17.3.1.

[28] Common Sense Approach to Thermal Imaging, Holst.

[29] Electrical Applications, InfraMation 2004 IR Clinic.

Beaufort Wind Scale[1]

Beaufort Number	Name	Wind Speed			Description
		mph	kph	m/s	
0	Calm	<1	<1.6	<0.4	Smoke rises vertically.
1	Light air	1–3	1.6–4.8	0.4–1.3	Direction of wind shown by smoke but not wind vanes.
2	Light breeze	4–7	6.4–11	1.8–3.1	Wind felt on face. Leaves rustle; wind vane moves.
3	Gentle breeze	8–12	13–19	3.6–5.4	Leaves and small twigs in constant motion, and wind extends a small flag.
4	Moderate breeze	13–18	21–29	5.8–8.0	Wind raises dust, loose paper, and small branches move
5	Fresh breeze	19–24	31–39	8.5–10.7	Small-leafed trees begin to sway; crested wavelets form on inland waters.

[1] kph = kilometers per hour; m/s = meters per second.

Since there is no reliable way to correct for wind quantitatively (i.e., using correction factors), the following guidance is given for wind conditions:[30]

- Use an anemometer to determine wind speed.
- Always be aware of the wind and know that the wind will affect the temperature rise, often significantly.
- Perform *quantitative* inspections in as close to no-wind conditions as possible.
- Perform inspections on indoor equipment as soon as possible after removing covers and doors to minimize the effects of natural convection and forced cooling in the building.
- Turn off the ventilation system, if possible.
- If possible, measure the component temperature on the leeward (downwind) side of the hot spot. Measuring out of the wind will produce a result closer to the no-wind condition.

Qualitative inspections are not affected in the same way by wind. As long as all components being surveyed are affected equally by the wind—for example, three phases of buswork—then the thermal signatures will be comparable. It is critical that electrical

[30] Wind Effects on Electrical Hot Spots—Some Experimental IR Data, Madding, 2002.

equipment be examined at full load. Partial loads may have a noted anomaly with no wind; but in the presence of a wind, the anomaly may be completely obscured.

High humidity and smoke reduce transmittance of IR energy—thus, reducing the effectiveness of the inspection. IR inspection in high humidity or smoky conditions is not recommended.

Solar loading will affect the apparent temperature, and transient solar loading (for example, passing clouds) is even more difficult to address. Early morning, evening, or nighttime inspections will provide more accurate IR results. However, many systems often are not loaded as heavily at night or during off-peak hours. Extra care should be exercised in analyzing the results because light loads may not adequately heat a problem area.

Due to difference in wavelengths detected, MWIR instruments are more susceptible to solar reflection than are LWIR instruments. However, this does not mean that solar reflection is not a problem if using LWIR cameras. Thermographers must recognize that reflective targets provide challenges no matter which IR system is used. When conducting outdoor inspections, care must be exercised to avoid incorrectly analyzing reflections or reflective targets.

7.4.2 Current Loading

When possible, IR inspections should be conducted with equipment operating at or near full load, both mechanically and electrically. Current loading of electrical equipment must be considered when determining temperatures quantitatively. Temperature rises vary considerably with different loads. Therefore, it is difficult to correct the temperature rise from partial load to full load.

Studies have shown that there are no simple load correction factors. However, if used cautiously, published factors can provide some reasonable correction.

Load Correction[1]

Percent Load	Multiplication Factor
100	1
80	1.4
70	1.8
60	2.2
50	3
40	4.3
30	7

[1] Adapted from figure 6, Important Measurements That Support IR Surveys in Substations, Madding et al., 2002, InfraMation.

Thermographic surveys should not be performed at low load, in windy conditions. Correct diagnosis requires knowing wind conditions and the electrical load at the time of the inspection. Both affect temperature readings and interact with each other. For example, a temperature rise of 45 °F under a 50-percent load is a more severe problem than the same temperature rise under a 90-percent load. This same temperature rise measured in a 10-mph wind is much more severe than in no wind.[31]

It is important to record the loading as part of the IR inspection, but care should be taken that it is the steady state load. At least 45 minutes should expire after a load change before performing an IR inspection.[32]

Another goal of load correction is to be able to calculate a safe loading level for a given maximum allowable temperature rise. In other words, the allowable temperature rise determines the maximum safe load.

[31] Important Measurements That Support IR Surveys in Substations, Madding et al., 2002, InfraMetrics.

[32] The Relationship Between Current Load and Temperature for Quasi-Steady State and Transient Conditions, Lyon et al., 2002.

8.0 Evaluating Results

8.1 Analyzing Results

The most important part of a thermal analysis process is evaluating the result. For qualitative analysis using comparison with like operating elements, it is best to evaluate the image once the picture has been recorded or downloaded. If a color change is noted between the like operating elements indicating higher thermal activity, the information should be forwarded to the maintenance manager as soon as possible for followup action.

A correct understanding of the equipment being inspected is essential if one is to make a proper thermographic diagnosis.[33]

In evaluating thermal analysis inspections, there are four possible outcomes:

1. A problem can be found when the problem actually exists.
2. A problem can be missed when there is a problem.
3. A problem will be diagnosed where no problem exists.
4. No problem is located because no problem exists.

Reliable testing processes and evaluations should identify all problems of concern with no problems overlooked. There should be no errors, as in number 2 above; and no false callouts relating to outcome, as in number 3.[34] Great care must be used when using a hand-held radiation thermometer to ensure all problems and nonproblems are correctly recorded. Using hand-held radiation thermometers requires considerably more time to perform a quality thermal inspection.

NETA's Maintenance Testing Specifications 2005 for Electrical Power Distribution Equipment recommends the following guidelines when measured temperatures differ from reference temperatures or temperatures of similar equipment:

Electrical Equipment Severity Criteria[1]

Temperature Difference from Reference	Implication
1–10 °C O/A 1–3 °C O/S	Possible deficiency—monitor and repair when possible
11–20 °C O/A 4–15 °C O/S	Probable deficiency—investigate further and repair when possible
21–40 °C O/A	Deficiency—repair at next opportunity
> 40 °C O/A > 15 °C O/S	Major deficiency—repair immediately

[1] O/A = over ambient/reference; O/S = over similar.

[33] Important Measurements That Support IR Surveys in Substations, Madding et al., 2002, InfraMetrics.

[34] Nondestructive Testing Handbook, Third Edition, ASNT.

Temperature specifications vary depending on the exact type of equipment. Even in the same class of equipment (i.e., cables), there are various temperature ratings. Heating is related to the square of the current; therefore, the load current will have a major impact on the difference in temperature or ΔT. In the absence of consensus standards for ΔT, the values in the above table will provide reasonable guidelines.[35]

Bearing Severity Criteria

Temperature Difference from Ambient	Implication
10–24 °C above	Normal operating conditions — no action is warranted
25–39 °C above	Probable deficiency — investigate further and repair when possible
40–69 °C above	Deficiency — repair at next opportunity
70 °C or more above	Major deficiency — repair immediately

Source: Mechanical Applications, InfraMetrics 2004 IR Clinic.

8.2 Recordkeeping and Reporting

Recordkeeping is essential to an effective thermal analysis maintenance process. Recordkeeping falls into five key areas:[36]

- Program documentation (what, where, how, and reporting requirements)
- Inspection documentation
- Report preparation
- Personnel qualifications
- Equipment calibration

8.2.1 Inspection Documentation

Complete and accurate records of inspected equipment are required for an effective thermal analysis process. To the degree possible, records should be kept in the computerized maintenance management system (CARMA) or in linked documents. For PM purposes, CARMA should be used to schedule thermal analysis inspections according to the required interval and to record results found. Thermograms are not appropriate to be kept in CARMA but can be linked or referenced. Documentation for inspections made for purposes other than PM also should be kept in or linked to CARMA for a complete record.

In CARMA, it should be possible to find what was inspected, when the inspection took place, under what conditions, who performed the inspection, thermal analysis equipment

[35] NETA Maintenance Testing Specifications 2005 for Electrical Power Distribution Equipment.

[36] IR Thermography – Level I Curriculum, EPRI.

used, and what was found during the inspection. If equipment scheduled for inspection was not inspected, an explanation should be recorded. Corrective work orders should be generated when problems are found.

Records of corrective work, with feedback provided to the thermographer, will improve the diagnostic process. Followup thermal analysis inspections should be preformed to verify that the corrective actions or repairs were successful in eliminating the problem.

Thermograms should be retained in the appropriate media (digital images, videotapes, etc.) and linked to the appropriate CARMA record.

8.2.2 Reports

Reports are often required for management awareness or to document a special problem. There is no required format for a thermal analysis report, but it should include the following recommended topics:

- Executive Summary
- Names of Responsible Individuals
- Inspection Date and Time
- Weather Conditions
- Inspection Equipment Used
- Identity of the Equipment or Structures Inspected
- Operating/Loading Conditions of the Equipment or Structure
- Inspection Procedure
- Data Analysis Techniques
- Data
- Thermograms and Associated Visual Photos
- Results
- Conclusions
- Recommendations
- Appendices

Some software packages used to analyze thermograms also provide assistance in report writing. An example report is shown in appendix D.

9.0 Personnel Qualifications

If personnel are performing a simple qualitative review of facility equipment, then no official certification is required. However, it is recommended that some training be given on the use of IR equipment.

Records should be kept on training and certification if required for personnel performing IR inspections.

Records of all IR training, including formal and on-the-job, should be kept. These records should include dates, locations, number of hours of inspection, and source and qualifications of instruction.

Records also should be kept on thermographer renewal certification. For basic troubleshooting, it is best if the thermographer is completely familiar with the equipment and has been instructed on proper procedures and analysis. The ASNT has defined training requirements. See Section 4.6, "Training and Certification."

10.0 Equipment Calibration

Properly calibrated thermal imaging equipment is needed to achieve accurate results. CARMA should be used to trigger calibration on the interval recommended by the manufacturer. The date that the calibration was completed and any other pertinent information should be kept in CARMA. A copy of the calibration schedule also should be kept with the instrumentation.

11.0 Complementary Technologies

IR inspection is an important tool for preventive and predictive maintenance, but it has limitations. Other technologies can be used to confirm or enhance thermal analysis inspection findings, making it possible to find the source of problems even more effectively.

Some of these complementary technologies include:

- **Ultrasonic**: Ultrasonic detection identifies frequencies above the sonic, or audible, level. Ultrasonic frequencies sometimes accompany problems that may cause heating. Sometimes, heating is not present when problems emitting a high frequency are present.

- **Vibration Analysis**: Vibration analysis can supplement thermal analysis in finding the source of mechanical problems.

- **Motor Current Analysis**: Motor current analysis, used in conjunction with thermal analysis, can provide insight into electrical motor problems.

Appendix A

Glossary of Thermography Terms

Adapted from Guideline for Developing and Managing and Infrared Thermography (IR) Program, Appendix A, Electric Power Research Institute, September 2001.

Absolute temperature scale: Temperature scales that are measured from absolute zero. Rankine and Kelvin scales are both absolute.

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

Ambient temperature: Temperature of immediate surroundings and environment where a test or measurement takes place. A parameter used to compensate for radiation reflected from test object and air in the field of view.

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

Apparent temperature: The target surface temperature as indicated by an IR point sensor, line scanner, or imager, generally taking into account the emissivity of the object.

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: Decrease in signal magnitude during energy transmission from one point to another. This loss may be caused by absorption, reflection, scattering of energy, or other material characteristics or may be caused by an electronic or optical device such as an attenuator or IR windows.

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

Background temperature: The temperature of the source of radiation that reflects off of the target that the thermal analysis instrument is viewing. Most quantitative thermal analysis instruments provide a means for correcting measurements for this reflection.

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

Blackbody reference source: A traceable, calibrated high emissivity device with an adjustable temperature. A blackbody reference source is used to calibrate or check the calibration of a radiometer.

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 by 1 degree Fahrenheit (°F) at sea level (standard pressure). A Btu is equal to approximately 1,055.06 joules.

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 blackbody reference source.

Calorie: Commonly referred to as the amount of heat needed to raise the temperature of 1 gram of water 1 degree Celsius (°C). The modern definition is the amount energy equal to about 4.2 joules. Symbol is c or cal.

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

Celsius scale: A temperature scale where water boils at 100 °C and freezes at 0 °C (both at standard pressure). Celsius scale was formerly called the Centigrade scale.

Characterize: To understand. Specifically, to understand the response of an IR system, 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. Composition is 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 also is present in fluids (liquids and gasses) when atoms or molecules of different energy levels come in contact with each other. Heat always travels from warmer to cooler.

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.

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).

Convection: The type of heat transfer that takes place in a moving medium and is almost always associated with transfer between a solid and a moving fluid, whereby energy is transferred from higher temperature sites to lower temperature sites.

Convective heat transfer coefficient: A value that represents the relative efficiency with which an object transfers heat between a surface and a fluid. This coefficient is often determined by experimentation, but typical values can be found in charts.

Data: The thermal information gathered by the IR system, stored either in an analog or digital format. For qualitative thermal analysis, thermograms contain the data; where as for quantitative thermal analysis, actual temperature values may be recorded.

Data capture rate: The rate at which the thermal data or information can be gathered by the IR system and stored either in an analog or digital format. Data typically has been captured at a rate of 30 or 60 frames per second; new high speed systems are capable of capture rates over 500 Hertz (Hz).

Density: The mass of a substance per unit volume. In United States units, it is weight in 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: Surface that reflects a portion of the incident radiation in such a manner that the reflected radiation is equal in all directions. A mirror is *not* a diffuse reflector.

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 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, temperature, wavelength, and other factors.

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

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 (T^4).

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

Filter: A semitransparent covering that is installed over the lens or detector to provide for selective transmission of various wavelengths. Filters also can provide protection of the primary lens.

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.

Focal Plane Array (FPA): An IR imaging system that uses a matrix type detector such as 240 x 320 pixels; can be either radiometric or qualitative.

Forced convection: Heat movement as a result from an outside force such as wind, pumps, or fans.

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."

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

Hand-held Radiation Thermometer: A device often known as an IR temperature gun. This instrument can be used to determine an approximate temperature of an object. The principles of operation for these instruments are similar to using a thermal imaging camera and require the user to adjust for field of view and emissivity.

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 (Hz): The International System of Units (SI) unit of frequency defined as 1 cycle per second.

High temperature filter: A filter used to restrict overall radiation so that higher temperatures can be viewed or measured.

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. This will be part of the camera specifications.

Instantaneous field of view measurement: See "IFOVmeas."

Instantaneous field of view: See "IFOV."

Instantaneous measurement field of view (IMFOV): The smallest detail that you can get an accurate temperature measurement upon at a set distance. This can be used to determine the maximum distance from a target.

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

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.

Joules: The SI unit of energy and work.

Kelvin scale: Absolute temperature scale related to the Celsius (or Centigrade) relative scale. The kelvin unit is equal to 1 °C; 0 kelvin = -273.15 °C. The degree sign and the word "degrees" are not used when expressing kelvin temperatures.

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 used to create or break the bonds in the solid state of a material.

Latent heat of vaporization: The energy 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 generally can 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 (LWIR): (Also abbreviated as LW.) Thermal radiation generally accepted to have wavelengths between 8–15 micrometers (µm). See also "Shortwave."

Micrometer: See "Micron."

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

Midwave (MWIR): (Also abbreviated as MW.) Thermal radiation generally accepted to have wavelengths between 3–5.5 µm. See also "Shortwave."

Minimum detectable temperature (MDT): (Also abbreviated as MDTD.) Rarely used for condition monitoring or predictive maintenance activities.

Minimum resolvable temperature difference (MRT): (Also abbreviated as MRTD) The smallest temperature difference that can be distinguished by an operator of an IR system. Typically, this measurement is used to determine the performance aspect of a thermal imagining device and is rarely used for condition monitoring or predictive maintenance activities.

Narcissus: The situation in which an IR system sees its own detector in a reflective surface, usually dramatically affecting the temperatures being viewed or displayed; however, this typically only occurs if the camera has a cooled sensor.

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 one state to another (i.e., a solid to a liquid or 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.

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

Qualitative: Thermal imaging without radiometric temperature measurement. Thermal imaging also could use a comparison of observed temperatures or thermographic heating patterns of like objects. Qualitative analysis also can be performed using a hand-held radiation thermometer.

Quantitative: Radiometric temperature measurement where all temperatures, ambient, background, etc., are included in the camera settings along with the correct emissivity and distance.

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

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

Radiometric: Noncontact 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.

Range: The term used with many IR thermographic 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.

Rankine scale: Absolute temperature scale related to the Fahrenheit relative scale. The Rankine unit is equal to 1 °F; 0 Rankine = -459.67 °F; the degree sign and the word "degrees" is not used in expressing Rankine temperatures. It is a nonmetric scale, which is used exclusively in the United States.

RAT Law: See "Conservation of Energy Law."

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

Reflectivity: Ratio ρ of the intensity of the total energy reflected from a surface to total radiation on that surface; ($\rho = 1 - \varepsilon - \tau$); for a perfect mirror, this approaches 1.0; for a blackbody, the reflectivity is 0. Technically, reflectivity is the ratio of the intensity of the reflected radiation to the total radiation, and reflectance is the ratio of the reflected flux to the incident flux. In IR thermography, the two terms often are used interchangeably.

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 shortwave sensing systems, this parameter is important so that atmospheric attenuation can be accounted for.

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.

R-value: The measure of a material's 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, thus, can 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 semitransparent covering is added to the primary lens.

Shortwave: Thermal radiation generally accepted to have wavelengths between 2–6 µm. See also "Midwave."

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

Solar filter: A filter used to reduce the effects of the shortwave lengths 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 IR 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 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: 0.1714×10^{-8} Btu • hr^{-1} • ft^{-2} • R^{-4} (5.670×10^{-8} watt • $meter^{-2}$ • $kelvin^{-4}$).

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 with clear delineations between colors or shades of gray as opposed to a continuous palette. When using a stepped palette, 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 of heat required to raise the temperature of 1 cubic foot of material 1 °F. 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 measured ability of a material 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 United States units, it is the amount of heat that flows through 1 square foot of material that is 1 inch thick, induced by a 1 °F temperature difference in 1 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 resistance: The inverse of thermal conductivity. It is the measure of a material's 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.

Transmissivity: The proportion of IR radiant energy impinging on an object's surface, for a given spectral interval, which is transmitted through the object. ($\tau = 1 - \varepsilon - \rho$). For a blackbody, transmissivity = 0. Transmissivity is the internal transmittance per unit thickness of a nondiffusing material.

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

Vaporization: See "Latent heat of vaporization."

Wien's Displacement Constant: The value, 5,215.6 µm • R (2,897 µm • K), determined by Wien to quantify the relationship between the temperature of a blackbody and the peak wavelength of radiation it gives off.

Wien's Displacement Law: The law that describes the relationship between the temperature of a blackbody and the peak wavelength of radiation it gives off. At higher temperatures, there is a displacement to shorter wave lengths. The law is stated as b/T = µm where b is Wien's Constant (5,215.6 µm • R), T is the blackbody absolute temperature (R), and µm is the peak wavelength. SI value is 2,897 µm • K.

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

12-bit system: An IR system capable of storing data that can be divided into 4,096 thermal levels.

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

Appendix B

Helpful Operations Hints

Below is a list of helpful hints that will be useful to perform a quality thermal imaging survey.

1. Circuit loading must be taken into account when inspecting electrical equipment. Comparative inspections should be done when the load is similar to the last inspection to make a fair comparison. See Section 8, "Evaluating Results," for more information.

2. Inspections should take place during periods of maximum possible loading but not less than 40 percent of rated load of the equipment being inspected.[37] A 10-percent temperature rise may be negligible near full load but may be significant on lightly loaded circuits.

3. Temperatures take time to stabilize after load changes, so inspection should be delayed for 45 minutes following changes in loading. This is particularly true when temperatures are being read indirectly.

4. A front-surface mirror (i.e., one that has the reflective surface on the front surface of the glass) can be used to inspect the backside of a component. An everyday mirror with the reflective surface on the back of the glass cannot be used for IR inspection because it has internal reflections.[38]

5. It is useful to compare one phase of a circuit to the other phases because: 1) the emissivities are similar, 2) heat generation and dissipation effects should be similar, 3) all phases are the same distance from the IR temperature device, and 4) all phases are (hopefully) equally loaded.

6. Unbalanced loads may account for some temperature differences between conductors. In some cases, unbalance may be a normal operating condition.

7. Surge arresters and bushings are best inspected at night because reflections associated with daylight will be reduced.

8. Load tap changers (LTC) on transformers always should have a lower temperature than the transformer itself due to separation of the LTC from the warmer transformer tank and the effects of convection cooling.

9. Large vertical motors usually show several vertical hot "stripes" on the side of the casing, while horizontal motors show hot spots on the middle of the casing in an even pattern.

10. Heat on an enclosure surface might be the result of a resistor, heater, or transformer mounted on the other side rather than a critical component.

[37] National Fire Protection Association 70B, section 21.17.5.2.

[38] Common Sense Approach to Thermal Imaging, Holst, chapter 11.

Remember, heating patterns on an enclosure are most likely the result of indirect heating because the heat source is much hotter than the temperatures recorded on the enclosure surface.

11. Most mechanical components are painted, and this affects the emissivity. Flat paint emissivity values are typically in the 0.90 range. Glossy paint emissivity is usually high, but it may produce different results between midwave infrared (MWIR) and long-wave infrared (LWIR) equipment. Metallic paints have emissivities as low as 0.3 or less.[39]

12. The simple act of opening an enclosure door or removing a protective covering can quickly change the temperature of a component, thus giving a reading not typical of normal operating conditions.

Keep a copy of this checklist with the camera to ensure that the necessary steps have been completed and that all hardware is with the camera.

- Perform a job hazard analysis for each inspection.
- Assemble and check thermal analysis equipment.
- Inspect personal protective equipment.
- Check camera and accessories (batteries, lenses, and storage media) and make sure everything is located with the thermal analysis equipment.
- Have a digital camera, if not available on the thermal analysis equipment.
- Compile previous survey results.
- Compile drawings and other reference material.
- Wear appropriate personal protective equipment.
- Follow all appropriate safety procedures.
- Check that the thermal analysis instrumentation calibration is current.
- Check battery charge.
- Make adjustments to the thermal analysis instrumentation settings as needed.
- Set or check the correct distance to the target.
- Set or use the correct emittance value.
- Set or check the correct background energy levels.
- Ensure the camera is properly focused.
- Set the correct temperature range in the camera.
- Record wind speed, relative humidity, and other environmental factors.
- Make sure the target is larger than the instantaneous field of view measurement (IFOVmeas) of the instrument or spot size on hand-held radiation thermometer.

[39] Mechanical Applications, InfraMation 2004 IR Clinic.

- Aim the instrument as close as possible to perpendicular with the target surface. (Angles of incidence exceeding 45 degrees can cause errors.)
- Check for thermal reflections from other point sources off the target surface.
- Keep instrument as far away as possible from very hot objects and energized equipment.
- Keep accurate records and trend data.

Appendix C

Hardware and Software Features

When selecting, specifying, and procuring an infrared (IR) imaging system, many factors must be considered to arrive at the hardware and software that is appropriate for use. The following has been adapted from criteria identified by IRINFO.ORG (http://www.irinfo.org) and is based on the Bureau of Reclamation's experience to date. It may be used to compare imaging systems.

Comparison of Specifications		
	Imager 1	Imager 2
OBJECTIVE SPECIFICATIONS		
Environment		
Operating Temperature Limits		
Imaging		
Spectral Response		
Visual Field of View		
Detector Type		
Detector Size (Resolution)		
Cooling Type		
Focus		
Minimum Focus Distance		
Imager Frame Rate		
Visual Camera Resolution		
Image Display		
Display Type		
Color Palettes		
Measurement		
Measurement Range		
Thermal Sensitivity		
Emissivity Correction		
Spot Measurement Size		
Temperature Measure Tools		
Reflected Temperature Comparison		
Accuracy		

Comparison of Specifications (continued)		
	Imager 1	Imager 2
OBJECTIVE SPECIFICATIONS (continued)		
Data Storage		
Storage Media (Internal/External/Both)		
Storage Media Type (SD, SDHC, CF, etc.)		
File Format		
Number of Images Stored		
Voice Recording		
Text Recording		
Data Transfer		
IEEE 1394 (FireWire)		
USB		
S-Video		
RCA Jack		
Others		
Power Source		
External Power		
Battery Type/Run Time		
Other Accessories		
BlueTooth®		
Laser Pointer		
Lens Options		
Filter Options		
Data Interface		
Video Format		
Video Output		
Physical		
Dimensions		
Weight with Battery		
Shock Withstand		
Encapsulation		
Vibration		

SUBJECTIVE SPECIFICATIONS		
Are imager controls easy to use and understand?		
Is equipment designed to be rugged and durable?		
Is imager ergonomically comfortable?		
Will imager size or weight present problems for long-term use?		
Is the imager display clear and free of noise and distortion?		
Is imager display adequate and compatible with operator's safety glasses or other personal protective equipment (PPE) such as hard hats, face shields, hoods, respirators, etc.?		
Is the imager display viewable in direct sunlight?		

OTHER CONSIDERATIONS		
Length of time imager has been in production		
Experience in building and servicing infrared (IR) equipment and capability to provide future service		
Recommended service or calibration frequency and costs		
Expected delivery time for repairs		
Length of warranty and covered parts		
Location of equipment service center		
Loaner/rental available during repair periods		
Training available from vendor		
Quality of documentation		
Equipment Cost		

Appendix D

Sample IR Report

Technical Service Center | Hydroelectric Research | D-8450

RECLAMATION
Managing Water in the West

Infrared Inspection at Any Plant

May 2006

General Information

At the request of the Conservancy District, Any Pumping Plant, I conducted an electrical and mechanical survey of the pumping plants. Due to operating restrictions, only one pump unit at a time was put on line and operated for a minimum of 45 minutes to allow components to heat to normal operating temperatures before IR scanning was initiated.

All of the equipment located on the main pump floor, the mezzanine, and the two floors located below the main floor were examined and included: cabinets 1F through 6F as they related to the operating unit. Each excitation panel/cabinet (front and back) was scanned. Control cubicles for high-pressure oil pump, space heaters, and RTUs were examined as appropriate. Load centers were scanned as best possible. Main breaker panelboards LCA, LCB, and LCC were scanned.

Transformers inside the plant were examined. The power transformers outside the plant also were included in the survey.

Each unit's bearings and cooling water pumps were examined during unit operation. The air compressor was operated and examined.

The battery room was examined and no anomalies were found. However, the loads on the batteries and charger were minimal.

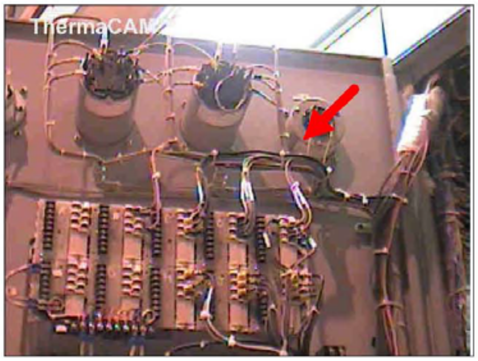
Unless included for future reference, only the images of anomalies are presented in this report.There are two suspect locations at the pumping plant which require further investigation. The connections identified as being high resistance connections could possibly be corrected by examining the connection, making sure all crimped connections are secure, cleaning and retightening the connections.

Thermographer: I.R Hot, Elec. Engrg. Tech.

Table of Contents

	Equipment Inspected:	*Thermographer:*
	Electrical and Mechanical	I.R Hot, Elec. Engrg. Tech.

Identification



Equipment	Unit control
Thermographer:	I.R Hot, Elec. Engrg. Tech.
Inspection Dates	May 2006
Date	May 2006
Time	11:23:10 AM

Working conditions: Main unit was operational for 45 minutes at 100 % load prior to IR examination

Fault description

Watthour meter	Connection A8-11

Object parameter	**Value**
Emissivity	0.86
Object distance	1.5 m
Label	**Value**
SP01	37.3°C
SP02	26.4°C

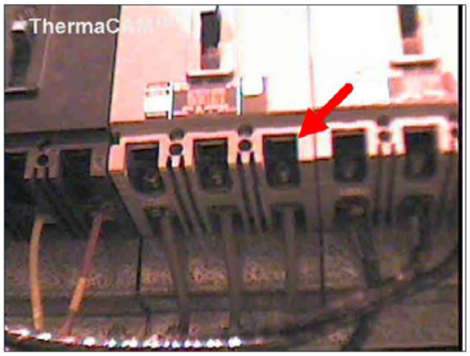
Recommendation

Examine and repair

The connection is suspect since the heat appears to originate at the connection and is conducted along the wire.

	Equipment Inspected:	*Thermographer:*
	Electrical and Mechanical	I.R Hot, Elec. Engrg. Tech.

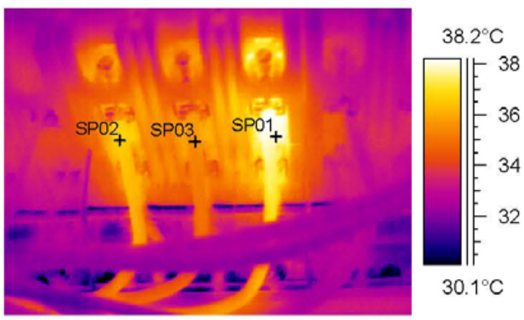
Identification



Equipment	Breaker 5
Thermographer:	I.R Hot, Elec. Engrg. Tech.
Inspection Dates	May 2006
Date	May 2006
Time	12:02:21 PM

Working conditions: Main equipment operational for 45 minutes minimum at 80% load

Fault description



Breaker 5	Connections to transformer

Object parameter	**Value**
Emissivity	0.86
Object distance	1.5 m
Label	**Value**
SP01	38.1°C
SP02	36.8°C
SP03	35.6°C

Recommendation

Examine and repair

Although there apears to be a 2.5 °C difference between the "hottest" connection and the "coolest" connection, it is recommended that the connections be examined for proper contact. It is also adviseable to monitor the currents of each conductor to confirm balanced loading.

Technical Service Center | Hydroelectric Research | D-8450

Summary of Inspection at

Any Plant

List of Inspected Items

Section	Equipment	Fault	Recommendation
Main Unit floor	Unit control	High resistance connection	Examine and repair
Main unit control	Breaker 5	High resistance connection	Examine and repair

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Appendix E

Methods of Determining or Enhancing the Emittance of a Target

Thermographers calculate or determine the emissivity of different targets in a number of ways. Accurate emissivity values are needed if quantitative temperature measurements are required. If possible, emissivity enhancement coatings can be applied to target areas. Coatings, usually in the form of paint, have known emissivities. These coatings are usually applied to shiny or reflective surfaces to provide a higher known emissivity and to provide accurate temperature measurements. Most of the coatings today have emissivities at or near 0.95.

Black electrical tape (3M Scotch 33™) can be used to determine the emissivity of targets. This tape has been measured and is used as a reference by many thermographers. Emissivity of the tape is 0.95. This technique requires the tape to be placed on the target material prior to energizing, loading, or heating the equipment to be monitored.

For the following technique to work properly, the measured target or component temperature must be raised 20 degrees Fahrenheit (°F) or higher above ambient temperature. This technique will not work if the target is at ambient temperature.

Place a ½- to 1-inch square of the electrical tape on the target. Measure the background temperature by setting the emissivity to 1.0 in the infrared (IR) camera and pointing the camera away from the target. In most cases, defusing the focus will give an average background temperature. The background temperature also can be measured by using a piece of cardboard with an aluminum foil cover set next to the target. Again, set the camera emissivity to 1.0 and the camera slightly out of focus. Measure the temperature at the center of the cardboard/aluminum foil.

The background temperature should be entered into the camera if the camera being used allows this. The correct distance to the target should be added to the camera settings. The thermographer needs to recognize the spot size and ensure that the target size is adequate and is in focus. Set the camera to an emissivity of 0.95. Once the target is at temperature, measure the temperature of the taped (or emissivity enhanced) area. Note the temperature. Move the measuring spot just off of the tape and on to the surface for which emissivity is to be determined. Adjust the emissivity in the camera, until the temperature of this spot matches the temperature measured on the tape. Once the temperatures match, read and record the emissivity. This emissivity now can be used in the future for this particular equipment and perhaps similar equipment.

Other techniques for increasing emissivity of targets include using the geometry of the components. For instance, the intersection where a lug or nut meets the connection surface will form a small cavity that, when viewed in the IR camera, will have an increased emissivity. All types of cavities will tend to have higher emissivities and should be used whenever possible.

Other techniques or formulas for calculating emissivity can be found in numerous publications and are usually included in most training classes.

Appendix F

Material Emissivity Table

Material	Detail	Temp °F (°C)	Emissivity
Metals			
Alloys			
	20-Ni, 24-CR, 55-FE, Oxidized	392 (200)	0.90
	20-Ni, 24-CR, 55-FE, Oxidized	932 (500)	0.97
	60-Ni, 12-CR, 28-FE, Oxidized	518 (270)	0.89
	60-Ni, 12-CR, 28-FE, Oxidized	1,040 (560)	0.82
	80-Ni, 20-CR, Oxidized	212 (100)	0.87
	80-Ni, 20-CR, Oxidized	1,112 (600)	0.87
	80-Ni, 20-CR, Oxidized	2,372 (1,300)	0.89
Aluminum			
	Unoxidized	77 (25)	0.02
	Unoxidized	212 (100)	0.03
	Unoxidized	932 (500)	0.06
	Oxidized	390 (199)	0.11
	Oxidized	1,110 (599)	0.19
	Oxidized at 599 °C (1,110 °F)	390 (199)	0.11
	Oxidized at 599 °C (1,110 °F)	1,110 (599)	0.19
	Heavily Oxidized	200 (93)	0.20
	Heavily Oxidized	940 (504)	0.31
	Highly Polished	212 (100)	0.09
	Roughly Polished	212 (100)	0.18
	Commercial Sheet	212 (100)	0.09
	Highly Polished Plate	440 (227)	0.04
	Highly Polished Plate	1,070 (577)	0.06
	Bright Rolled Plate	338 (170)	0.04
	Bright Rolled Plate	932 (500)	0.05
	Alloy A3003, Oxidized	600 (316)	0.40
	Alloy A3003, Oxidized	900 (482)	0.40
	Alloy 1100-0	200–800 (93–427)	0.05
	Alloy 24ST	75 (24)	0.09
	Alloy 24ST, Polished	75 (24)	0.09
	Alloy 75ST	75 (24)	0.11
	Alloy 75ST, Polished	75 (24)	0.08

Material	Detail	Temp °F (°C)	Emissivity
Bismuth			
	Bright	176 (80)	0.34
	Unoxidised	77 (25)	0.05
	Unoxidised	212 (100)	0.06
Brass			
	73% Cu, 27% Zn, Polished	476 (247)	0.03
	73% Cu, 27% Zn, Polished	674 (357)	0.03
	62% Cu, 37% Zn, Polished	494 (257)	0.03
	62% Cu, 37% Zn, Polished	710 (377)	0.04
	83% Cu, 17% Zn, Polished	530 (277)	0.03
	Matte	68 (20)	0.07
	Burnished to Brown Color	68 (20)	0.40
	Cu-Zn, Brass Oxidized	392 (200)	0.61
	Cu-Zn, Brass Oxidized	752 (400)	0.6
	Cu-Zn, Brass Oxidized	1,112 (600)	0.61
	Unoxidized	77 (25)	0.04
	Unoxidized	212 (100)	0.04
Cadmium			
		77 (25)	0.02
Carbon			
	Lampblack	77 (25)	0.95
	Unoxidized	77 (25)	0.81
	Unoxidized	212 (100)	0.81
	Unoxidized	932 (500)	0.79
	Candle Soot	250 (121)	0.95
	Filament	500 (260)	0.95
	Graphitized	212 (100)	0.76
	Graphitized	572 (300)	0.75
	Graphitized	932 (500)	0.71
Chromium			
		100 (38)	0.08
		1,000 (538)	0.26
	Polished	302 (150)	0.06
Cobalt, Unoxidised			
	Unoxidized	932 (500)	0.13
	Unoxidized	1,832 (1,000)	0.23

Material	Detail	Temp °F (°C)	Emissivity
Columbium, Unoxidised			
	Unoxidized	1,500 (816)	0.19
	Unoxidized	2,000 (1093)	0.24
Copper			
	Cuprous Oxide	100 (38)	0.87
	Cuprous Oxide	500 (260)	0.83
	Cuprous Oxide	1,000 (538)	0.77
	Black, Oxidized	100 (38)	0.78
	Etched	100 (38)	0.09
	Matte	100 (38)	0.22
	Roughly Polished	100 (38)	0.07
	Polished	100 (38)	0.03
	Highly Polished	100 (38)	0.02
	Rolled	100 (38)	0.64
	Rough	100 (38)	0.74
	Molten	1,000 (538)	0.15
	Molten	1,970 (1,077)	0.16
	Molten	2,230 (1,221)	0.13
	Nickel Plated	100–500 (38–260)	0.37
Dow Metal			
		0.4–600 (-18)–316)	0.15
Gold			
	Enamel	212 (100)	0.37
	Plate (.0001) on 0.0005 Silver	200–750 (93–399)	.11–.14
	Plate (.0001) on 0.0005 Nickel	200–750 (93–399)	.07–.09
	Polished	100–500 (38–260)	0.02
	Polished	1,000–2,000 (538–1,093)	0.03
Haynes Alloy C,			
	Oxidized	600–2,000 (3,16–1093)	.90–.96
Haynes Alloy 25,			
	Oxidized	600–2,000 (316–1093)	.86–.89
Haynes Alloy X,			
	Oxidized	600–2000 (316–1,093)	.85–.88
Inconel Sheet			
		1,000 (538)	0.28
		1,200 (649)	0.42
		1,400 (760)	0.58

Material	Detail	Temp °F (°C)	Emissivity
Inconel X, Polished			
		75 (24)	0.19
Inconel B, Polished			
		75 (24)	0.21
Iron			
	Oxidized	212 (100)	0.74
	Oxidized	930 (499)	0.84
	Oxidized	2,190 (1,199)	0.89
	Unoxidized	212 (100)	0.05
	Red Rust	77 (25)	0.7
	Rusted	77 (25)	0.65
	Liquid	2,760–3,220 (1,516–1,771)	.42–.45
Cast Iron			
	Oxidized	390 (199)	0.64
	Oxidized	1,110 (599)	0.78
	Unoxidized	212 (100)	0.21
	Strong Oxidation	40 (104)	0.95
	Strong Oxidation	482 (250)	0.95
	Liquid	2,795 (1,535)	0.29
Wrought Iron			
	Dull	77 (25)	0.94
	Dull	660 (349)	0.94
	Smooth	100 (38)	0.35
	Polished	100 (38)	0.28
Lead			
	Polished	100–500 (38–260)	.06–.08
	Rough		0.43
	Oxidized	100 (38)	0.43
	Oxidized at 1,100 °F	100 (38)	0.63
	Gray Oxidized	100 (38)	0.28
Magnesium			
		100–500 (38–260)	.07–.13
Magnesium Oxide			
		1,880–3,140 (1,027–1,727)	.16–.20

Material	Detail	Temp °F (°C)	Emissivity
Mercury			
		32 (0)	0.09
		77 (25)	0.1
		100 (38)	0.1
		212 (100)	0.12
Molybdenum			
		100 (38)	0.06
		500 (260)	0.08
		1,000 (538)	0.11
		2,000 (1093)	0.18
	Oxidized at 1,000 °F	600 (316)	0.8
	Oxidized at 1,000 °F	700 (371)	0.84
	Oxidized at 1,000 °F	800 (427)	0.84
	Oxidized at 1,000 °F	900 (482)	0.83
	Oxidized at 1,000 °F	1,000 (538)	0.82
Monel, Ni-Cu			
		392 (200)	0.41
		752 (400)	0.44
		1,112 (600)	0.46
	Oxidized	68 (20)	0.43
	Oxidized at 1,110 °F	1,110 (599)	0.46
Nickel			
	Polished	100 (38)	0.05
	Oxidized	100–500 (38–260)	0.31–0.46
	Unoxidized	77 (25)	0.05
	Unoxidized	212 (100)	0.06
	Unoxidized	932 (500)	0.12
	Unoxidized	1,832 (1,000)	0.19
	Electrolytic	100 (38)	0.04
	Electrolytic	500 (260)	0.06
	Electrolytic	1,000 (538)	0.1
	Electrolytic	2,000 (1,093)	0.16
Nickel Oxide			
		1,000-2,000 (538–1,093)	0.56–0.86
Palladium Plate			
	0.00005” on 0.0005” silver	200–750 (93–399)	0.16

Material	Detail	Temp °F (°C)	Emissivity
Platinum			
		100 (38)	0.05
		500 (260)	0.05
		1,000 (538)	0.1
	Black	100 (38)	0.93
	Black	500 (260)	0.96
	Black	2,000 (1093)	0.97
	Oxidized at 1,100 °F	500 (260)	0.07
	Oxidized at 1,100 °F	1,000 (538)	0.11
Rhodium Flash			
	0.002 on 0.0005Ni	200–700 (93–371)	0.10–0.18
Silver			
	Plate (0.0005 on Ni)	200–700 (93–371)	0.06–0.07
	Polished	100 (38)	0.01
	Polished	500 (260)	0.02
	Polished	1,000 (538)	0.03
	Polished	2,000 (1093)	0.03
Steel			
	Cold Rolled	200 (93)	0.75–0.81
	Ground Sheet	1,720–2,010 (938–1,099)	0.55–0.61
	Polished Sheet	100 (38)	0.07
	Polished Sheet	500 (260)	0.1
	Polished Sheet	1,000 (538)	0.14
	Mild Steel, Polished	75 (24)	0.1
	Mild Steel, Smooth	75 (24)	0.12
	Mild Steel, liquid	2,910–3,270 (1,599–1,793)	0.28
	Steel, Unoxidized	212 (100)	0.08
	Steel, Oxidized	77 (25)	0.8
Steel Alloys			
	Type 301, Polished	75 (24)	0.27
	Type 301, Polished	450 (232)	0.57
	Type 301, Polished	1,740 (949)	0.55
	Type 303, Oxidized	600–2,000 (316–1,093)	.74–.87
	Type 310, Rolled	1,500–2,100 (816-1,149)	.56–.81
	Type 316, Polished	75 (24)	0.28
	Type 316, Polished	450 (232)	0.57
	Type 316, Polished	1,740 (949)	0.66
	Type 321	200–800 (93–427)	.27–.32

Material	Detail	Temp °F (°C)	Emissivity
	Type 321 Polished	300–1,500 (149–815)	.18–.49
	Type 321 w/BK Oxide	200–800 (93–427)	.66–.76
	Type 347, Oxidized	600–2,000 (316–1,093)	.87–.91
	Type 350	200–800 (93–427)	.18–.27
	Type 350 Polished	300–1,800 (149–982)	.11–.35
	Type 446, Polished	300–1,500 (149–815)	.15–.37
	Type 17-7 PH	200–600 (93–316)	.44–.51
	Type 17-7 PH, polished	300–1,500 (149–815)	.09–.16
	Type C1020, Oxidized	600–2,000 (316–1,093)	.87–.91
	Type PH-15-7 MO	300–1,200 (149–649)	.07–.19
Stellite			
	Polished	68 (20)	0.18
Tantalum			
	Unoxidized	1,340 (727)	0.14
	Unoxidized	2,000 (1,093)	0.19
	Unoxidized	3,600 (1,982)	0.26
	Unoxidized	5,306 (2,930)	0.3
Tin			
	Unoxidized	77 (25)	0.04
	Unoxidized	212 (100)	0.05
Tinned Iron, Bright			
		76 (24)	0.05
		212 (100)	0.08
Titanium			
	Alloy C110M, Polished	300–1,200 (149–649)	
	Oxidized at 1,000 °F	200–800 (93–427)	.51–.61
	Alloy Ti-95A, Oxidized at 1,000 °F	200–800 (93–427)	.35–.48
	Anodized onto SS	200–600 (93–316)	.96–.82
Tungsten			
	Unoxidized	77 (25)	0.02
	Unoxidized	212 (100)	0.03
	Unoxidized	932 (500)	0.07
	Unoxidized	1,832 (1,000)	0.15
	Unoxidized	2,732 (1,500)	0.23
	Unoxidized	3,632 (2,000)	0.28
	Filament (Aged)	100 (38)	0.03
	Filament (Aged)	1,000 (538)	0.11
	Filament (Aged)	5,000 (2,760)	0.35

Material	Detail	Temp °F (°C)	Emissivity
Uranium Oxide			
		1,880 (1,027)	0.79
Zinc			
	Bright, Galvanized	100 (38)	0.23
	Commercial 99.1%	500 (260)	0.05
	Galvanized	100 (38)	0.28
	Oxidized	500–1,000 (260–538)	0.11
	Polished	100 (38)	0.02
	Polished	500 (260)	0.03
	Polished	1,000 (538)	0.04
	Polished	2,000 (1,093)	0.06
Nonmetals			
Adobe			
		68 (20)	0.9
Asbestos			
	Board	100 (38)	0.96
	Cement	32–392 (0–200)	0.96
	Cement, Red	2,500 (1,371)	0.67
	Cement, White	2,500 (1,371)	0.65
	Cloth	199 (93)	0.9
	Paper	100–700 (38–371)	0.93
	Slate	68 (20)	0.97
	Asphalt, pavement	100 (38)	0.93
	Asphalt, tar paper	68 (20)	0.93
Basalt			
		68 (20)	0.72
Brick			
	Red, rough	70 (21)	0.93
	Gault Cream	2,500–5,000 (1,371–2,760)	.26–.30
	Fire Clay	2,500 (1,371)	0.75
	Light Buff	1,000 (538)	0.8
	Lime Clay	2,500 (1,371)	0.43
	Fire Brick	1,832 (1,000)	.75–.80
	Magnesite, Refractory	1,832 (1,000)	0.38
	Grey Brick	2,012 (1,100)	0.75
	Silica, Glazed	2,000 (1,093)	0.88
	Silica, Unglazed	2,000 (1,093)	0.8
	Sand lime	2,500–5,000 (1,371–2,760)	.59–.63

Material	Detail	Temp °F (°C)	Emissivity
Carborundum			
		1,850 (1,010)	0.92
Ceramic			
	Alumina on Inconel	800–2,000 (427–1,093)	.69–.45
	Earthenware, Glazed	70 (21)	0.9
	Earthenware, Matte	70 (21)	0.93
	Greens No. 5210–2C	200–750 (93–399)	.89–.82
	Coating No. C20A	200–750 (93–399)	.73–.67
	Porcelain	72 (22)	0.92
	White Al2O3	200 (93)	0.9
	Zirconia on Inconel	800–2,000 (427–1,093)	.62–.45
Clay			
		68 (20)	0.39
	Fired	158 (70)	
	Shale	68 (20)	
	Tiles, Light Red	2,500–5,000 (1,371–2,760)	
	Tiles, Red	2,500–5,000 (1,371–2,760)	
	Tiles, Dark Purple	2,500–5,000 (1,371–2,760)	
Concrete			
	Rough	32–2,000 (0–1,093)	
	Tiles, Natural	2,500–5,000 (1,371–2,760)	
	Tiles, Brown	2,500–5,000 (1,371–2,760)	
	Tiles, Black	2,500–5,000 (1,371–2,760)	
Cotton Cloth			
		68 (20)	0.77
Dolomite Lime			
		68 (20)	0.41
Emery Corundum			
		176 (80)	0.86
Glass			
	Convex D	212 (100)	0.8
	Convex D	600 (316)	0.8
	Convex D	932 (500)	0.76
	Nonex	212 (100)	0.82
	Nonex	600 (316)	0.82
	Nonex	932 (500)	0.78
	Smooth	32–200 (0–93)	.92–.94

Material	Detail	Temp °F (°C)	Emissivity
Granite			
		70 (21)	0.45
Gravel			
		100 (38)	0.28
Gypsum			
		68 (20)	.80–.90
Ice			
	Smooth	32 (0)	0.97
	Rough	32 (0)	0.98
Lacquer			
	Black	200 (93)	0.96
	Blue, on Al Foil	100 (38)	0.78
	Clear, on Al Foil (2 coats)	200 (93)	.08 (.09)
	Clear, on Bright Cu	200 (93)	0.66
	Clear, on Tarnished Cu	200 (93)	0.64
	Red, on Al Foil (2 coats)	100 (38)	.61 (.74)
	White	200 (93)	0.95
	White, on Al Foil (2 coats)	100 (38)	.69 (.88)
	Yellow, on Al Foil (2 coats)	100 (38)	.57 (.79)
Lime Mortar			
		100–500 (38–260)	.90–.92
Limestone			
		100 (38)	0.95
Marble			
	White	100 (38)	0.95
	Smooth, White	100 (38)	0.56
	Polished, Grey	100 (38)	0.75
Mica			
		100 (38)	0.75
Oil on Nickel			
	0.001 Film	72 (22)	0.27
	0.002 Film	72 (22)	0.46
	0.005 Film	72 (22)	0.72
	Thick Film	72 (22)	0.82
Oil, Linseed			
	On Al Foil, uncoated	250 (121)	0.09
	On Al Foil, 1 coat	250 (121)	0.56

Material	Detail	Temp °F (°C)	Emissivity
Oil, Linseed (continued)			
	On Al Foil, 2 coats	250 (121)	0.51
	On Polished Iron, .001 Film	100 (38)	0.22
	On Polished Iron, .002 Film	100 (38)	0.45
	On Polished Iron, .004 Film	100 (38)	0.65
	On Polished Iron, Thick Film	100 (38)	0.83
Paints			
	Blue, Cu2O3	75 (24)	0.94
	Black, CuO	75 (24)	0.96
	Green, Cu2O3	75 (24)	0.92
	Red, Fe2O3	75 (24)	0.91
	White, Al2O3	75 (24)	0.94
	White, Y2O3	75 (24)	0.9
	White, ZnO	75 (24)	0.95
	White, MgCO3	75 (24)	0.91
	White, ZrO2	75 (24)	0.95
	White, ThO2	75 (24)	0.9
	White, MgO	75 (24)	0.91
	White, PbCO3	75 (24)	0.93
	Yellow, PbO	75 (24)	0.9
	Yellow, PbCrO4	75 (24)	0.93
Paints, Aluminum			
		100 (38)	0.27–0.67
	10% Al	100 (38)	0.52
	26% Al	100 (38)	0.3
	Dow XP–310	200 (93)	0.22
Paints, Bronze			
		Low	0.34–0.80
	Gum Varnish (2 coats)	70 (21)	0.53
	Gum Varnish (3 coats)	70 (21)	0.5
	Cellulose Binder (2 coats)	70 (21)	0.34
Paints, Oil			
	All colors	200 (93)	0.92–0.96
	Black	200 (93)	0.92
	Black Gloss	70 (21)	0.9
	Camouflage Green	125 (52)	0.85
	Flat Black	80 (27)	0.88
	Flat White	80 (27)	0.91

Material	Detail	Temp °F (°C)	Emissivity
Paints, Oil (continued)			
	Grey–Green	70 (21)	0.95
	Green	200 (93)	0.95
	Lamp Black	209 (98)	0.96
	Red	200 (93)	0.95
	White	200 (93)	0.94
Quartz, Rough, Fused			
		70 (21)	0.93
	Glass, 1.98 mm	540 (282)	0.9
	Glass, 1.98 mm	1,540 (838)	0.41
	Glass, 6.88 mm	540 (282)	0.93
	Glass, 6.88 mm	1,540 (838)	0.47
	Opaque	570 (299)	0.92
	Opaque	1,540 (838)	0.68
Red Lead			
		212 (100)	0.93
Rubber, Hard			
		74 (23)	0.94
Rubber, Soft, Grey			
		76 (24)	0.86
Sand			
		68 (20)	0.76
Sandstone			
		100 (38)	0.67
Sandstone, Red			
		100 (38)	0.60–0.83
Sawdust			
		68 (20)	0.75
Shale			
		68 (20)	0.69
Silica, Glazed			
		1,832 (1,000)	0.85
Silica, Unglazed			
		2,012 (1,100)	0.75
Silicon Carbide			
		300–1,200 (149–649)	0.83–0.96

Material	Detail	Temp °F (°C)	Emissivity
Silk Cloth			
		68 (20)	0.78
Slate			
		100 (38)	0.67–0.80
Snow, Fine Particles			
		20 (–7)	0.82
Snow, Granular			
		18 (-8)	0.89
Soil			
	Surface	100 (38)	0.38
	Black Loam	68 (20)	0.66
	Plowed Field	68 (20)	0.38
Soot			
	Acetylene	75 (24)	0.97
	Camphor	75 (24)	0.94
	Candle	250 (121)	0.95
	Coal	68 (20)	0.95
Stonework			
		100 (38)	0.93
Water			
		100 (38)	0.67
Waterglass			
		68 (20)	0.96
Wood			
		Low	0.80–0.90
	Beech, Planed	158 (70)	0.94
	Oak, Planed	100 (38)	0.91
	Spruce, Sanded	100 (38)	0.89