Technique	Thermography is the practice of quantitatively measuring radiative heat emissions from objects for predictive and preventative maintenance programs. Thermographic Inspection can be used to pinpoint components that are operating at a temperature higher than other components, indicating degradation, or to locate where energy losses are occurring such as in cryogenic fluid lines or steam pipes.
Thermography	***Reduces maintenance costs and enhances reliability***
Benefit	Use of thermography in predictive and preventative maintenance programs reduces equipment (both facility and GSE) down time, prolongs equipment life, prevents schedule impacts due to untimely failures, and increases availability. Mechanical or electrical breakdowns of components are often preceded by changes in normal operating temperature. Advance notice of developing problems results in cost savings by resolving them before catastrophic failure occurs that could also damage other associated components.
Key Words	Infrared, Thermography, Thermal Imaging, Failure Prediction, Corrective Action, Predictive Maintenance.
Application Experience	• Space Transportation System (STS) KSC Ground Support Equipment (GSE) and Facilities. • Electrical Substations, Electrical Panels, Cryogenic Fuel Lines, Electrical Connections. Electric Motor shafts, couplings, bearings, and insulation.
Technical Rationale	Infrared scanning is a nondestructive technique which can be performed while the equipment is operating so there is no need for machine downtime and lost production. Portable thermal imaging measurement systems provide images that can be stored on video recorders or built-in floppy disk drives for later recall during post analysis. Advance notice of developing problems means they can be resolved or repaired during normal machine shutdowns rather than after a catastrophic failure that would cause lost man-hours and possible damage to other components associated with the failed item.
Contact Center	**Kennedy Space Center (KSC)**

Thermography
Technique AT-9

Radiation Heat Transfer

Thermal radiation is the rate at which energy is emitted by matter as a result of its finite temperature. Radiation is emitted by all forms of matter above 0°K (degrees Kelvin), and is the result of thermally excited electron oscillations or transitions within the matter. Radiation is emitted from a solid or a liquid originating from the molecules that are within a distance of approximately 1 μm (micrometers) from the exposed surface. For this reason, thermal radiation is viewed as a surface phenomenon.

There are two theories that describe how thermal radiation leaves the surface of an object. In the first theory, radiation is viewed as the propagation of electromagnetic waves. The second theory views radiation as the propagation of a collection of particles called *photons* or *quanta.* In either case, radiation can be expressed in terms of the standard wave properties of frequency ν (units s^{-1}) and wavelength λ. The two properties, for radiation propagating in a particular medium, are related by:

$$\lambda = c/\nu$$

where c is the speed of light in the medium. In a vacuum, the speed of light is 2.998×10^8 m/s. The complete electromagnetic spectrum is shown in Figure 1.

The units of measurement for λ and μ or μm which stands for micrometers or microns. A micron is one-millionth of a meter and is the measurement for radiant energy wavelength.

Thermal radiation that is pertinent to heat transfer occurs in the portion of the spectrum which extends approximately from 0.1 to 100μm which includes a portion of the ultraviolet (UV), all visible, and infrared (IR) regions. The basis of thermography inspection is the measurement of radiation heat transfer from a body.

As a body temperature increases, more energy is radiated. High temperature targets radiate in the visible range of the electromagnetic spectrum. The visible range of the spectrum ranges from wavelengths of 0.4 μm for violet light to about 0.7 μm for red light. The sun, at a temperature of about 6000 K, appears to glow white hot, and an electric stove element appears red at a temperature of 800 K.

There are two physical laws that describe the radiant behavior illustrated in Figure 2. To describe the radiation characteristics of real surfaces, it is useful to describe the surface as a blackbody, an ideal surface. A blackbody is a perfect absorber and emitter and serves as a standard against which the radiative properties of actual surfaces may be compared.

In the first law, the temperature and wavelength of a blackbody surface can be related by Wien’s Displacement Law.

$$\lambda_{max} T = C$$

where the constant C = 2897.6 μm · K

The locus of points described by the law is plotted as a dashed line in Figure 2. According to Wien’s Law, the maximum spectral emissive power is displaced to shorter wavelengths with increasing temperature.

The second law describes how the amount of radiation energy emitted by a blackbody can be related to its temperature using the Stefan-Boltzmann law.

$$E = \varepsilon \sigma T^4$$

Where the numerical value of ε, emissivity (unitless), is dependent on the material property and is up to one for a blackbody, $\sigma = 5.67 \times 10^{-8}$ $W/m^2 \cdot K^4$, and temperature is in degrees Kelvin. Energy is in units of W/m^2. Thus the temperature of an object can be found by measuring the emitted thermal energy and from this temperature, T, can be calculated.

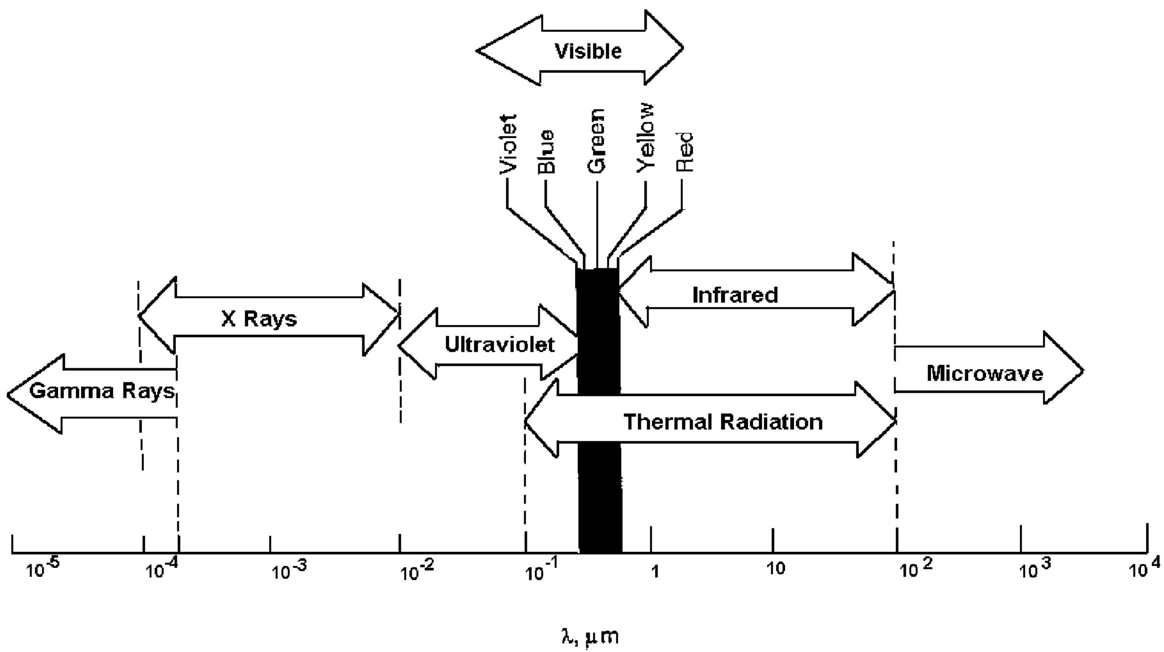

FIGURE 1. ELECTROMAGNETIC RADIATION SPECTRUM

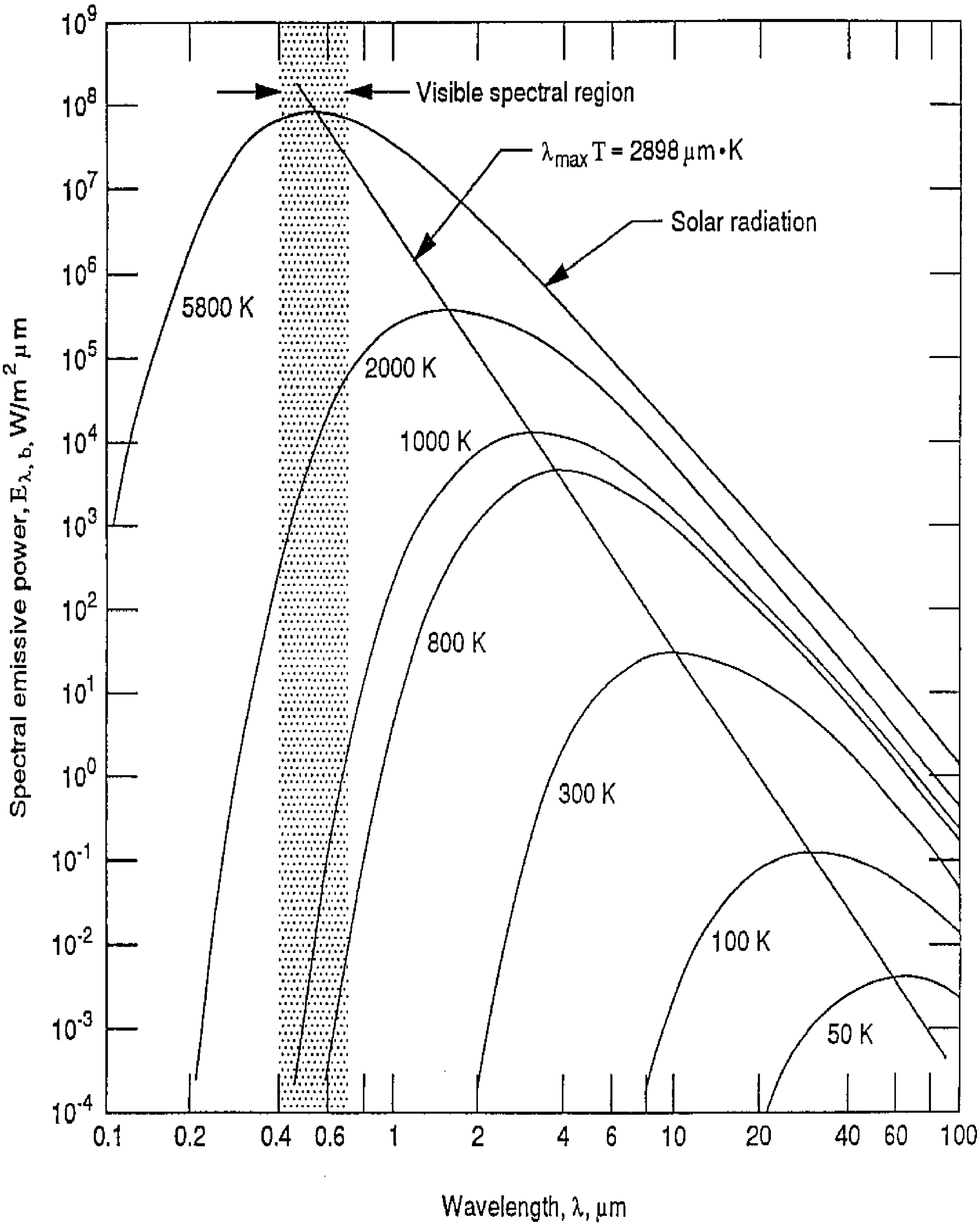

FIGURE 2. SPECTRAL BLACKBODY CURVES AT VARIOUS TEMPERATURES

Though the eye is incapable of sensing radiant energy,infrared detectors can measure the amount of radiant energy and convert this to electrical signals proportional to the temperature of the target surface. Instruments that combine this measurement capability with mechanisms such as optics for scanning a target surface are called infrared thermal images. These instruments produce thermograms which are pictures that show the brightness intensity or color hue on the body that is representative of the temperature of the body at different points.

The emissity value is dialed into the instrument. Emissivity value is dialed into the instrument. Emissivity values can be found from tables or charts. For industrial equipment inspection a value of 0.96 can be used with reasonable accuracy.

Figure 3 shows the primary components of an infrared radiation detector. When the infrared radiation thermometer is aimed at a target, the energy is collected and formed into a beam where the shape is determined by the optical configuration of the detector. A cross section of the beam is the field of view of what the instrument "sees" and the beam determines the size of the target surface measured by the instrument. Collecting optics focuses the beam onto the sensitive surface of an infrared detector and turns the energy into an electrical signal. The beam is called the "instantaneous field of view" and becomes one picture element on the thermogram.

Applications

- *Electrical*

Electrical applications represent the most straightforward application of the equipment and the most common findings are caused by high electrical resistance, short circuits, open circuits, or energized grounds (which can be life threatening).

HIGH ELECTRICAL RESISTANCE

The most common cause of hot spots in electrical equipment is resistance. Ohm's law states that the power dissipated in an electrical element is equal to the square of the current multiplied by the resistance ($P=I^2R$). If the current is constant and the resistance is higher than normal, additional power is dissipated and an increase in temperature results. This is always costly for the following reasons:

1. The connection dissipates power in the form of heat instead of useful work.

2. Increased resistance causes a loss in circuit efficiency requiring an increase in input power to maintain the load requirements.

3. The increase in temperature causes accelerated aging of the equipment resulting in earlier replacement.

4. Component failure due to overheating can cause delays (lost time).

Examples of resistive heating are loose connections, corroded connections, fuse banks, missing or broken conductor strands, undersized breakers or conductors.

Figure 4 shows a thermogram of an auxiliary air handling unit circuit breaker for Orbiter Processing Facilities 1 and 2. The target is where a wire connects. A vertical bar to the right of the thermogram shows different shades that corresponds to a different temperature on the thermogram image. Above the target, to the right of the vertical cross hair, is a light on the control panel that should be ignored.

An exact temperature of the target is given at 145° F shown on the bottom right, below the x and y coordinates (in millimeters), of the target. In comparison, the other breakers are at approximately 95° F determined by comparing the shade of the breaker terminal with the shades on the vertical temperature bar. The high temperature of the breaker developed from corrosion and loose connection. After the terminal was cleaned and tightened, the temperature was the same as the neighboring terminals.

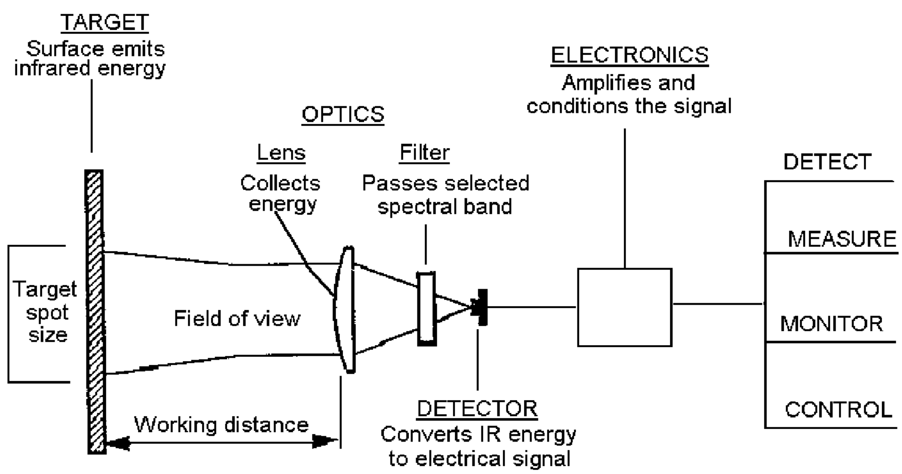

FIGURE 3. BASIC COMPONENTS OF AN INFRARED RADIATION THERMOMETER

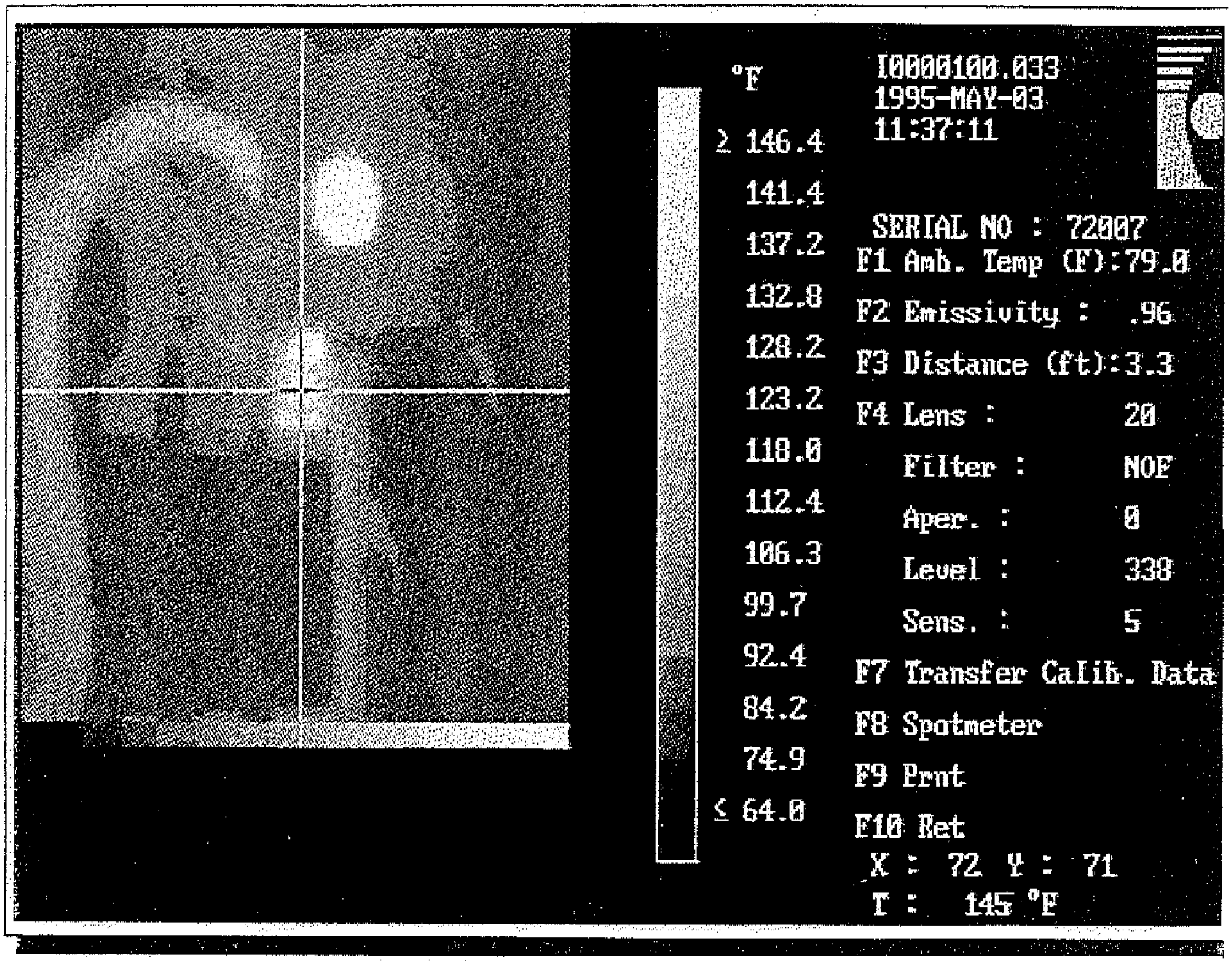

FIGURE 4. Auxiliary Handling Unit Breaker Panel Orbiter Processing Facility 1 and 2.

SHORT CIRCUITS

Short circuits are areas of high current flow in electrical equipment that results in heating of the area. For example, a shorted transformer winding would appear hotter than other similar devices. However, an operating element operating cooler than similar devices may indicate that there is an open circuit and the element is inoperative.

Motor windings are designed to operate at or below a designated temperature to provide adequate life. As a general rule, the insulation life is decreased by half for each 10 degree C temperature increase. Thermal effects result in swelling or general puffiness of the insulation. As the insulation degrades, this can cause the motor windings to short. An overheated motor can be identified by a temperature reading of the motor case.

ENERGIZED GROUNDS

Energized Grounds is a phenomenon that can be life threatening. Energized Grounds are, in most cases, extremely hot and can be easily detected with thermographic equipment. The problem with energized grounds is tracing the cause which may be elusive. The cause may be partial insulation breakdown of an operating element or the ground connection may be carrying induced currents due to an element in close proximity. Diagnosis usually requires considerable input from knowledgeable facilities personnel.

- ***Mechanical***

Mechanical anomalies that can be measured with thermographic equipment are classified in one of four categories; friction, pipe or valve blockage/leakage.

FRICTION

Most of these problems occur in rotating machinery and electric motors. Problems encountered include poorly lubricated or worn bearings and couplings, or misaligned shafts. Bearing spheres that become worn will begin to pit on the surface. The pitted bearing surface or poor lubrication causes friction as the spheres rotate on a shaft. Because a shaft may be rotating at several hundred rpm, heat will be generated. Thermographic imagining can identify which bearings need changing before failure occurs that can cause damage to other motor components such as the motor shaft.

The most likely causes of high bearing temperature are the following:

1. Misalignment. A misaligned shaft will result in unequal loading and cause heating at the point of highest mechanical resistance either at the bearing, coupling, or pulley/belt arrangement. Misalignment can be corrected using laser alignment.

2. Time and Use. Bearings eventually wear out. Maintenance records can determine when the equipment was originally installed or when the bearings were last replaced. Equipment used infrequently may cause the bearing lubricant to dry out causing increased friction.

3. Design. Bearings are designed to operate within a rpm range. If the number of rpm's go above this, they can heat up. For example, if a system is modified where the number of rpm's are increased such as a fan or blower system to deliver more air, the design parameters of the bearings should be considered to determine if they need to be changed.

4. Installation. The bearing should be checked for proper installation. If the bearing is misaligned, this can cause increased friction.

If left alone, increasing bearing temperature can lead to the lubricant breaking down causing increased friction, wear, and possible bearing seizure.

PIPE OR VALVE BLOCKAGE/LEAKAGE

Depending on the conditions blockages/leaks in fluid systems may be simple or involved. If the pipe or section is not covered with insulating material and if the temperature of the fluid is sufficiently different than ambient, then detection of a blockage or leakage is usually simple.

For example, when a hot fluid passes through a partially blocked valve, the temperature becomes elevated on the far side of the valve and can be observed thermographically by the temperature distribution across the valve. An elevated temperature on one side compared to the other side of the valve indicate blockage.

Another application is used on oil cooled power transformers. Blocked areas where oil transverses can cause the transformer to operate at a higher temperature. If the blockage is not corrected, this may cause premature failure of the transformer.

Similarly, if the fluid temperature is different than ambient temperature, valve or pipe leakage can be detected by a temperature differential at a small distance from the body.

Thermographic Equipment Type

Infrared Display, Qualitative or Quantitative

The simplest instruments only provide qualitative, i.e., cool/warm/hot/or hotter type image and no associated temperature. Handwritten notes must be used; although some units have an output jack to permit viewing on a Video Display Terminal (VDT) or the image can be fed into a Video Cassette Recorder (VCR). Other instruments have the capability to record the images and data on a floppy disk for input into a PC for further analysis. Other thermographic units have the capability for instant replay without the need for downloading into a VCR or VDT.

Images

Some units produce only black and white, others display in color, and some have the capability selection for either black and white or color. Color images provide quick-glance identification of differences in temperature profiles. However, color images do not necessarily provide more definitive information than black and white. While the number of discrete color palettes that can be incorporated into an imaging unit are limited, some black-and-white units can quantify the temperatures associated with as many as 256 shades of gray.

Temperature Operating Range

Thermographic scanners used for predictive maintenance have a temperature range that exceeds the demands of virtually any PM application. However, for extraordinarily high on low temperatures, the instruments temperature sensing range should be checked. Some units have a user selectable temperature scale range.

Ease of Use

Equipment operating complexity, instrument setup time, and extent of operator training should be considered. Another criteria is the equipment weight. Some units weigh less than 4 lbs.; others weigh over 10 lbs. Along with weight consideration is the camera size. If the inspection area is confined such as around machinery, a small hand held camera would allow imaging inaccessible to larger units.

Accessories and Special Features

- Lenses ranging from wide angle through telephoto.
- Pertinent information such as time, date, and temperature documented with the recorded image.
- Freeze-frame capability for capture and playback of moving scans.
- Moving crosshairs on the camera that allow zeroing in on a particular point and documentation of the points selected.
- User temperature range selection in either Fahrenheit or Celsius.
- User-adjustable setting to “flag” any temperatures in excess of the setpoint.
- Integral audio-recording that allows the image to be annotated with the voiced

observations of the operator.

- Software Options
  - Graph generation capability to plot progressively worsening conditions.
  - Capability for generating information of equipment history reports combining IR inspection with other information such as vibration analysis.
- “Windows” comparison and analysis capability from stored images with accompanying data.

Implementation

The baseline reference temperature for identified components can be established from manufacturers data. Another alternative is reference temperature can be established by examining local components or comparison with components at another location under similar operating conditions.

Inspection frequency for critical equipment may be more frequent than noncritical equipment. Trends may indicate that inspection frequency can be decreased. To determine priority of maintenance scheduling based on temperature rise, use the following guideline.

- Nominal, 0 to 10 deg C above reference - Failure is unlikely and the possibility of permanent damage is slight. Repair is deferred until the next survey period or planned outage.
- Intermediate, 10 to 35 deg C above reference - Indicates that failure and permanent damage is likely. The component should be repaired or replaced within 2 to 4 weeks.
- Serious, 35 to 65 deg C above reference - Indicates the possibility of permanent damage to the component and surrounding area. Certain failure is immediate and the component should be repaired ore replaced within the week.
- Critical, 65 deg C or more above reference - Indicates that component and surrounding area may have been damaged and failure is imminent. Immediate repair required.

Case Histories

The following are a sample of cases experienced at KSC where thermographic imaging has prevented untimely failures and saved money as a result of early detection.

At the Vertical Processing Facility (VPF), used to process vertical payloads, an overheating circuit breaker was detected using thermography inspection. The circuit breaker, located in a motor control center (MCC), supplies power to air conditioning in the VPF. If the circuit breaker failed, this would have interrupted the supply of conditioned air to the VPF and risking permanent damage to sensitive electronic components. The circuit breaker failure could have taken weeks to correct. Instead, the system was planned to be taken off line for about 20 minutes, and the breaker was replaced. The new breaker was retested under the same conditions and confirmed the problem was corrected.

A three phase breaker assembly feeding one of six pumps, supplying hydraulic fluid to the Shuttle during ground processing, was found to be operating higher than normal. The breaker was thoroughly cleaned. Upon reinspection, the breaker was found to be operating within normal capacity. A pump failure due to a failed breaker would have been costly because of the impact to numerous personnel due to an unscheduled shutdown.

Three hundred electrical panels were inspected at the Operations and checkout Building (O&C). Of the 300 panels, 180 defects, mostly loose connections, were found before they created problems later.

Thermography inspection found significant heat losses on the GN_2 Heater System piping used to prevent ice buildup before launch on the Shuttle External Tank (ET) oxygen Vent Line. Gaseous Nitrogen is heated and transmitted via piping to the oxygen vent hood on top of the ET (also known as the "Beanie Cap"). Heat losses were occurring through pipe mounting brackets and areas with insufficient insulation. Heat losses signify extra power consumption to heat the gaseous nitrogen and component duty cycle time. The problem was corrected by adding insulation to those parts that showed heat loss.

Summary of Predictive Maintenance Thermography Applications

The following is a summary and additional examples of equipment where Thermal Imaging inspection can be applied.

Electrical

- Poor contact at fuse clips, disconnect switch blades, busway stabs, motor starter, and relay movable contacts.
- Defective potheads, bushings, surge arresters, and other substation ancillary equipment.
- Defective circuit breakers and switchgear.
- Overheated motor or generator bearings or brush rigging.
- Blocked transformer cooling fins.
- Phase imbalances on three phase circuits.

General Mechanical

- Defective Bearings on all types of equipment.
- Excessive friction on sliding surfaces, i.e., belt/pulley, clutch, and brake slippage, improper gearing fit or lubrication.

Steam and Other Fluid Systems

- Faulty piping insulation.
- Valve leakage.
- Air Leaks (detected as excessive cooling).
- Blocked radiator fins; thermal distribution in cooling towers.
- Sedimentation or improper liquid level in tanks.

Facilities

- Heat/Air Conditioning loss through building envelope.
- Identifies trapped moisture in built-up roofs.

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