BUILDING ELECTRICAL SYSTEM
MAINTENANCE
THERMOGRAPHY

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1. SCOPE

1.01 This section provides the necessary guidance in the selection of equipment for and the measurement of electromagnetic energy in the infrared range. The purpose of such measurements is the determination of the temperature of electrical components and equipment such as busbar joints, conductor terminations, fuse holders, transformer and motor windings, and other apparatus.

1.02 Whenever this section is reissued, the reason(s) for reissue will be listed in this paragraph.

2. GENERAL

2.01 The presence of excessive heat in electrical equipment is a sign of potentially hazardous conditions. Excessive heat can be an indication of the following problems:

(a) Loose or corroded connections

(b) Defective components

(c) Worn equipment

(d) Unbalanced circuits

(e) Overloaded apparatus.

2.02 The measurement of heat in electrical equipment must be performed when the equipment is energized and operating under load. Under such conditions, measurements made using a contact-type thermometer may be difficult. However, the use of infrared heat detecting equipment allows such measurements to be made without physically touching the equipment.

2.03 An understanding of the infrared theory is essential to the proper application of thermography equipment and interpretation of the resultant measurements.

3. INFRARED THEORY

3.01 Thermography is the technique for detecting and measuring variations in the heat emitted by various objects and transforming these variations into visible signals that can be recorded photographically. The term thermography has been loosely used to describe the broader technique of infrared heat detection which achieves either a photograph or a value of temperature of the object in question.

3.02 The temperature of an object is a way of describing the energy state of the object. The higher the temperature of an object, the higher the energy state or molecular excitation of the object. There is a temperature, called absolute zero, which is defined as the temperature at which all material is in its lowest energy state. All material above absolute zero radiates electromagnetic energy due to its molecular excitation.

3.03 Electromagnetic (e-m) radiation is wave-like in nature and is characterized by its wave-

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length or frequency. The electromagnetic spectrum is the arrangement of all types of e-m radiation according to their wavelength as shown Fig. 1.

3.04 The wavelength of e-m energy radiated by objects at so called "earth temperatures" (from about 40°F to 120°F) starts at 2.5 microns (1.2×10^{14} Hz) and runs to about 10 microns (0.3×10^{14} Hz). The region between 2.5 microns and 100 microns is commonly referred to as thermal infrared.

3.05 Electromagnetic radiation can be transmitted, reflected, and absorbed by all material. The relative amounts of energy transmitted, reflected, and absorbed depends upon how the e-m radiation interacts with a given material. Both the nature of the material and the nature of the e-m radiation must be considered. For the purpose contained herein, characterizing the radiation by wavelength will be adequate.

3.06 The ability of an object to absorb e-m energy at a given wavelength equals the ability of that object to emit e-m energy at that wavelength. The term emissivity (ε) refers to the efficiency of an object to emit e-m energy. For most materials, the emissivity for all wavelengths in the thermal infrared region is listed as a constant value. (See Table A and Table B.) Only by accounting for the emissivity of a material can a thermographic instrument be calibrated to read temperature directly as the instrument reads both the energy emitted and the energy reflected by an object.

4. THERMOGRAPHIC EQUIPMENT

4.01 The human eye can see objects by the e-m energy that is ***reflected*** by the object, while infrared sensing instruments "see" objects by the e-m energy that is ***emitted*** by the object. While the human body can sense heat radiation (e-m energy emitted by an object), infrared heat sensing instruments are much more sensitive to heat radiation. Some instruments form an image by converting the invisible heat radiation to visible light. Some scan a single line across an object and portray the heat radiation graphically. (See Fig. 2.) Others view a single spot on the scene and convert the heat radiation from that spot into a "temperature." Each type of instrument has its own advantages for a given application. What each type measures, how they work, their limitations, and their application must be understood to properly apply infrared heat sensing equipment in an electrical equipment maintenance program.

4.02 There are two major design components for thermal radiation instruments:

1. Radiometric
2. Geometric.

The radiometric component deals with the type of detector. Detector properties include wavelength sensitivity (ie, what part of the e-m spectrum the detector covers), speed of response, and output (detector change for a given amount of thermal radiation). The geometric component deals with the collecting optics and, if applicable, the display. To provide a structured format, the thermal instruments have been categorized by their geometric component. The geometric categories are:

(a) Spot Radiometers (zero-dimensional)

(b) Line Radiometers (one-dimensional)

(c) Imaging Systems (two-dimensional).

A well-designed instrument will have the proper radiometer component (detector) for the type of sensing geometry employed, ie, an imaging type system must have a faster detector response time than a spot reading system.

Resolution

4.03 A geometric property common to all categories is ***resolution*** (the size spot an instrument sees at a given instant). Resolution is usually given as an angle, or an angular field of view (FOV). This means that the size spot the instrument sees depends on the distance between the instrument and the target. The spot size increases with increasing distance between the target and the radiometer, the exact spot size depending on the angular FOV, θ. A chart of spot size versus target distance is usually available from the equipment manufacturer. The spot size is for viewing the target straight-on; that is, target surface is perpendicular to the line-of-sight of the instrument.

Radiometric Accuracy and Stability

4.04 The radiometric accuracy and stability of any thermographic instrument affects the accuracy of determining temperatures. Two areas relevant to radiometric stability are detector temperature and electronic drift. As the temperature of the operating environment of the instrument changes, the temperature of the detector will also want to change. Electronic drift presents another stability problem as radiometric detector signals must be highly amplified.

5. SPOT RADIOMETERS

5.01 In its simplest form, a spot radiometer collects the radiant energy coming from the target through a lens and focuses it on a detector. The detector converts the radiant energy into an electrical signal which is amplified by solid-state electronics. The amplified signal drives a meter providing either an analog or a digital readout.

5.02 Instrument price varies from about $700 to about $7,000. Devices are portable and usually hand held. Some have an attached telescope to enable the user to precisely select the target. Depending on the application, this can be a very important feature. The readout is in degrees Celsius (C) or Fahrenheit (F), although these instruments do not measure temperature directly.

5.03 Some spot radiometers have an adjusting knob to compensate for emissivity variations. The operator obtains the appropriate emissivity from a table of values and dials it in. ***The temperature and emissivity of the surroundings are very important when measuring temperatures with a spot radiometer.*** For example, a low emissivity material such as aluminum at room temperature will give a radiometer reading close to room temperature. However, only part of the radiometer reading is influenced by the actual temperature of the aluminum; the remainder is reflected energy, influenced by the temperature and emissivity of the surroundings. Taking the same piece of aluminum outside where the air temperature is the same as room temperature will produce a much different reading, especially under a clear sky. In this case, the radiometer sees the ***emitted*** energy from the aluminum (room temperature) plus the ***reflected*** sky energy (90°F or colder than room temperature). Thus, a material whose actual temperature is constant can give extreme radiometer variations (10°F or more) depending on the surroundings. An emissivity dial on a radiometer can magnify the error if the effects of the surroundings are not carefully considered. If the target temperature is much higher than the surrounding temperature (eg, 500°F versus 50°F), the reflected energy will usually be negligible. In this case, instrument correction for target emissivity is viable.

5.04 Because radiometers are unable to measure actual surface temperatures directly, the term ***apparent temperature*** is defined as the surface temperature of an object as read by a radiometer. The apparent temperature equals the actual surface temperature for a blackbody. Usually, the apparent temperature does not equal the actual temperature. For many applications, only changes in the target temperature are important. If the background (surrounding) temperature remains constant, the spot radiometer will accurately detect changes in target temperature.

5.05 Since there are a wide variety of instruments on the market, general rule-of-thumb comments concerning temperature accuracy can be made:

- Under $1000—apparent temperature accuracy is usually about ±6°F.
- Between $1000 and $5000—apparent temperature accuracy is about ±3°F.
- Over $5000—apparent temperature accuracy is about ±0.5°F.

These costs are for portable devices. Laboratory instruments can be much more accurate. If an instrument manufacturer's claims are widely different than these rule-of-thumb accuracies versus cost, the following questions should be asked to find out how they achieve it:

- How does the instrument compensate for ambient temperature fluctuations of the detector?

  Possible ***Correct*** Answers:

  1. Dual detector differencing
  2. Temperature controlled detector cavity
  3. Constant temperature reference — chopped with target
  4. Combinations of the above.

  Possible ***Incorrect*** Answers:

1. Instrument is calibrated to external reference

2. It is not an important consideration.

- How does the instrument compensate for sensitivity of electronic components to ambient temperature fluctuations?

Possible ***Correct*** Answers:

1. Instrument uses ac electronics—There must be a constant temperature reference which the detector periodically sees (sometimes called chopper stabilization).

2. Expensive low drift dc electronics are employed—State-of-the-art amplifiers can approach the necessary temperature stability but are about five times more expensive than those commonly used.

Possible ***Incorrect*** Answers:

1. Instrument is calibrated to an external reference.

2. It is not an important consideration.

These are answers to questions regarding ***apparent*** temperature accuracies approaching or better than ±1°F. If ***actual*** temperature accuracy of ±1°F is desired, emissivities must be considered. The instrument ***cannot*** correct for emissivity variations without considerable operator assistance.

5.06 To determine the maximum spot size, one might assume a spot size equal to the smallest spot of interest. This may be optimistic, depending on the temperature contrast between the background and the target and the shape of the target. For temperature ***measurements,*** the maximum working distance should be chosen to provide a spot size about 1/4 the target size. The reason for the target size being larger than the spot size is associated with the inherent spread of the signal, which is due to the optical system and finite detector size. The 1/4 factor is based on experience and can be considered a conservative rule-of-thumb estimate. Actual values can be obtained for a given instrument through proper experimentation.

> ***Note:*** The target size definition for temperature measurement is a surface of uniform emittance and constant temperature.

5.07 As with any instrument, proper selection of the output is very important. For portable spot radiometers, a simple meter readout is typical. The scale on the meter should be easy to read and sensitive enough to not limit instrument accuracy. The latter sounds obvious but sometimes, for the sake of convenience and cost, the apparent temperature accuracy is limited by the ability of the operator to read the meter scale. On the other hand, this constraint (properly applied) can give the user an idea of the expected uncertainty in apparent temperature readings.

5.08 The environment in which the instrument will be used should also be considered. An operator forced into an awkward position in a dark location can be frustrated just trying to read the instrument output. Some manufacturers provide digital light emitting diode (LED) or liquid crystal diode (LCD) displays. The digital output is easy to read even in poorly illuminated environments. Also, there are fewer incorrect readings with digital outputs than with analog-type meters.

6. LINE RADIOMETERS

6.01 A line-scanning radiometer can be thought of as a spot radiometer with additional optics which move the spot across the target. The visible scene passes through the scanning mirror and is viewed by the operator. The scanning mirror performs a dual function. It reflects the thermal energy from the scene onto a thermal infrared detector, and it simultaneously reflects a LED signal off its back side to be superimposed on the visual image. The LED signal is derived from the output of the thermal detector. It provides a graphical display of the amount of thermal radiation coming from a line across the scene. The operator sees and can photograph this graphical display superimposed over a visual image of the scene.

6.02 Figure 2 shows a typical display. The squiggly line (A-trace) is the LED output representing the apparent temperature variations along a line in the scene shown by the almost solid lower line or baseline. The height above the baseline varies with the apparent temperature along the baseline. (The term ***A-trace*** means amplitude-modulated analog single-line scan.) The base line is clamped to the coldest temperature in the scan, so the LED display is at or above it. Several apparent temperature ranges from 10C° to 1000C° can be selected. To view details of a hot area, the LED signal can be offset and a lower range selected. For example, an A-trace with a hot peak 80C° above the coldest point in the scan would ordinarily be observed on the 100C° range. This peak can be offset and the range switched to 10C° to observe variations in the peak temperature. [Although often neglected, there is a real difference between °C (degrees Celsius) and C° (Celsius degrees). The first implies an absolute temperature; the second a temperature difference.]

6.03 To measure apparent temperatures, a polaroid picture is taken of the scene and A-trace. Clear plastic overlays with the apparent temperature in C° for each temperature range are used to calibrate the A-trace in the photo. Apparent temperature ***differences*** for points on the A-trace can then be found. Frequently, the differences in apparent temperatures is all that is desired. To tie these temperature differences to the rest of the world, additional measurement is required. One point on the object along the baseline measured with a spot radiometer generally suffices.

6.04 Considerations must be given to reflections from surroundings when attempting the calculation of actual temperatures from apparent temperatures. Apparent temperature differences on the A-trace can be attributed to differences in:

- Actual temperature
- Target emissivities
- Reflected energy.

6.05 The advantage of the line radiometer is spatial registration of the thermal data and the visual image. However, considerable skill is necessary to properly locate and interpret thermal images. An ordinary photograph of the same scene can ease these difficulties to a degree, but to become a good thermal image interpreter requires experience.

7. IMAGING RADIOMETERS

7.01 There are two approaches to portable thermal imaging systems. The first, which will not be discussed, is the pyroelectric vidicon (PEV) system. The second is the solid-state detector system, also called an infrared camera. In all these instruments, the target scene is scanned both horizontally and vertically. This is achieved in one manufacturer's device by two silicon prisms rotating at right angles to each other. The horizontal scanning prism rotates at a speed of 200 rps (12,000 rpm), 100 times faster than the vertical scanning prism. This high scan rate requires a fast-response detector necessitating use of a solid state materials such as Indium-Antimonide (InSb) or Mercury-Cadmium-Telluride (HgCdTe). These detectors must be cryogenically cooled to perform properly. Most systems employ liquid nitrogen (LN_2) to cool the detectors.

7.02 The operational waveband is determined by the detector and an infrared filter. The most popular wavebands correspond to two atmospheric windows (where atmospheric effects are minimal). InSb is used for the 2- to 5.6-micron atmosphere window and HgCdTe for the 8- to 14-micron window. The electrical output of the detector depends on the amount of thermal infrared radiation impinging upon it. The detector output is amplified and electronically processed to form a visual image. One typical method of image formation is to scan the signal across a cathode ray tube (CRT) similar to producing a television picture. The horizontal sweep corresponds to the horizontal scanning prism, the vertical sweep to the vertical scanning prism. Tonal variations on the screen correspond to signal voltage variations (changes in radiant energy incident on the detector). Usually, the lighter tones correspond to higher apparent temperatures. The number in the upper left-hand corner is the approximate apparent temperature range in Celsius degrees. The scale on the left-hand side may be accompanied by a color bar. This scale multiplied by the temperature range gives an indication of the apparent temperature difference for each color.

7.03 Lighter tones corresponding to higher apparent temperatures are used so frequently in black and white thermograms that it is almost conventional. However, the image can be reversed. That is, darker tones can be made to correspond to higher temperatures. Other processing techniques are sometimes used to enhance or clarify the thermogram.

7.04 As with the line radiometer, a drawback of black and white thermal images is the difficulty in evaluating apparent temperature differences. Color enhancement can be used to overcome this problem. The apparent temperature range for a given thermogram is segmented or sliced into several (ten is typical) discreet levels. A color is assigned to each level, and the resulting image formed on a color video screen. For example, with an instrument range setting of 10C°, each color would correspond to an apparent temperature difference range of 10C°. One problem with the slicing technique is that it is impossible to tell the begining, middle, or the top of a step as it is all one color. The color patterns on the thermogram can be used by an interpreter to determine roughly where a point is within each color. That is, if one step is blue and the next green, areas where blue changes to green will be near the top of blue and the bottom of green.

7.05 There are two disadvantage to color enhancement. Additional (and expensive) equipment is necessary to produce color-sliced images, and the physical nature of the image is much more difficult to discern. The latter can be overcome by using an ordinary photo, black and white thermogram, and color-sliced thermogram of the same scene for a comparative interpretation.

7.06 Isothermal contouring is another way of increasing the interpreter's ability to extract information from a black and white thermogram. The operator selects a narrow voltage range. This voltage range is converted to a higher voltage, which produces white on the screen. (Ordinarily, the selected voltage would produce a shade of gray.) Manipulation of the contouring voltage range and level allows the operator to produce white lines on the thermogram, which are essentially isothermal contours for a given temperature level. Only one temperature at a time can be contoured. There is usually an indicator showing the apparent temperature level being contoured.

7.07 ***As with the line radiometer, solid-state imaging systems portray apparent temperature differences.*** An additional measurement must be made to determine their absolute values. Either color enhancement or isothermal contouring can be used to compare the measured apparent temperature (reference) with the rest of the scene. For color enhancement, the width of the color bar gives the approximate uncertainty in apparent temperature. With isothermal contouring, the apparent temperature uncertainty is shown by the width of the contouring interval. This is usually about 1 to 5 percent full scale.

7.08 The accuracy with which the reference apparent temperature is measured must also be considered. The instrument which is used to measure the reference temperature should have the same waveband response as the imaging system. That is, an imaging system sensitive in the 2- to 5.6-micron waveband would require a radiometer sensitive in the 2- to 5.6-micron waveband. Use of a black and white thermogram for quantitative temperature measurement is not recommended.

7.09 Imaging systems have a much smaller resolution than spot radiometers. Since imaging systems scan across the scene, the resolution is often called the instantaneous field of view (IFOV). The IFOV of an imaging system can be compared to the FOV of a spot radiometer. For example, the resolution of an imaging system might be in the range of 5 milliradians to 1 milliradian. (A milliradian is one-thousandth of a radian or about 0.06°.) Thus, the resolution is about 10 to 30 times smaller than for a 2° FOV radiometer.

8. APPLICATION

General Methodology

8.01 Application for a thermographic survey exists wherever a surface temperature differential indicates an abnormal condition. Any maintenance program designed to use thermography as a method of determining potential problem areas must ensure that all measurements are made with the equipment energized and operating under load. It is advantageous to survey the electrical system under peak load; however, a formula is available to determine the maximum temperature rise based on the percentage of load at the time the survey is taken.

8.02 A thermographic survey can be performed without interruption of service and during normal working hours. The survey should include the complete electrical system, ac, dc, and standby power from the incoming cables downstream to the local distribution panels, including the motor control centers and busways.

8.03 The survey should be made by a qualified operator who is trained to interpret the image on the monitor screen or through the viewer. Several national companies offer a complete thermographic scanning service. The service includes the survey by a trained operator; a pictorial report with captions which describe the temperature variations and possible causes.

8.04 Real Estate Management shall arrange to provide a thermographic survey on all new buildings and significant electrical additions and/or rearrangements in existing buildings prior to final acceptance of equipment. It is also beneficial to perform a thermographic survey of the electrical system prior to a scheduled switchgear maintenance routine (approximately 5-year intervals), or when an abnormal condition is suspected. A thermographic survey made prior to a scheduled switchgear maintenance program will offer advanced knowledge of potential trouble areas and may greatly reduce or eliminate the need to tighten or torque all connections and bus joints. A copy of the report shall be furnished to the Switchgear Coordinator.

8.05 There are many items to be considered before purchasing thermographic equipment, ie, costs, estimated usage, ease of handling, sensitivity, temperature range, field of view, quality of the picture, storage of equipment, transportation of operator and equipment between locations, and the training of qualified operators. There is a variety of thermographic equipment available, but the cost (training of operators) and usage may not warrant its purchase.

8.06 In a majority of the cases, the need for actual surface temperature is not necessary. All that is required is a temperature difference or temperature rise above ambient. This is the case with cable terminations, busbar and busway joints, switchblade and circuit breaker contacts, and fuse clips. For these items, a measurement of temperature rise will show bad connections.

8.07 The following criteria determines the priority of maintenance scheduling based on temperature rise above ambient or adjacent material:

TEMPERATURE RISE	REMARKS
0 to 10°C	Corrective measures should be taken at next maintenance period.
10 to 20°C	Corrective measures required as scheduling permits.
20 to 30°C	Corrective measures required as soon as possible depending upon the class of load carried and the severity of temperature rise in this range.
30°C and over	Corrective measures required immediately.

The above criteria have been determined by past field experience and should be used as a guideline for maintenance scheduling. Final decision as to priorities and order of maintenance should be determined by the degree of temperature rise and criticality of the equipment involved.

Spot Radiometers

8.08 Spot radiometers are useful for qualitative surveys where temperature differences give clues to improper construction or operation. They can also be used for temperature measurement if proper consideration is given to the emissivity of the surroundings. Best results are obtained when:

- Target has a high emissivity.
- Target temperature is much greater than surroundings temperature.

Frequently, the limitation of target emissivity coupled with background reflections can be circumvented by judicious application and/or calculating corrections.

8.09 Typical applications include measurement of bus-joint temperature rise by comparing joint temperature to bus temperature in area where bus and joint are readily visible for direct measurement. Similar methodology can be emplored for conductor terminations where the terminations are visible. Where such connections are not visible and any heat the junction might generate is diffused through insulating or other material, the spot radiometer may not provide readings sufficient to indicate potential problems. Such would be the case with circuit breaker contacts or busway joints obscured by metal enclosures.

Line Radiometers

8.10 The line radiometer can be used for most applications where a thermal infrared camera could be used. The lack of cryogenic cooling allows the instrument to be oriented in any direction. One advantage line radiometers have over imaging systems is that the information is easier to interpret. Temperature variations are more difficult to determine from tonal variations (shades of gray) than from a graphical display. The trade-off is that there is less thermal information per image as there is one line instead of 60 to 250. For many applications, one line is sufficient. By knowing where to look, additional time need not be spent finding the right line on the scene. There are instances, though, where thermal patterns are important and where much additional time would have to be spent with a line radiometer to locate a flaw.

8.11 The advantages of spot and line radiometers are:

(a) Compared to imaging radiometers, they are less expensive and usually weigh less.

(b) They are noncontact devices; inaccessible areas can be monitored; monitoring can be done rapidly without destructive testing or dismantling.

(c) Detectors need not be cooled as in most imaging systems.

8.12 The disadvantages of spot and line radiometers are:

(a) They do not measure temperature directly, although the display is in degrees. They measure apparent temperature. A good understanding of thermal radiation is necessary to properly interpret these readings.

(b) The less expensive instruments are overly sensitive to instrument temperature fluctuations.

(c) Imaging systems are better at discerning real target temperature variations from anomalous reflections caused by the target.

(d) Identification of the target can be difficult.

(e) The field of view often limits the target distance, especially for small targets.

Imaging Radiometers

8.13 There are many applications of portable thermal imaging systems. In general, thermal imaging systems are problem-finding tools where the clues are surface temperature patterns; that is, to ascertain a defect or malfunction, thermal anomolies must be present on the ***surface***. It is possible for a thermal disturbance to be buried so deeply within a structure that it has diffused by the time it reaches the surface. The problem may be functional, structural, or operational.

8.14 Most applications could also be handled by a spot radiometer or line radiometer. Careful attention must be paid to spatial resolution constraints. Readings must be taken a lot closer to the target with a spot radiometer than with a line or imaging system. When looking for functional defects, ie, maintenance problems, first obtain data under proper operating conditions. For a spot radiometer, this could be a graph of apparent temperatures. When this reading changes significantly, look for a functional problem. By observing the same device under the same operating and environmental conditions, a performance record can be obtained. Then the thermographic instruments can be used as a preventive maintenance tool. For such periodic measurements, correction of the apparent temperature is not needed unless, of course, the surface being monitored or the surrounding environment is altered. What is desired is a thermal change due to deterioration or malfunction of a device.

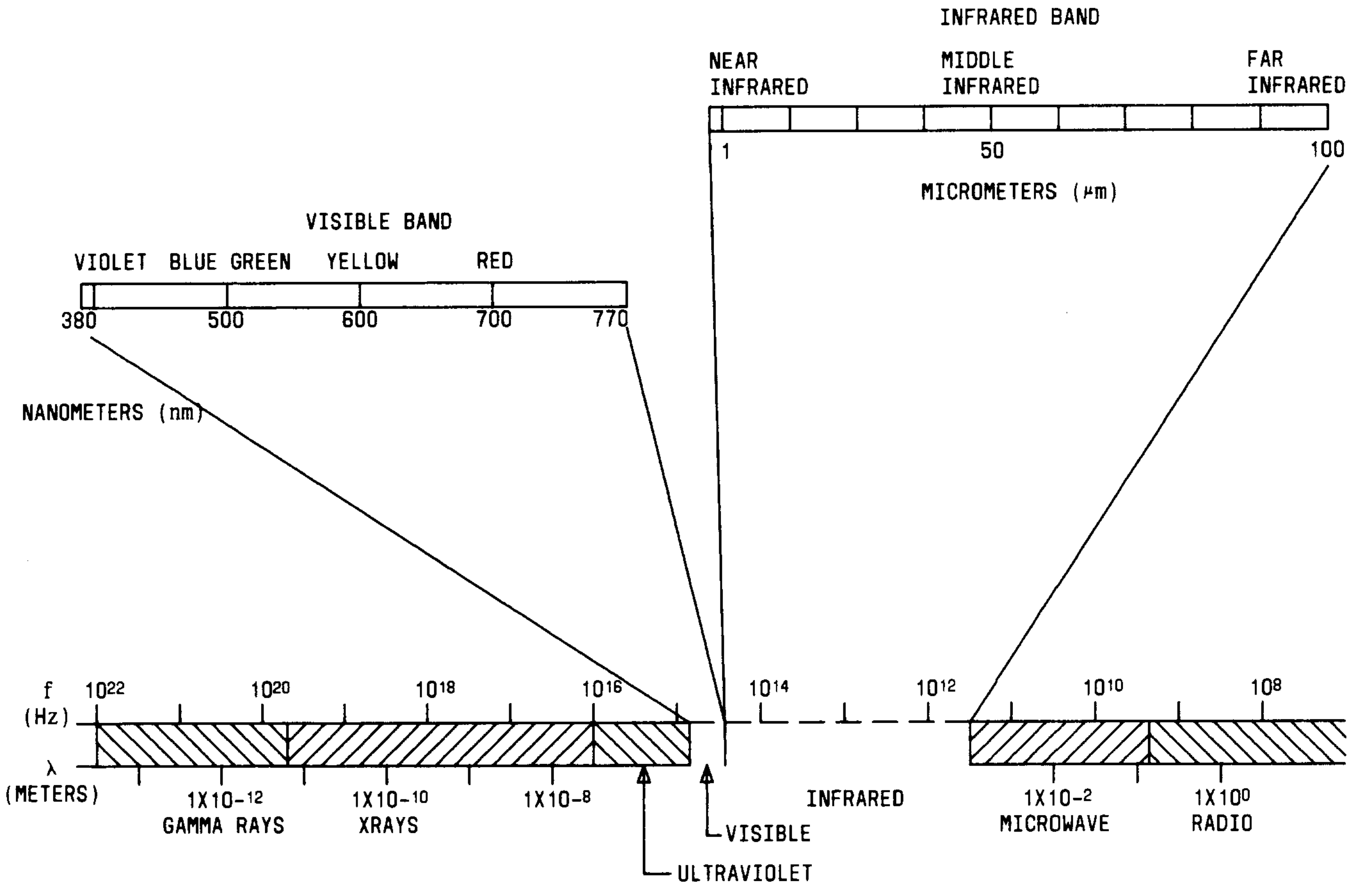

Fig. 1—Electromagnetic Spectrum

TABLE A

NORMAL TOTAL EMISSIVITY OF VARIOUS SURFACES METALS AND THEIR OXIDES

SURFACE	T,°F	EMMISSIVITY,ϵ
Aluminum:		
Highly polished plate, 98.3% pure	440-1070	0.39-0.057
Commercial sheet	212	0.09
Heavily oxidized		0.20
Brass:		
Highly polished	530	0.030
Hard-rolled, polished, but direction of polishing visible	70	0.038
Copper:		
Polished	212	0.052
Plate, heated long time, covered with thick oxide layer	77	0.78
Gold, pure, highly polished	440-1160	0.018-0.035
Iron and steel (not including stainless):		
Steel, polished	212	0.0666
Iron, polished	800-1880	0.14-0.38
Cast iron, newly turned	72	0.44
Mild steel: A	450-1950	0.20-0.32
Oxidized surfaces:		
Iron plate, pickled, then rusted red	68	0.61
Iron, dark gray surface	212	0.31
Sheet steel with strong, rough oxide layer	75	0.80
Lead:		
Unoxidized, 99.96% pure	260-440	0.057-0.075
Gray oxidized	75	0.28
Oxidized at 300°F	390	0.63
Magnesium, magnesium oxide	530-1520	0.55-0.20
Nickel:		
Polished	212	0.072
Nickel oxide	1200-2290	0.59-0.86
Nickel alloys:		
Copper nickel, polished	212	0.059
Platinum: polished plate, pure	440-1160	0.054-0.104
Silver:		
Polished	100-700	0.022-0.031
Stainless steels:		
Polished	450-1725	0.54-0.63
Tin, bright tinned iron	76	0.043 & 0.064
Tungsten, filament	6000	0.39
Zinc, galvanized sheet iron, fairly bright	82	0.23

For more detailed information, refer to J. P. Holman's ***Heat Transfer***, second edition, McGraw-Hill, New York, 1968.

TABLE B

NORMAL TOTAL EMISSIVITY OF VARIOUS SURFACES REFRACTORIES, BUILDING MATERIALS, PAINTS, AND MISCELLANEOUS

SURFACE	T,°F	EMISSIVITY,ε
Alumina (85-99.5% Al_2O_3,)-12% SiO_2, 0-1% Ge_2O_3); effect of mean grain size, microns ( ):		
10		0.30-0.18
50		0.39-0.28
100		0.50-0.40
Abestos, board	74	0.96
Brick:		
Red, rought, but on gross irregularities	70	0.93
Fireclay	1832	0.75
Carbon:		
Filament	1900-2560	0.526
Rough plate	212-608	0.77
Lampblack, rough deposit	212-932	0.84-0.78
Concrete tiles	1832	0.63
Enamel, white fused, on iron	66	0.90
Glass:		
Smooth	72	0.94
Pyrex, lead, and soda	500-1000	0.95-0.85
Paints, lacquers, varnishes:		
Snow-white enamel varnish on rough iron plate	73	0.906
Black shiny lacquer, sprayed on iron	76	0.875
Black shiny shellac on tinned iron sheet	70	0.821
Black matte shellac	170-295	0.91
Black or white lacquer	100-200	0.80-0.95
Flat black lacquer	100-200	0.96-0.98
Aluminum paints and lacquers:		
10% A1, 22% lacquer body, on rough or smooth surface	212	0.52
Other A1 paints, varying age and A1 content	212	0.27-0.67
Porcelain, glazed	72	0.92
Quartz, rough, fused	70	0.93
Roofing paper	69	0.91
Rubber, hard, glossy plate	74	0.94
Water	32-212	0.95-0.963

For more detailed information, refer to J. P. Holman's ***Heat Transfer***, second edition, McGraw-Hill, New York, 1968.

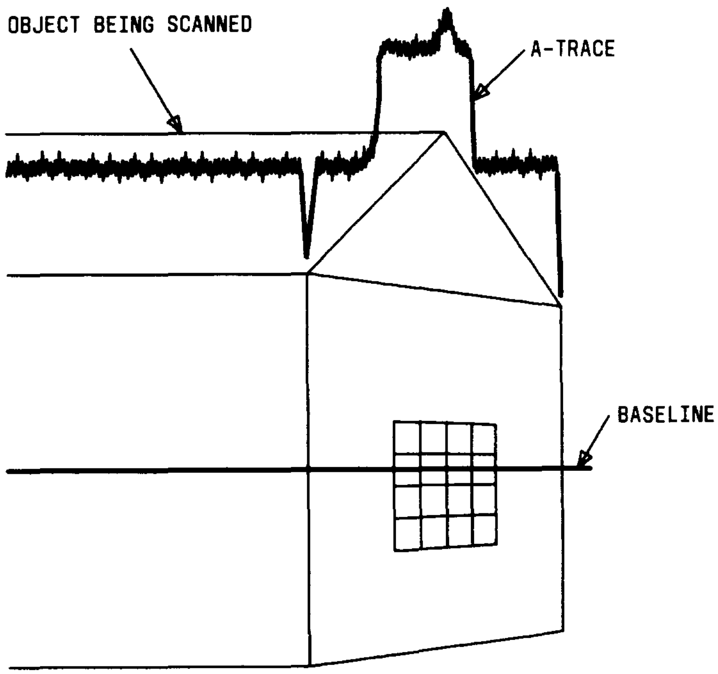

Fig. 2—Line Radiometer Display