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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TOP 1-1-058	2. GOVT ACCESSION NO. AD-A122177	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) US ARMY TEST AND EVALUATION COMMAND TEST OPERATIONS PROCEDURE "TEMPERATURE-MEASURING DEVICES"		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US ARMY ABERDEEN PROVING GROUND (STEAP-MT-M) ABERDEEN PROVING GROUND, MARYLAND 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DARCOM-R 310-6
11. CONTROLLING OFFICE NAME AND ADDRESS US ARMY TEST AND EVALUATION COMMAND (DRSTE-AD-M) ABERDEEN PROVING GROUND, MARYLAND 21005		12. REPORT DATE 30 November 1982
		13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DTIC ELECTE DEC 7 1982 S D B

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Pyrometers
Temperature-measuring Devices
Thermal Imaging System
Thermometers

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Describes various temperature-measuring devices used in conducting tests of Army materiel subjected to a range of temperatures to ensure functioning in all environments.

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US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

DRSTE-RP-702-100
*Test Operations Procedure 1-1-058 30 November 1982
AD No.

TEMPERATURE-MEASURING DEVICES

Page

1. SCOPE. This TOP describes various temperature-measuring devices used in conducting tests of Army materiel subjected to a range of temperatures to ensure functioning in all environments. These devices are also used to measure the temperature of the environment itself.

2. INTRODUCTION. Four temperature scales are currently used (see Figure 1). Reference positions on these scales are called fixed points because they are easily reproducible and under standard conditions, produce the same effect. The two most commonly used are the Celsius scale (°C) and the Fahrenheit scale (°F). The other two are absolute temperature scales wherein 0° is absolute zero: the Kelvin scale (°K) and the Rankine (°R); 1° K = 1° C, and 1° R = 1° F, but the reference positions are different. In order to convert Fahrenheit to Celsius or vice-versa, use the following formulas:

$$°F = (°C \times 1.8) + 32$$
$$°C = (°F - 32) \div 1.8$$
$$°R = °F + 460$$
$$°K = °C + 273$$

*This TOP supersedes MTP 4-1-002, dated 7 June 1968.

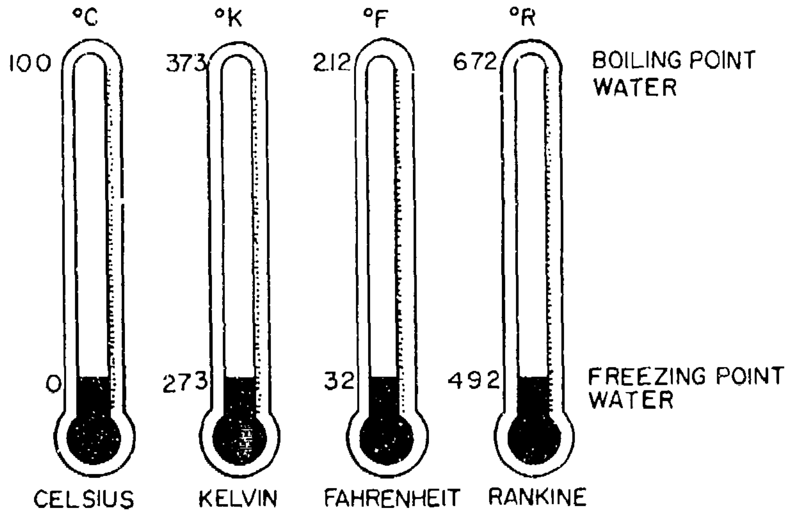

Figure 1. Comparison of fixed points on temperature scales at atmospheric pressure.

2.1 Heat. The control of heat flow is a major activity in calibrating heat-sensitive devices and their use in measuring. Since temperature is a measure of the relative heat of different bodies, it determines the direction in which heat transfer takes place. Heat always "flows" from a warmer body to a cooler body. This flow can occur by any the following methods.

a. Radiative Heat. This energy exchange occurs in the absence of direct contact and depends, to a large extent, on the temperature level of the process. The exchange is accompanied by a conversion of thermal energy to energy in the electromagnetic spectrum. When absorbed, this electromagnetic energy is partially or completely transformed into thermal energy. See TOP 2-2-812[1*] for further information on radiant heat in the IR region.

b. Convection. This is the process by which heat is transferred through a fluid (either a gas or a liquid). Free convection occurs because of differences in density. Forced convection occurs in a fluid that is moving due to influences other than convection currents.

c. Conduction. This is the process by which heat is transferred within a solid medium due to direct intra-molecular transfer of thermal energy.

3. TEMPERATURE-MEASURING DEVICES. Actual devices for measuring temperature fall into three categories: 1) when the body whose temperature is to be measured serves as its own thermometer; 2) when a solid thermometer element is inserted into the body; and 3) when the temperature-measuring device or pyrometer operates at a distance by sensing radiation emanating from the body.

*Footnote numbers correspond to reference numbers in Appendix B.

3.1 Liquid-in-Glass Thermometer. Nearly all substances expand when their temperature is raised. This thermometer employs the volumetric expansion of a liquid contained in a thick-walled glass tube with a capillary bore (stem). The bulk of the liquid supply is kept stored in a glass bulb at the base of the stem. The liquid used in these thermometers is chosen on the basis of the temperature range to be measured by the device. The freezing point of the liquid must be below the lower limit of measurement, and the liquid boiling point must be above the upper limit. Common liquids include mercury, water, oil, alcohol, and toluene. The colorless liquids must have a dye additive.

Unless otherwise specified, glass stem thermometers are graduated for complete immersion of the bulb and stem during the taking and reading of a temperature measurement. Since thermometers should be read without removal from the immediate measurement area, it is often necessary to leave a portion of the stem protruding in such a manner that it will be at a different temperature than the bulb, unless it is used to monitor ambient temperature. NOTE: In thermometers for normal temperature ranges, the capillary bore is evacuated above the liquid fill. In thermometers for high temperatures, however, the capillary bore is pressurized with nitrogen or some other suitable gas to prevent evaporation of the liquid.

3.2 Pressure Thermometer. The pressure produced by any fluid in a completely enclosed container is a function of the fluid temperature. An application of this principle appears in pressure thermometers. The fluid may be either a liquid, a gas, or a vapor. The indicator is usually a Bourdon-type pressure gage.

The design of a pressure thermometer is such that the indicating device is located some distance from the bulb where actual measurements are being taken and where the bulk of the fluid is stored. The indicator and bulb are joined to a coiled capillary tube that forms the elastic tube of the Bourdon movement. Factors to consider in choosing a fluid for a vapor-pressure thermometer are: the lower limit of measurement is the boiling point of the liquid, and the upper limit is the critical temperature - at which the vapor-liquid equilibrium no longer exists. The bulb of a vapor-pressure thermometer must be large enough to contain all of the liquid used (more than enough to fill the Bourdon elastic tube and the connecting tubing). This ensures that the liquid-vapor interchange will occur inside the bulb.

With various fluids, temperatures from -29° to 371° C (-20° to 700° F) can be measured; however, the working range for any one liquid is limited to 93° or 149° C (200° or 300° F). High-quality vapor-pressure thermometers are used as primary-standard instruments in the low temperature region above 1° K.

Because of the large size of the bulb, pressure thermometers have a long time lag between application of temperature and final reading of the gage.

3.3 Resistance Thermometer. The electrical resistance of a conductor changes as its own temperature changes. Usually, the hotter the material, the greater the resistance. A positive temperature coefficient indicates that resistance will increase as temperature increases. A negative temperature coefficient indicates that resistance will decrease as temperature increases. Some resistance thermometers are metallic, while others are semiconductor; the platinum resistance thermometer is the most common metallic type. This type of thermometer is very accurate and precise, and is generally used for laboratory experiments.

Varieties of this thermometer are available for covering very accurately a portion of the range from -184° to 650° C (-300° to 1200° F).

The resistive element used as the pickup or temperature monitor is normally made of platinum which is ordinarily in the form of a wire. Depending on the purpose for which the thermometer is designed, the wire can be very small in diameter (0.05 mm) or as large as 0.6 mm. For general use, however, the wire is normally 0.1 mm in diameter adjusted to have a resistance at 0° C of about 25.5 ohms, so that the resistance changes by about 0.1 ohm per degree Celsius. This describes a typical "wire-wound" type of "precision" resistance thermometer. The characteristics of simple "wire" thermometers are considerably different and are made in diameters as low as 0.00025 mm for temperature response of 0.001 second, as opposed to 30 seconds for the wire-wound example. This type of temperature measurement is usually accomplished with the use of a Mueller bridge (see Figure 2); this is a precision tool used in calibrating "resistance" thermometers. When the resistance bridge is used for temperature measurements, resistor Rx becomes the temperature-sensing element located in the probe connected to the bridge by long leads. The resistance thermometer can be calibrated by placing the probe into various known temperature baths. An example of the characteristics of a typical resistance thermometer is as follows:

Temperature measurement range: -220° to 650° C (standard)
Response time: 30 seconds to reach response time
Accuracy: $\pm$.001° C

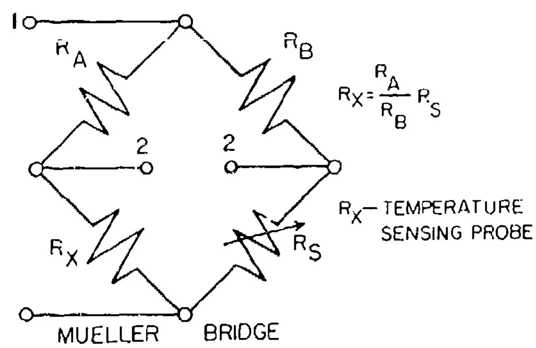

Figure 2. Temperature-sensing resistance thermometer (a special form of Wheatstone bridge).

3.4 Thermoelectric Thermometer (Thermocouple). This is probably the most versatile temperature-measuring device. It employs the Seebeck effect which states, "When two dissimilar metals are joined at both ends, with their junctions at different temperatures, opposing electromotive forces develop within the loop. The net emf varies directly with the difference in the temperatures of the two junctions". Since the net emf produced by a thermocouple-type arrangement is a function of the difference between the temperatures of the measuring and reference junctions, these devices can be usefully employed to measure temperature changes. Figure 3 shows a typical thermoelectric circuit. When long lead lines are used or many thermocouple junctions are monitored, copper wires can be used as extension leads. Anywhere a connection is made, it is necessary to place the connection in a zone box. This box is constructed to give a uniform temperature field.

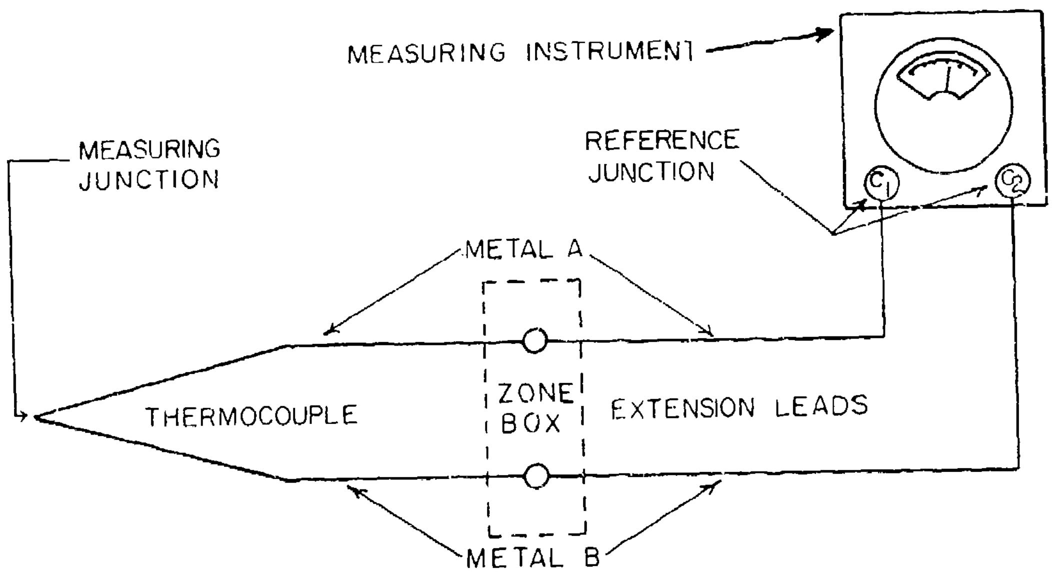

Figure 3. Thermoelectric circuit.

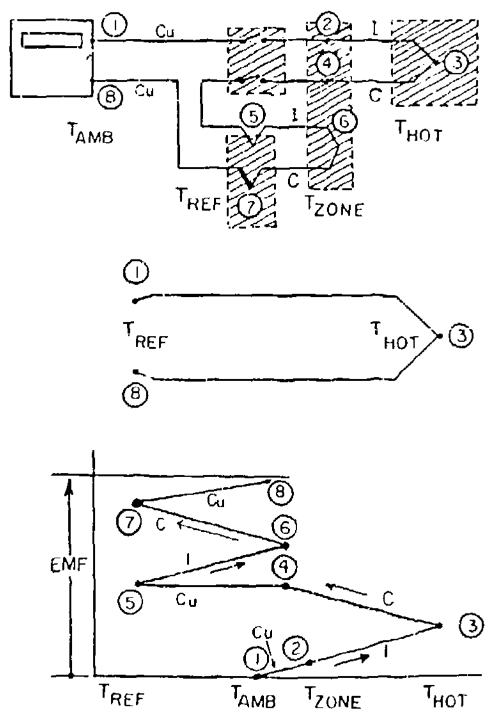

Figure 4. Multiple measurements using a zone box and selector switch.

The following tabulation shows some of the various combinations of metals used to make thermocouples, their working range, and the approximate millivolt change in each combination over the working range.

TABLE 1

PRINCIPAL METAL COMBINATIONS FOR THERMOCOUPLES*

Element/Metal	ISA TYPE	Working Ranges °C	Working Ranges °F	Limit of Error of Measured Value Standard	Limit of Error of Measured Value Special	Approximate Output in Millivolts for Working Range Indicated
copper to constantan	T	-184 to -59	-300 to -75	+2%	+1%	0.01-0.028
		-59 to 93	-75 to 200	±17°C	±17.4°C	0.028-0.036
		93 to 371	200 to 700	±3/4%	±3/8%	0.036-0.034
iron to constantan	J	0 to 277	0 to 530	±15.6°C	±16.7°C	0.027-0.031
		277 to 760	530 to 1400	±3/4%	±3/8%	0.031-0.036
chromel to alumel	K	0 to 277	0 to 530	±15.6°C	±17.4°C	0.021-0.023
		277 to 137	530 to 2500	±3/4%	±3/8%	0.023-0.019
chromel to constantan		0 to 982	32 to 1800			0-75.12
platinum 10% rhodium/platinum		0 to 1538	32 to 2800			0-15.979
platinum 13% rhodium/platinum		0 to 1593	32 to 2900			0-18.636
platinum 30% rhodium/platinum 6%		38 to 1799	100 to 3270			.007-13.499

*For more information, refer to ASTM or industry specifications.

Welding or silver soldering the measuring junction of the thermocouple to the unit being checked will produce the most reliable temperature data. Figure 3 shows the measuring junction point, extension leads that have the same thermocouple properties as the thermocouple junction, and the meter. Junctions C1 and C2 should be maintained at the same temperature. Otherwise, it would be difficult to ascertain the true reference junction of the setup. However, this is not a problem when the measuring devices have a reference junction compensator, since connectors C1 and C2 are close to one another. It is recommended that the monitoring equipment be located as close as possible to the area being monitored.

3.5 <u>Thermistor</u>. This is a semiconductor device having a negative temperature coefficient of resistance and can serve as a temperature-sensing element. It is usually connected to a bridge circuit in which the circulating current in that "arm" of the bridge can be kept low. This keeps the thermistor from self-heating and giving erroneous readings. When the thermistor is placed in a heat source, the change in resistance becomes a measure of the source temperature. The calibration curve of resistance as a function of temperature, over a wide temperature range, generally gives an exponential curve. Over a limited range of temperature, the resistance change may be linear.

There are two types of thermistors currently in use: the disk type, which is used for surface and skin measurements, and the bead type, used for measurements. A typical use of the thermistor for general application is in RF measurements. In microwave measurements, a thermistor is used to terminate a transmission line so that all the power flowing down the line is absorbed by the thermistor which serves as the load. The amount of power absorbed by the thermistor is indicated by a resistance change. An example of the characteristics of a typical thermistor is as follows:

Temperature measurement range: 0° to 100° C
Response time: 5 seconds to reach response time
Accuracy: $\pm$.5% full-scale reading

3.6 Radiation Pyrometer. The temperature-measuring devices discussed thus far are limited to measurements below a few thousand degrees Fahrenheit, since the materials employed would melt at higher temperatures. However, the high radiant heat energy emitted by bodies at temperatures above 2000 to 3000 degrees can be used to make temperature measurements. Devices that employ this phenomenon are called radiation pyrometers. The radiation pyrometer (see Figure 5) consists of a blackened disk (thermal detector) suitably shielded from stray radiation and provided with sensitive means to indicate small changes in its surface temperature. When exposed to a hot surface to be measured, the thermal detector is warmed by the absorbed radiation and assumes a temperature much lower than, but related to, that of the portion of the surface of the body to which it is exposed.

The source of radiation must entirely fill the viewing field (θ) and be focused on the thermal detector. Since the temperature of a pyrometer is negligible with respect to the temperature of the hot body being measured, the hot body temperature is given by:

$$T = K^4 \sqrt{\frac{\Delta T}{\varepsilon A}}$$

In which ε is the emissivity of the hot body; A is the area of the hot body; and ΔT is the change in temperature of the thermal element from its normal temperature. The constant K represents the sensitivity of the instrument determined by calibration. The construction of this device makes the measurement independent of the distance between the pyrometer and the hot body. This distance may be large, as with the temperature measurements of heavenly bodies. An example of the characteristics of a typical radiation pyrometer is as follows:

Temperature measurement range: 50°C to >3000°C
Response time: medium, but depends on the operator
Accuracy: $\pm$10°C or $\pm$2% (whichever is greater)

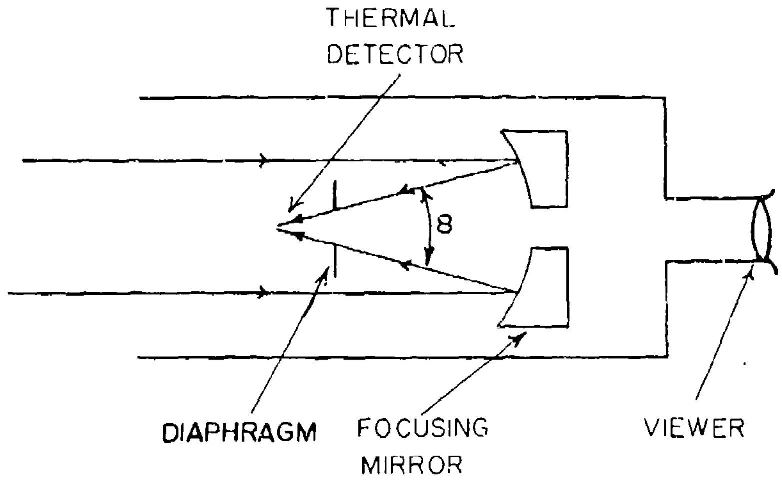

Figure 5. Radiation pyrometer.

3.7 Optical Pyrometer. This is a non-contact device that compares radiant energy from a target with reference source, typically a tungsten strip lamp mounted in the optical system of the pyrometer. The image and filament are viewed through a specially designed telescope focused on the object. The filament current is adjusted by rotating a dial until the object and glowing filament appear equally bright. The data are collected from a scale calibrated in °C or °F. The precision of this instrument is directly dependent upon the qualifications and knowledge of the operator. For an in-depth review, refer to the National Bureau of Standards Monograph 41, entitled "Theory and Methods of Optical Pyrometry". Some uses of optical pyrometers included: determining temperatures of lamp filaments; and obtaining internal temperatures of fire ovens. An example of the characteristics of a typical optical pyrometer is as follows:

Temperature measurement range: 775°C to 6200°C
Response time: depends on operator
Accuracy: ±4°C at 800°C; ±3°C at 1064.4°C; ±8°C at 2800°C; ±40°C at 4000°C

3.8 Quartz Thermometer. This device eliminates many of the steps now required for precision temperature measurements. It can detect temperature changes to a resolution of 0.0001° C. The operation of the quartz thermometer is based on the temperature sensitivity of quartz piezoelectric resonators. The resonator is a precisely ground disc of quartz crystal about 0.18 mm thick by 6.3 mm in diameter. Gold electrodes are vacuum-deposited on either side and brazed to platinum ribbons that serve as supports and electrical connections. The resonator is sealed into a cold-welded copper case containing helium at standard temperature and pressure. An oscillator supplies a small amount of power to the resonator which acts as a highly selective filter that holds the frequency of oscillation very close to the natural frequency of the resonator. A special LC (linear coefficient) cut is used in the quartz thermometer sensor crystal that exhibits a very linear, yet sensitive correspondence between resonant frequency and temperature. The resonant frequency is 28,208 kHz at 0° C, and varies by 1000 Hz per °C. The typical operating range of the quartz thermometer is -80° to 250° C (-112° to 482° F).

The quartz crystal sensor, unlike other thermometers, indicates temperature by a proportional change in frequency rather than a change in resistance, dimension, or voltage generation. Two advantages gained by this method of sensing are: 1) the temperature indication is almost immune to changes in connecting wire resistance, and 2) reading frequency eliminates some of the problems in calibration, allowing a more precise setting to be made.

3.9 IR Thermometer. The noncontact IR thermometer usually consists of two units: an optical sighting head that is focused on the area of interest and a display console to indicate temperature. The assembly also contains an emissivity correction control setting used to obtain true temperature on non-blackbody surfaces. The IR thermometer can also be used to obtain temperature measurements of mortars and other weapons during and after firing. It can be operated on regular ac power or a portable ac power supply. For additional information and photo of the IR thermometer, refer to TOP 2-2-812. An example of the characteristics of a typical IR thermometer is as follows:

Temperature measurement range: -30°C to 5000°C
Response time: 1.0 second
Accuracy: ±2% or 11°C (whichever is greater)

3.10 IR Spot Radiometer. This noncontact device measures apparent temperature by integrating the IR flux in its "angular field of view" (FOV) within a specified band of wavelengths. Some instruments allow a selection such as 2-20 microns bandwidth. The temperature and emissivity of the surroundings are very important when measuring temperatures with this instrument.

Some spot radiometers contain a knob to compensate for the target's emissivity values. In this case, the emissivity of the target must be known. Caution: An emissivity dial on a radiometer can magnify the error if the effects of the surroundings are not carefully considered. Spot radiometers are generally used in qualitative measurements. For example: spotting targets used in thermal night vision devices; contrast readings for detection; average radiant energy in its FOV. A thorough understanding of thermal radiation is necessary to properly interpret these readings. An example of the characteristics of a typical IR spot radiometer is as follows:

Temperature measurement range: -20°C to +75°C
Response time: 5 ms to 500 ms, depending on bandwidth
Accuracy: ±0.5°C

3.11 Thermal Imaging System. This system uses improved techniques in photo detectors and opto/mechanical scanning, and is normally referred to as a "fast scan IR imager". It is cryogenically cooled. Some of these devices have pyroelectric sensors and are non-wavelength-specific. Others operate in a broad band mode in the 3-5 μm and 8-14 μm regions. The thermogram is displayed on a video monitor and can be videotaped for later analysis. A picture can be taken of the video monitor image with a camera to provide photos of the scene being viewed. The information obtained is an apparent temperature, not a spectral distribution of energy. Apparent temperature can be converted to a known temperature by physically locating a blackbody source, with known temperature, in the field of view of the detector and then performing the appropriate calculations. Corrections must be made for atmospheric transmission. Examples of use are: reconnaissance and surveillance; thermal mapping; detection of underground missile silos, personnel, vehicles, weapons, cooking fires, and encampments; submarine detection; nondestructive testing; study efficiency of thermal insulators. An example of the characteristics of a typical thermal imaging system is as follows:

Temperature measurement range: −20°C to +1500°C (extrapolated)
Scan rate: 30 frames/sec
Response time: 33 ms
Resolution: 0.2°C

Signal Transfer Function (SiTF) and Minimum Resolvable Temperature (MRT) should be evaluated for these systems. If a quantitative analysis is required, the reader should refer to TABLES OF BLACKBODY RADIATION FUNCTIONS[2] by Mark Pivovonsky and Max Nagel for more information. The basic Planckian blackbody equation is:

$$N = \int_{\lambda_1}^{\lambda_2} \frac{2C^2 h}{\lambda^5} \left(e^{\frac{hc}{\lambda hT}} - 1 \right)^{-1} d2\lambda$$

A note of caution should be mentioned here: thermal imaging, or thermography as it is sometimes called, should only be evaluated by experienced personnel. For more information and photo, refer to Report APG-4543.[3]

3.12 Visual Non-Instrumented Techniques. Other temperature-monitoring devices are also available which require no specific technical knowledge: 1) pyrometric cones, 2) crayons, pellets, and paints, and 3) color indicators.

3.12.1 Pyrometric Cones. These are slender trihedral pyramids made of such mixtures of minerals that when heated uniformly at a specified rate deform on reaching temperatures characteristic of these mixtures. They are commercially available in a series of 61 cone numbers about equally spaced over the temperature range of 585° to 2015° C (1085° to 3659° F).

3.12.2 Crayons, Pellets, Paints. Mineral mixtures of definite melting temperatures are available commercially in the forms of crayons, pellets, and paints. The temperatures in the range of 38° to 1371° C (100° to 2500° F) are monitored. These temperatures are indicated by the advent of a wet or molten appearance. As applied to the surface of a body, they indicate by this wet appearance when the local surface area has reached the corresponding temperature.

3.12.3 Color Indicators. In the heat treatment of steel, tempering temperatures have long been estimated by the colors attained by surface oxide formations as these develop during the heating. A special alloy has been produced to indicate temperature by its vividly changing color in the range of 500° to 882° C (932° to 1620° F).

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APPENDIX A

GLOSSARY

APPARENT TEMPERATURE	The surface temperature as read by a radiometer.
BLACKBODY	An ideal surface that completely absorbs (and emits) all incident radiation with no reflection. Its emissivity is unity.
CONSTANTAN	An alloy of 45-60 percent copper and 40-55 percent nickel.
EMITTANCE	The intrinsic properties of a material. (This term is used interchangeably with emissivity.)
HEAT	Energy in the process of transfer from one body to another by a thermal process.
MEASURING JUNCTION	Sometimes called hot junction, it is that end of a thermocouple subjected to the temperature to be measured.
OPTICAL PYROMETER	A pyrometer of which the indications depend upon the brightness at some wave length, of the hot body whose temperature is being measured.
RADIATION PYROMETER	A pyrometer of which the indications depend upon the radiancy of a source.
PRECISION	The closeness of agreement of repeated measurements of the same quantity.
RANGE	(of a temperature-measuring device), the span in degrees of its calibrated scale.
REFERENCE JUNCTION	Sometimes called cold junction, it is that end of a thermocouple either subjected to a known temperature or so located with respect to suitable measuring equipment that changes in its temperature are without effect upon the measurement of the temperature of the measuring junction. Usually, there are two or more reference junctions in a thermoelectric circuit, so arranged that all of them are maintained at one temperature.
RESISTANCE THERMOMETER	A thermometer in which the electrical resistance of a definite part, the resistor, serves as a measure of temperature of radiant energy.
SEEBECK EFFECT	The generation of a current in a circuit of two dissimilar metals, the junctions of which are at different temperatures.
TEMPERATURE	The thermal state of a body considered with reference to its ability to transfer heat to other bodies.

THERMOCOUPLE A pair of dissimilar electrically conducting materials joined together at one end in which a difference in temperature of the junction from that of the other ends generates an emf.

THERMOSTAT A device for the automatic control or regulation of temperature.

VAPOR-PRESSURE THERMOMETER A thermometer of which the indications depend upon the vapor-pressure of a liquid partially filling an enclosure.

THERMAL WARNING DEVICE (TWD) A device designed to show when the temperature of a cannon tube is high enough to cause propelling charge cookoff.

APPENDIX B

REFERENCES

1. Test Operations Procedure (TOP) 2-2-812, Infrared Measurements of Vehicles and Weapons, 18 July 1979.

2. Pivovonsky, Mark, and Nagel, Max, Tables of Blackbody Radiation Functions, 1961.

3. Methodology Report APG-MT-4543, Solution of Special Problems Using Infrared Techniques, November 1974.