AEROSPACE STANDARD

AIR1900™ REV. B

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Superseding AIR1900A

(R) Guide to Temperature Monitoring in Aircraft Gas Turbine Engines

RATIONALE

This update of AIR1900 to revision B has been made to incorporate the contents of AIR1900A with three other documents to create a single comprehensive report covering temperature monitoring. The details of the other three documents are as follows:

- ARP464 - Mount - Thermocouple
- ARP465B - Flange - Thermocouple
- ARP485A - Temperature Measuring Devices Nomenclature

Due to the availability of similar and more up-to-date information in the public domain, together with the extensive effort required, the original material has not been brought up to date.

Upon publication, the three superseded documents—ARP464, ARP465B, and ARP485A—will be cancelled. This strategy was agreed to by the SAE E-32 Committee to reduce the number of documents it is required to maintain.

FOREWORD

This document, originally prepared in 1991, was reviewed by industry and committee members between 2008 and 2010. Changes were made in 2015 to incorporate the content of ARP464, ARP465B, and ARP485A, thus rendering those three documents obsolete. These changes combine mechanical and installation considerations, nomenclature and a general overview of temperature measurement for engine monitoring systems in various areas of aircraft gas turbine engines.

TABLE OF CONTENTS

1. SCOPE

This SAE Aerospace Information Report (AIR) provides an overview of temperature measurement techniques for various locations of aircraft gas turbine engines while focusing on current usage and methods, systems, selection criteria, and types of hardware.

1.1 Purpose

The purpose of this document is to provide information and guidance on the selection and use of aircraft turbine engine temperature monitoring systems and elements.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR46 The Preparation and Use of Thermocouples for Aircraft Gas Turbine Engines

AIR1828 Guide to Engine Lubrication System Monitoring

AIR1873 Guide to Limited Engine Monitoring Systems for Aircraft Gas Turbine Engines

ARP755 Aircraft Propulsion System Performance Station Designation and Nomenclature

ARP1217 Instrumentation Requirements for Turboshaft Engine Performance Requirements

ARP1587 Aircraft Gas Turbine Engine Health Management System Guide

AS793 Total Temperature Measuring Instruments (Turbine Powered Subsonic Aircraft)

AS8005 Minimum Performance Standard, Temperature Instruments

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

STP470B-EB Manual on the Use of Thermocouples in Temperature Measurement

2.1.3 NIST Publications

Available from NIST, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

ITS-90 Thermocouple Database

2.1.4 Other Publications

Anixter. (2013). Chapter 7: Electrical characteristics. *Technical information handbook: Wire and cable* (85-102).

Beynon, T.G.R. (1982). Radiation thermometry applied to the development and control of gas turbine engines. *Temperature*, 471-477.

Beynon, T.G.R. (2015). Turbine pyrometry: An equipment manufacturer's view (Paper No. 81-GT-136). *American Society of Mechanical Engineers*, https://doi.org/10.1115/81-GT-136.

Doebelin, E.O. (1966). Measurement systems: Application and design. *McGraw Hill*.

Douglas, J. (1980). High speed turbine blade pyrometry in extreme environments. *Measurement methods in rotating components in turbo machinery*. American Society of Mechanical Engineers.

Moffat, R.J. (1962). Gas temperature measurement. In C.M. Herzfeld (Ed.), *Temperature—Its measurement and control in science and industry* (Vol. 3, part 2, 553-571).

Shambrook, K.P. (1982). Signal processing techniques for temperature measurement. *Temperature—Its measurement and control in science and industry* (1167-1172).

Stringfellow, K. (1982). Improving the accuracy of thermocouple temperature measuring circuits (Report No. PNR90148). *Rolls-Royce Ltd.*

Sydenham, P. (1982). Basic electronics for instrumentation. *Instrument Society of America*.

Trenkle, F. and Reinhardt, M. (1973). *In-flight temperature measurements* (Vol. 2). NATO Advisory Group for Aerospace Research and Development.

2.2 Definitions/Glossary

General temperature measurement related terms are defined first, followed by nomenclature specific to temperature measuring devices, particularly thermocouples, as applied to aircraft turbines for use by:

a. Power plant manufacturers.

b. Airframe manufacturers.

c. Procurement organizations.

d. Equipment organizations.

e. Service and maintenance personnel.

f. Other interested organizations.

2.2.1 BIMETALLIC ELEMENT

A temperature sensitive device composed of two materials having different thermal coefficients of expansion resulting in a proportional movement of the free segment of the device with changes in temperature.

2.2.2 COCKPIT INDICATOR

An instrument used to translate the EMF from a temperature measurement system into a visual indication of the temperature to the measuring junction or junctions.

2.2.3 TEMPERATURE INDICATOR

A temperature indicator is a device which responds to a signal from a temperature measuring system to provide a reproducible indication of the signal level.

2.2.4 NULL BALANCE INDICATOR

A null balance indicator is a cockpit indicator which provides a visual indication by means of a potentiometer circuit whose accuracy is not affected by external resistance.

2.2.5 CONDUCTION ERROR

The difference between the gas temperature and the sensed temperature caused by conduction of heat along the thermocouple assembly support tubes and leads and mounting surface or adjacent components.

2.2.6 LIMITING ZONE TEMPERATURE

The maximum permissible zone operating temperature.

2.2.7 MEASURING JUNCTION

That junction of a thermocouple sensing system immersed in or in contact with the medium whose temperature is to be observed. That junction may be separated from the measured medium by insulation and/or a protective sheath.

2.2.7.1 Types of Junctions

a. Twisted

b. Looped

c. “V”

d. “U”

e. Stirrup

f. Pencil

See Appendix A.

2.2.8 RADIATION ERROR

The difference between the gas temperature and the sensed temperature caused by radiant heat transfer between the sensing element and surrounding areas.

2.2.9 RADIATION PYROMETER TEMPERATURE MEASUREMENT SYSTEM

A system depending for its indication on the wavelength and intensity of radiation from the medium to the measuring element of the pyrometer.

2.2.10 RECOVERY FACTOR

That ratio of the difference in indicated temperature and static temperature to the difference in total temperature and static temperature, expressed in (k).

2.2.10.1 RECOVERY RATIO

Recovery ratio is the ratio of the measured temperature versus true air temperature as recorded in a wind tunnel or open jet facility.

$$R = \frac{T\,\text{indicated}}{T_T} \quad \text{(Eq. 1)}$$

2.2.11 REFERENCE JUNCTION

That union of two dissimilar metal wires that is maintained at a known signal level and is used to determine an absolute temperature indication from the relative temperature measured at the measuring junction.

2.2.12 RESISTANCE TEMPERATURE DEVICE

A temperature sensitive device composed of a material whose resistance increases in a reproducible manner as the temperature increases with negligible hysteresis. Typically, wire wound on to a mandrel or screen printed onto a substrate.

2.2.13 RESISTANCE SPOOL

A variable resistance used to adjust the resistance of the thermocouple measurement system to predetermined values under given conditions.

2.2.14 STAGNATION TEMPERATURE

This term is sometimes used as an alternative to total temperature. Though they are different concepts thermodynamically, they are numerically the same for ideal gasses.

2.2.15 STANDARD RESPONSE TIME

The time required for a temperature measuring element to register 63.2% of a step change in temperature of a gas stream flowing at a rate of 29.295 $kg/m^2/s$ (6 $lb/ft^2/s$), also referred to as “standard time constant.”

2.2.16 STANDARD STEADY-STATE REPRODUCIBILITY FACTOR

The ratio, expressed in percent, between the indicated gas temperature and a standard indicated temperature under predetermined gas temperature, radiation, and conduction losses and mass flow conditions over the range of in-flight engine operations.

2.2.17 STATIC TEMPERATURE (GAS AND THERMAL EQUILIBRIUM)

A measurable property that is directly proportional to the mean kinetic energy of the particles. In a moving gas, the static temperature would be indicated by an instrument moving in the same direction and at the same velocity as the gas.

2.2.18 SUPPORT TUBE

The support tube is the portion of the thermocouple assembly immersed in the medium to be measured and provides support for the measuring junction and lead wires.

2.2.19 TEMPERATURE

A measure of the average energy of motion, or kinetic energy, of particles in matter expressed in terms of units designated on a standard scale.

2.2.20 TEMPERATURE MEASUREMENT

The observation of the relative heat energy present as it affects engine performance and/or life, i.e., bearing, compressor inlet, turbine in or out, blade temperature, and any other pertinent material or gas temperature.

2.2.21 TEMPERATURE MEASUREMENT SYSTEM

A system consisting of one or more measuring elements to quantitatively measure temperature by heat transfer including a means of transmitting the resultant single output to and including the indicator, and if applicable, to the engine control device.

2.2.21.1 TEMPERATURE INDICATING SYSTEM

That part of the temperature measurement system extending physically from the engine-airframe interface up to and including the aircraft cockpit indicator.

2.2.21.2 TEMPERATURE SENSING SYSTEM

That part of the temperature measurement system extending physically from and including the temperature measuring element to the engine-airframe interface and, if applicable, to the engine control.

2.2.22 TEMPERATURE MEASURING ELEMENT

That element or portion of a temperature measuring system that yields a measurable signal that is reproducible as a function of temperature.

2.2.22.1 PROBE

A probe is an immersion type temperature measuring element.

2.2.22.2 CONTACT ELEMENT

A contact element is a temperature measuring element used in intimate contact with the solid-state body to be measured.

2.2.22.3 REMOTE MEASURING ELEMENT

A remote measuring element is a temperature measuring device removed from the medium to be measured.

2.2.23 COMPENSATED REFERENCE JUNCTION

A junction maintained at a known signal output level by circuitry designed to compensate for changes in ambient temperatures, which is used to of determine an absolute temperature indication from the relative temperature measured at the measuring junction.

2.2.24 INDICATING LEAD

That portion of the thermocouple indicating system from the engine / airframe disconnect to the reference junction.

2.2.25 THERMISTOR

A temperature sensitive device composed of a material whose resistance decreases in a reproducible manner as the temperature increases with negligible hysteresis.

2.2.26 THERMOCOUPLE ASSEMBLY

That part of the thermocouple sensing system including all components from the measuring junction to the electrical connector or to the harness junction box as is the case with the integral harness.

2.2.27 THERMOCOUPLE ASSEMBLY EXTENSION LEAD

An assembly that physically supports, protects, and insulates the conductors extending from the thermocouple assembly to a point within the thermocouple harness.

2.2.28 THERMOCOUPLE BOSS

The means of attaching a thermocouple assembly to the engine case.

2.2.29 THERMOCOUPLE CALIBRATION

The plot of the EMF output of a temperature measuring junction versus known temperatures.

2.2.29.1 THERMOCOUPLE CALIBRATION UNCERTAINTY

The ratio, expressed in percentage, of the difference between the EMF output of a temperature measuring junction at a given temperature and the specified EMF for that temperature, to that specified EMF.

$$\text{Measurement Uncertainty (\%)} = \frac{(\text{EMF}_{\text{test}} - \text{EMF}_{\text{ref}})}{\text{EMF}_{\text{ref}}} \times 100 \quad \text{(Eq. 2)}$$

2.2.30 THERMOCOUPLE HARNESS

An assembly that physically supports, protects, and insulates the conductors extending from the thermocouple assemblies to the thermocouple output harness connector.

2.2.31 Thermocouple Harness Construction

2.2.31.1 RIGID THERMOCOUPLE HARNESS

An assembly in which the lead supporting and protective structure is firm and non-flexible and requires application of appreciable force in order to obtain deflection. Typically composed of a metal sheathed material.

2.2.31.2 FLEXIBLE THERMOCOUPLE HARNESS

An assembly in which the lead supporting and protective structure is easily bent and adapts itself readily to change of shape.

2.2.31.3 THERMOCOUPLE HARNESS CIRCUITRY

The complete electrical path designed to conduct the output EMFs generated by the individual temperature measuring junctions into a single useable value.

2.2.31.4 COMMON JUNCTION CIRCUIT

A circuit in which each temperature measuring junction is paralleled by means of individual leads to a common point.

2.2.31.5 EQUAL RESISTANCE BRANCH CIRCUIT

A circuit in which the temperature measuring junctions are paired in parallel and symmetrically arranged about junction points, so that equal resistance paths are maintained around each loop. This is the simplest and most accurate system provided the branch circuits are of equal resistance.

2.2.31.6 LADDER CIRCUIT

Temperature measuring junctions geometrically and electrically paralleled to two bus bars.

2.2.31.7 OPEN LADDER CIRCUIT

A parallel circuit in which the bus bars are electrically discontinuous. Without resistance compensation, this type of circuit is no longer preferred for jet engine environments.

2.2.31.8 CLOSED LADDER CIRCUIT

A parallel circuit in which the bus bars are electrically continuous. Without resistance compensation, this type of circuit is no longer preferred for jet engine environments.

2.2.31.9 RESISTANCE COMPENSATED LADDER CIRCUIT

A parallel circuit in which compensating resistors have been inserted so that the output voltage of the circuit will equal the arithmetical average of the voltages of the several individual measuring junctions.

2.2.31.10 THERMOCOUPLE TYPE TEMPERATURE MEASUREMENT SYSTEM

A thermocouple and associated supporting structure, electrical insulation up to and including the indicator and, if applicable, to the control device. This system as applied to exhaust gas temperature measurement may include one or more thermocouple assemblies, a thermocouple harness, thermocouple harness lead, reference junction, resistance spool, and indicator.

2.2.32 THERMOCOUPLES

A pair of dissimilar electrically conducting materials joined together so that a difference in temperature at the junction generates an EMF across the ends not joined. Typical combinations of wire are as follows:

Table 1 - Thermocouple wire combinations

Type	+ (positive polarity)	- (negative polarity)
E	Nickel chromium (Kp)	Constantan
J	Iron	Constantan
T	Copper	Constantan
K	Nickel chromium (Kp)	Nickel aluminium or nickel silicon (Kn)
R, S, B	Platinum/rhodium	Platinum
	Iridium/rhodium	Iridium

2.2.33 THERMOMETER

An immersion or contact type device whose operation is based on thermal equilibrium between the sensitive measuring element and the medium to be measured. Types of thermometers include thermocouples, resistance bulbs, thermistors, bimetallic elements, vapor pressure elements, etc.

2.2.34 TOTAL TEMPERATURE (GAS AND THERMAL EQUILIBRIUM)

The temperature indicated by an error free instrument having a fixed position in the gas stream and is the sum of the static temperature and the temperature rise due to the conversion of kinetic energy to heat, as the compression occurs at the sensing element.

2.2.35 TRANSIENT REPRODUCIBILITY FACTOR

The ratio expressed in percent between the indicated standard response time and that standard response time predetermined for the configuration tested.

2.2.36 TYPES OF THERMOCOUPLE ASSEMBLIES

2.2.36.1 BARE OR EXPOSED JUNCTION

Has no shielding or support tube covering of any type over the measuring junction.

2.2.36.2 STAGNATION

Designed to measure a temperature which approximates the total temperature value.

2.2.36.3 SAMPLING

Has means for sampling gases at two or more points and for mixing these at the measuring junction so as to give a useful representative value.

2.2.36.4 ASPIRATED

Constructed so that the rate of heat transfer to the measuring junction is increased by causing the gas to flow over the junction at a rate which is higher than the free stream velocity.

2.2.36.5 SONIC

Designed so that the gas can be made to flow over the measuring junction at Mach 1.

2.2.36.6 SHIELDED

The measuring junction is partially or completely enclosed by a housing, the purpose being to reduce the free stream velocity and capture a higher percentage of the kinetic energy, as well as reduce the radiation error and provide mechanical protection.

2.2.37 VAPOR PRESSURE ELEMENT

A temperature sensitive device with a signal proportional to pressure of vapor in coexistence with its liquid phase and independent of the specific volume.

2.3 Acronyms

ECU Engine control unit

EGT Exhaust gas temperature

EMF Electromotive force

EMU Engine monitoring unit

FOD Foreign object damage

HP High pressure

IP Intermediate pressure

Kn Negative thermo element for type K thermocouples

Kp Positive thermo element for type K thermocouples

LP Low pressure

MIC Mineral insulated cable

MTBF Mean time between failures

MTBO Mean time between overhauls

MTBUR Mean time between unscheduled removals

RTD Resistance temperature detector

TBT Turbine blade temperature

TET Turbine entry temperature

UTR Uniform temperature reference

3. BACKGROUND

3.1 Need

Temperature is one of the most critical and widely measured variables in the monitoring of aircraft gas turbine engines. The measurement of temperature is accomplished by a variety of sensor types used in a number of locations (i.e., thermodynamic stations) in an engine. Furthermore, signal processing is often accomplished differently and used for a number of purposes by different engine manufacturers. This document will attempt to provide a common reference point for considerations of:

a. Sensor type.

b. Location.

c. Signal transmission.

d. Signal processing.

e. Signal uses.

f. Selection criteria.

g. Accuracy.

h. Potential problems.

3.2 Airframe Measurements

It is possible to take certain temperature measurements on the aircraft physically in regions other than the engine. For example, it is possible to make a total temperature measurement on the fuselage and to have this represent the engine inlet total temperature. However, there is an increasing tendency to make engine temperature measurements independent of those made on the airframe. This document will, therefore, concern itself primarily with measurements made on the engine.

3.3 Heat Transfer

The measurement of temperature depends upon the balance of three physical phenomena: convection, conduction, and radiation. This document will not address the theory of these phenomena. The reader is referred to AIR46 and Moffat (1962) for more in-depth information.

4. TYPICAL USAGE

The requirements on the temperature measurement system are dependent not only on the current state of technology available to the user but also critically on the purpose for which it is intended.

4.1 Functions

Temperature measurements on the engine are used for four basic functions: control, diagnostics and condition monitoring, cockpit display, and performance measurement.

4.1.1 Control

The signal is used, in an active sense, in a feedback control loop to correct a number of physical variables. For example, temperature is used to limit fuel flow in order to prevent turbine blades from overheating. Furthermore, temperature is used to correct a number of other physical variables such as rotor speeds; scheduling variable geometry; surge schedules; and acceleration and deceleration schedules.

4.1.2 Diagnostics and Condition Monitoring

Temperature signals from one location can be used to compute the temperature of other locations in an engine. This means the signal is used, in a passive sense, to measure thermal behavior in various parts of the engine. The time history of the thermal behavior is usually recorded for later examination. For example, exhaust gas temperature (EGT) margin is computed in order to determine timing of shop visits and to preclude EGT exceedances, which disturb routine operations of aircraft (Beynon, 2015).

4.1.3 Cockpit Display

Temperature measurements, especially in the engine turbine section, are displayed to the flight crew for purposes of monitoring engine operation.

4.1.4 Performance Measurement

Temperature measurements are critical to the determination of several important aspects of engine performance, such as specific fuel consumption (SFC), efficiency, and turbine exhaust gas temperature.

4.2 Media

Temperature measurements of different media are required in an aircraft gas turbine engine. These media include:

a. Gas paths.

b. Turbine metal parts, such as blades.

c. Liquids, including oil and fuel.

4.2.1 Gas Path

4.2.1.1 General

The purpose of a gas path temperature measurement generally dictates where it is made. Purposes include control, diagnostics and condition monitoring, cockpit display and performance measurement. Purposes specific to each location is discussed in the following paragraphs. The stations and their designation are described below and illustrated in Figure 1.

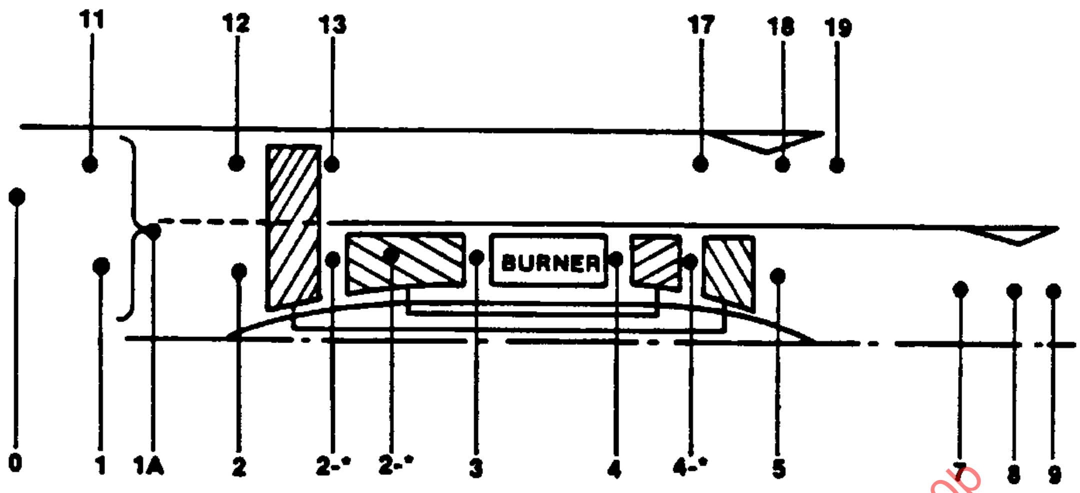


Figure 1 - Thermodynamic stations for twin-spool turbofan (ARP755)

- T_1 = Inlet/engine interface temperature
- T_{12} = First compressor front face tip section temperature
- T_2 = First compressor front face temperature
- T_{13} = Temperature at end of compression of bypass flow
- T_{2x} = Temperature at intermediate stage in 1st compressor
- T_3 = Last compressor discharge temperature
- T_4 = Burner discharge temperature
- T_{4x} = High-pressure turbine discharge temperature
- T_5 = Last turbine discharge temperature
- T_7 = Engine/exhaust nozzle interface temperature

ARP755 describes gas turbine engine performance station identifications and nomenclature, and Section 2 provides temperature measuring devices nomenclature.

If there is no asymmetrical distribution of temperature at the given station, it is possible for a single temperature transducer to be used. However, practically speaking, asymmetric temperature distribution (both radially and circumferentially) occurs regularly and steps must be taken to deal with this fact. Testing is usually accomplished to establish temperature profiles and placement of probes is chosen at representative locations. Depending upon the location, either one, two or several probes are used to make circumferential measurements. In the case of turbine discharge (T_5) temperature, a rake of thermocouples is usually designed to make the chosen temperature measurement. The number of thermocouples in a rake can vary, but eight is a typical number.

4.2.1.1.1 T_1, T_{12}, and T_2 Locations

Control functions often drive the need for these measurements. Schedules are often established for compressor speeds, fuel flows, and variable geometry. The schedules consist of nonlinear relationships between temperature and the variable being scheduled. Depending upon the temperature measured, the scheduled variable is controlled to a tolerance pre-established by the engine control software/hardware. These temperatures are used to correct shaft speeds and can also be used for condition monitoring to establish baseline temperatures from which T_{2x} and T_3 can be examined.

These temperatures are sometimes also selected for use in performance measurement. For example, depending upon the temperature selected, $NL/\sqrt{\theta}$ can be used to assess engine performance, where NL = low pressure compressor speed and θ = ratio of measured total (T_1, T_{12}, or T_2) temperature to reference (sea level) ambient temperature.

In many civil (commercial) applications, T_1 is measured external to the engine and generally on the fuselage. Furthermore, unless there is significant disagreement between engine inlet total temperature and fuselage total temperature, the airframe (fuselage) total temperature is selected for the measurement. This is generally not the case for military engines, however. In these instances, the engine inlet sensor is selected. In the event of disagreement, either the fuselage temperature is selected or some other engine temperature is used in its place.

4.2.1.1.2 T_{2x} and T_3

These temperatures are usually used for key engine control functions such as scheduling of the variable stator vanes in boosters and compressors, managing blowout margins for combustor operability, detecting ice accretion or water ingestion or parameterizing models to use in voting in signal selection logic. They are also often selected for diagnostics and condition monitoring purposes. They can be used to identify trends, track efficiencies of low (T_{2x}) and high (T_3) pressure compressors through examination of their discharge temperatures in order to establish relationships between temperatures in the engine (between T_1 and T_{2x}, for example) under various engine operating conditions.

4.2.1.1.3 T_{4x}, T_5 and T_7

These temperatures are used for all purposes, including control, diagnostics and condition monitoring, cockpit display, and performance measurement.

4.2.1.2 Temperature Range

Typical temperature ranges for each measurement are given by thermodynamic station in Table 2. They depend upon engine type (military, civil/commercial, corporate, helicopter) and flight envelope (maximum altitude and maximum Mach number). For ease of comparison, engine types are grouped as follows: high performance and low to medium performance. These are defined basically in terms of turbine entry temperature (TET) or station T_4. For high-performance engines, maximum TET exceeds 1400 °C (2550 °F), whereas maximum TET falls below 1150 °C for low- to medium-performance engines. Temperature ranges are relatively independent of the purpose for which the sensor is to be used.

In general, there is a trend toward higher core temperatures, particularly T_3, T_{4x}, T_5, and T_7. This is particularly true for high-performance engines where there is a need for increased performance (for example in military engines), increased efficiencies (in civil/commercial engines), or for both.

Table 2 - Normal operating temperature ranges

Station	High (°C)	Low/Medium (°C)
$T_1/T_{12}/T_2$	-55 to +175	-55 to +125
T_{2x}	-55 to +260	-55 to +200
T_3	0 to +650	0 to +500
T_{4x}	260 to +1200	260 to <1150
T_5/T_7	260 to +700	260 to +500

4.2.1.3 Accuracy

Accuracy requirements are established for the purpose for which the measurement is used. The measurement error includes several components, such as:

a. Sensor related errors.

b. Signal transmission errors.

c. Signal processing errors.

d. Signal display errors.

Typical accuracies are provided in Table 3 and discussed further in related SAE documents cited in Section 2 (such as ARP1587 and AIR1873).

Table 3 - Measurement accuracy/uncertainty requirements

Location	Accuracy or Uncertainty (°C)
T_1	±2.0
T_{12}	±2.0
T_2	±2.0
T_{2x}	±2.0
T_3	±5.0[1]
T_{4x}	±7.0[1]
T_5/T_7	±5.0[1]

[1] At the design point only. This widens considerably at other temperatures.

4.2.2 Turbine Blade

4.2.2.1 Purpose

Turbine blade temperature (TBT) is measured to ensure blade temperature limits are not exceeded. Exceedance of established maximum allowable temperature will significantly reduce the creep life of a part. The purposes of the measurement include control, diagnostics, and condition monitoring.

Prior to the development of optical pyrometers, the direct measurement of TBT was not possible. Instead, an estimate could be made of TBT by the use of thermocouple temperature measurements in the HP turbine discharge (T_{45}) position or in the LP turbine discharge (T_5) location. This remains the dominant means of estimating TBT at the time this document was prepared. Specifically, T_{45} or T_5 measurements are commonly used together with a predictable bias, to predict T_4, the turbine entry temperature. This is followed by an estimate of TBT based upon the estimate of T_4. This estimate must take into account cooling of the blades themselves by convective cooling, conduction, and radiation from the blades.

Nozzle guide vane temperature can also be targeted as a substitute to direct TBT measurement.

With the development of optical pyrometers, a direct measurement of TBT is now possible. The first stage turbine blades are often chosen for the measurement, although other stages can be selected as well.

It should be noted that a component's critical location may not be visible to the optical pyrometer due to mounting constraints (i.e., port location and direction, as well as mounting location temperatures and available physical space). In those cases, transfer functions might be employed to estimate the temperature at the critical location from the temperature measured elsewhere on the part.

4.2.2.2 Location

The most frequently chosen location for this measurement is the high-pressure turbine (HPT) blade. However, low-pressure turbine (LPT) blades may also be examined for diagnostics purposes.

4.2.2.3 Temperature Range

The typical operating temperature range is from 650 to 1150 °C but could approach 1500 °C for ceramic blades.

4.2.2.4 Accuracy

Accuracy requirements are meaningful only at the temperature design point selected. This may be any temperature over the operating range. At the design point, the maximum uncertainty will typically be ±9 °C.

4.2.3 Liquids (Oil and Fuel Temperature)

4.2.3.1 Purpose

The purpose of this measurement is for condition monitoring or diagnostics.

4.2.3.2 Location

Measurement of the liquid temperature is usually accomplished by use of a probe immersed directly into the medium. Locations may vary but oil temperature sensor will typically be before the oil cooler, whereas the fuel temperature sensor is normally downstream of the fuel heater and upstream of the fuel filter.

4.2.3.3 Temperature Range

The temperature range is from -55 to 200 °C.

4.2.3.4 Accuracy

The maximum uncertainty for the condition monitoring, diagnostic purposes and cockpit display is typically less than ±3.5 °C. These systems often do not require the high-level accuracy that is required for gas path sensors.

4.3 Sensor Types

There are many different technologies that have been used to measure temperature inside gas turbine engines. These include the following types:

a. Thermocouples.

b. Resistance temperature devices (RTDs).

c. Optical.

d. Thermistors.

e. Gas/liquid filled thermometers.

f. Acoustical.

g. Beta emission.

h. Resonating crystals.

i. Spectroscopic.

j. Color paints.

However, generally speaking, there are only four types that are used extensively, especially in production gas turbines. These are:

a. RTDs.

b. Thermocouples.

c. Optical pyrometers.

d. Gas-filled thermometers.

4.3.1 Resistance Temperature Device

RTDs operate on the principle that the resistance of a material to the passage of an electrical current is temperature dependent. The resistance of metals used as sensing elements usually increase with increased temperature, whereas commonly used semi-conductor materials (such as thermistors) decrease in resistance. Two metals commonly used for RTDs in engine temperature monitoring are platinum and nickel.

Engine manufacturers have increased their usage of RTDs in the compressor section of the engine. This usage has increased largely because of the needs for higher accuracies in this section and because RTDs offer the highest accuracy among proven technologies in this temperature range.

4.3.1.1 Platinum RTDs

4.3.1.1.1 Temperature Range

Platinum is very predictable and highly linear over a wide temperature range, from -260 to +800 °C. However, depending upon the materials used to fabricate the transducers, sensors used in engine monitoring typically operate over a range from -50 to +500 °C. Higher temperatures can be monitored, but this is usually limited by the ability of potting materials used inside the sensor to withstand higher temperatures.

4.3.1.1.2 Resistance/Temperature Relationship (R versus T)

The resistance (R) versus temperature (T) relationship of a platinum RTD is approximated by the Callendar-Van Dusen equation:

$$R_T = R_o\left\{1 + \alpha\left[T - \delta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) - \beta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right)^3\right]\right\} \quad \text{(Eq. 3A)}$$

where:

T = temperature (°C)

R_T = resistance at T degrees

R_o = resistance at the ice point

α = sensitivity coefficient, varies between 0.00385 and 0.003925

δ = 1.45 (international practical temperature scale-48) or 1.46 (international practical temperature scale-68)

β = 0.1 for T<0
= 0 for $T \geq 0$

This is often shown in its simpler form:

$$R_T = R_0\,(1 + AT + BT^2 + C(T\text{-}100)T^3) \qquad \text{(Eq. 3B)}$$

where C is only applicable for temperatures < 0 °C (otherwise it's zero).

4.3.1.2 Nickel RTDs

4.3.1.2.1 Temperature Range

Nickel can be used from -190 to +300 °C. It is generally less stable than platinum. Moreover, depending upon the type of nickel (high purity or Balco®, for example), the Curie point should not be exceeded. This effectively limits nickel to approximately 200 °C. The potting materials used in the sensor housing may restrict its use to temperatures below this limit as well.

4.3.1.2.2 R versus T

The resistance versus temperature relationship is given in MIL-T-7990B for R_o = 90.38 Ω, and in MIL-T-7258B where R_o = 1200 Ω. These are shown in Figure 2. Note that MIL-T-7990B is defined for temperatures up to 300 °C, beyond the normal operating range for nickel.

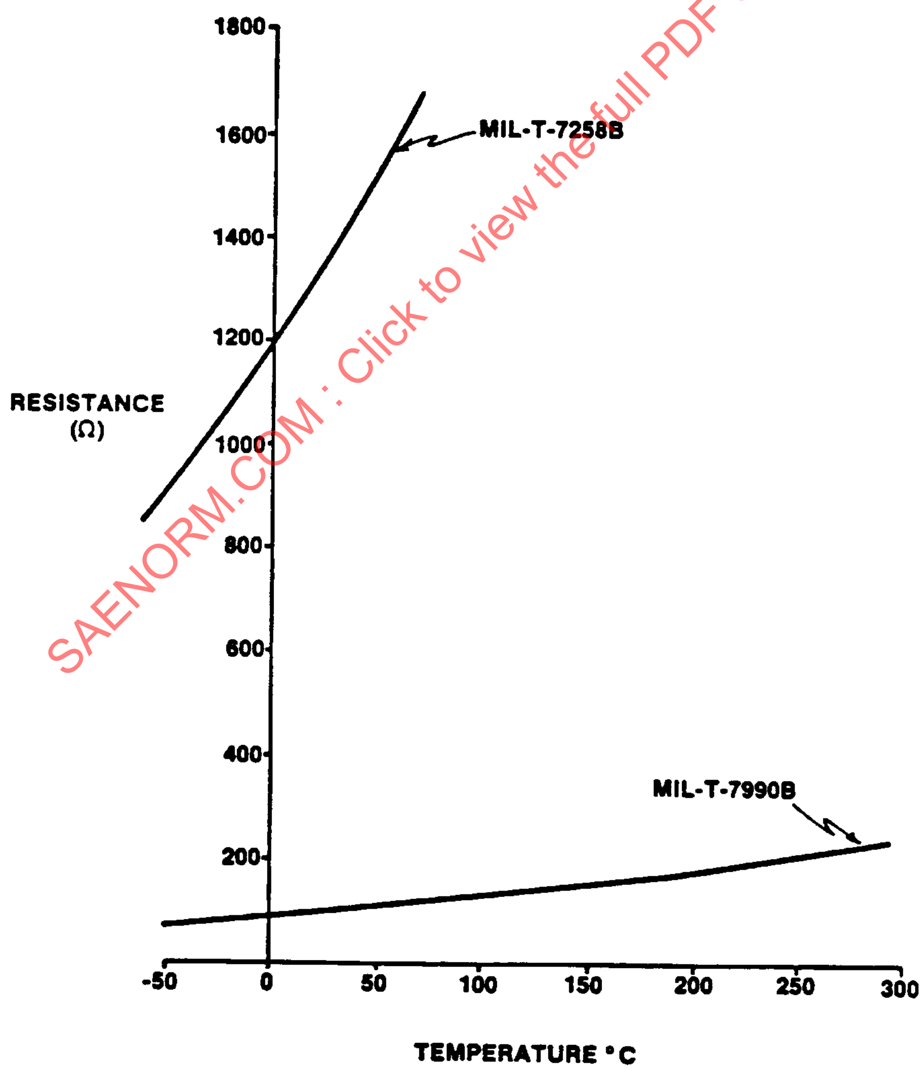


Figure 2 - R versus T two nickel sensors

4.3.2 Thermocouples

Thermocouples have been and remain the most widely used temperature measurement technology in a gas turbine engine. There are several reasons for this:

a. It is a well-understood technology.

b. It is widely available.

c. It is a relatively inexpensive product.

d. The accuracy, while not the highest, is generally acceptable.

e. The temperature ranges can be broad depending upon the type of thermo elements chosen.

There does seem to be a trend away from thermocouples towards RTDs for the compressor section. RTDs tend to provide better accuracy over the temperature range within the compressor. Furthermore, TBT are beginning to be measured by optical pyrometers for high-performance engines.

The basic thermoelectric circuit consists of two wires of different materials, joined at their ends to form a loop. When the two junctions of the loop are at different temperatures, an electromotive force (EMF) is generated. The magnitude and polarity of the EMF depends on the materials used and on the difference between the junction temperatures. This document is not intended to be a detailed reference on thermocouples. AIR46 provides more in-depth discussion. An explanation of the theory of thermocouples is given in STP470B-EB.

4.3.2.1 Types of Thermocouples

There are several types of thermocouples used on aircraft. These are shown in Table 4, along with their performance characteristics. Of these, type K thermocouples are the most commonly used on aircraft gas turbine engines.

4.3.2.2 Temperature Range

The temperature ranges shown in Table 4 apply to bare wire thermocouples. Exposure to these maximum temperatures will provide only a short life. To achieve a reasonable sensor life, these maximum temperatures should be lowered to between 100 to 150 °C for the wire sizes (16 to 18 gauge). However, most modern turbine engine applications will mount the wires in mineral insulated cable to increase sensor life.

4.3.2.3 Thermal-EMF Relationships

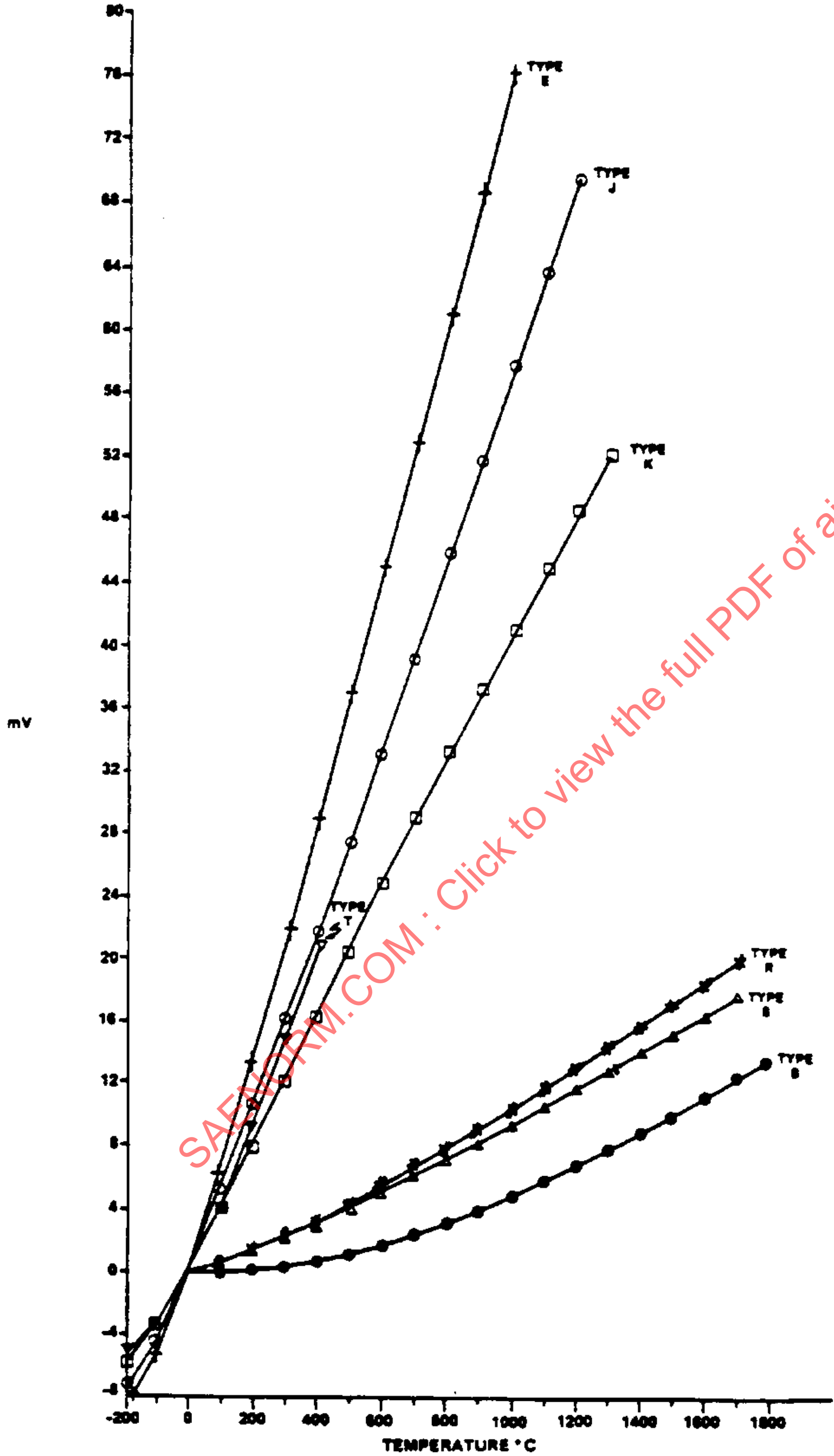
The EMF-temperature relationships are given in Figure 3 for several different thermocouples. Even though the outputs are nonlinear, they can be considered linear over short (10 to 20 °C) temperature spans. Reference tables or polynomials should be used to determine the correct temperature-EMF relationship for a given temperature (refer to ITS-90).

Table 4 - Selected thermocouples and their characteristics

Type[1]	Material	Average Output mV/°C	Temp Range[2] (°C)	Accuracy[3] Standard (°C)	Accuracy[3] Special (°C)
E	Nickel - 10% Chromium/Constantan	0.0756	-200 to 0 0 to 870	±1.7 °C or ±1%, whichever is greater ±1.7 °C or ±0.5%, whichever is greater	 ±1 °C or ±0.4%, whichever is greater
J	Iron/Constantan	0.054	0 to 875	±2.2 °C or ±0.75%, whichever is greater	±1.1 °C or ±0.4%, whichever is greater
T	Copper/Constantan	0.045	-270 to 0 0 to 400	±1 °C or ±1.5%, whichever is greater ±1 °C or ±0.75%, whichever is greater	 ±0.5 °C or ±0.4%, whichever is greater
N	Nickel - 14% Chromium Nickel - 4% Silicon	0.037	-200 to 1260	±2.2 °C or ±0.75%, whichever is greater	±1.1 °C or ±0.4%, whichever is greater
K	Nickel - 10% Chromium/ Nickel - 5% Al and Si	0.0396	-200 to 0 0 to 1260	±2.2 °C or ±2%, whichever is greater ±2.2 °C or ±0.75%, whichever is greater	 ±1.1 °C or ±0.4%, whichever is greater
R	Platinum - 13% Rhodium/Platinum	0.0115	-50 to 1600	±1.5 °C or ±0.25%, whichever is greater	±0.6 °C or ±0.1%, whichever is greater
S	Platinum - 10% Rhodium/Platinum	0.0102	-50 to 1540	±1.5 °C or ±0.25%, whichever is greater	±0.6 °C or ±0.1%, whichever is greater
B	Platinum - 30% Rhodium/Platinum - 6% Rhodium	0.0077	0 to 1800	±4.4 °C or ±0.5%, whichever is greater	±2.2 °C or ±0.25%, whichever is greater

[1] ANSI C96.1 standard.
[2] STP470B.
[3] Per ANSI C96.1 standard. % applies to temperature being measured.

NOTE: Suggest max S.S. 950 to 1000 °C.



Ref: NBS Monograph 125

Figure 3 - Output (mV) versus temperature for various thermocouples

4.3.3 Optical Pyrometers

Optical pyrometers operate on the principle that an object will radiate energy at various wavelengths, the frequency of which is proportional to its temperature. By focusing the emitted light onto a photoelectric sensitive material, an electrical signal can be generated that is proportional to a power of temperature of the radiation source.

Unlike other temperature technologies, the optical pyrometer does not come into contact with the media of interest. Optical pyrometers provide a means for noncontact surface temperature measurement. A viewing lens is used to gather the light emitted from a heated object (e.g., turbine blade) in a specific area and transmits the radiated light energy through either an optical fiber or metal tube to the photoelectric device. Additional signal conditioning is provided to generate a usable electrical signal.

Optical pyrometers measure temperature by measuring the total radiant energy gathered by the viewing lens. The radiant energy, however, is a function of absolute temperature. The relationship between the sensor measured temperature and the actual temperature of interest is a function of sensor design, viewing area environment and control of the photoelectric device. A more detailed explanation of the theory of optical pyrometers can be found in Sydenham (1982).

As mentioned previously, optical pyrometers are used in high-performance engines to measure turbine blade temperature (TBT) directly. At first they were used only on military engines, but they are now being applied to some new civil engines as technology advances have dramatically reduced susceptibility to lens contamination.

4.3.3.1 Temperature Range

Using silicon photodiodes, the operating temperature range is from 650 to 1500 °C.

4.3.4 Gas-Filled Thermometers

This type of temperature measuring device is typical for hydro mechanically controlled aircraft engines. The measurement is made by means of the pressure increase due to thermal expansion of a gas (usually helium) enclosed in a metal tube used as the temperature probe. The resulting increase in pressure is transmitted through a thermally insulated tubular extension to a reservoir to which a bellows is attached. The bellows in turn operates servo actuators to regulate fuel flow.

Many of the latest high-performance civil and military engines are controlled by full authority digital engine control systems. Such controls typically use thermocouples, RTD or other electrical temperature sensing techniques. Gas-filled thermometers are not compatible with these controls, and so this type of sensor is waning in popularity. However, a large number of gas filled thermometers continue to operate on existing engines.

4.3.4.1 Temperature Range

Currently, sensors in this category are limited to the range -55 to 125 °C.

4.3.5 Media and Application of Sensor Types

Table 5 shows the typical uses of each sensor type within the various engine media. It should be noted that turbine blade temperatures can be measured only by pyrometers. However, thermocouples are used to estimate TBT. Additionally, gas-filled thermometers are currently limited to gas path (air) temperatures.

Table 5 - Media applications of each sensor type

Sensor Type	Gas Path	Turbine Blade Temperature	Liquids
RTD	X		X
Thermocouple	X	X	X
Optical pyrometer		X	
Gas-filled thermometer	X		

5. SYSTEM CONSIDERATIONS

Proper design of a temperature monitoring system will account for each subsystem element. These elements include the locations of signal sources, appropriate mounting, how the signal is to be transmitted, how the signal(s) is to be processed, the sharing of signals and the end users for the signal itself. The next several paragraphs will account for each of these subsystem elements.

5.1 Signal Source Location

The selection of the best location for a temperature sensor will enhance the reliability of the signal output. Several questions must be addressed before proper location can be decided:

- What temperature is desired?
- Can the desired temperature be measured directly or must it be measured indirectly?
- If the temperature is to be indirectly measured, as in the case of calculating an upstream temperature from a downstream location, is there a functional relationship between the two temperatures?

Condition monitoring measurements in the gas path are commonly made at any or all of the following thermodynamic stations (see 4.2.1.1).

- T_{12} = First compressor front face tip section temperature.
- T_{25} = High-pressure (HP) compressor inlet temperature.
- T_3 = Last compressor discharge temperature.
- T_{45} = Low-pressure (LP) turbine inlet temperature or HP turbine discharge temperature.
- T_5 = LP turbine discharge temperature.

Generally speaking, these stations are of interest since they are made at locations where transitions occur between circular cross-sections of connecting ducts and annular cross-sections of compressor or turbine.

5.2 Mounting Considerations

Mounting of sensors to various locations within the engine must, at a minimum, account for the following:

a. Available space.

b. Vibration levels—mechanically or acoustically induced.

c. Means of securing.

d. Sealing.

e. Potential flow distortion.

f. Temperature distribution around probe.

g. Accessibility for providing cooling air (or other media) to the sensor, signal conditioner, or cabling as needed in the hot zones of the engine.

5.2.1 Space

The space available for mounting the sensor often determines the location of the sensor, as well as the configuration of sensor to be used. Space must be made for securing the sensor to the mounting surface, as well as for electrical connection on the backside. Furthermore, space must be provided for tools used to secure the unit and to remove it.

5.2.2 Vibration Levels

Care must be taken to mount the unit securely to the mounting surface since engine induced vibration levels can be very severe depending upon the type of engine to be instrumented. Specific frequencies are determined by the manufacturer's specification. However, they can range from 10 Hz to more than 20000 Hz. Vibration inputs can be random or sinusoidal. When the actual vibration specification is in doubt, MIL-STD-810 should be utilized to specify test levels and time duration.

5.2.3 Means of Securing

There are many means of attaching sensors to a mounting surface. Examples are shown in Figure 4. Figure 8 provides a recommended boss mount, while Figures 5 and 6 describe recommended flange designs for two holes flanges.

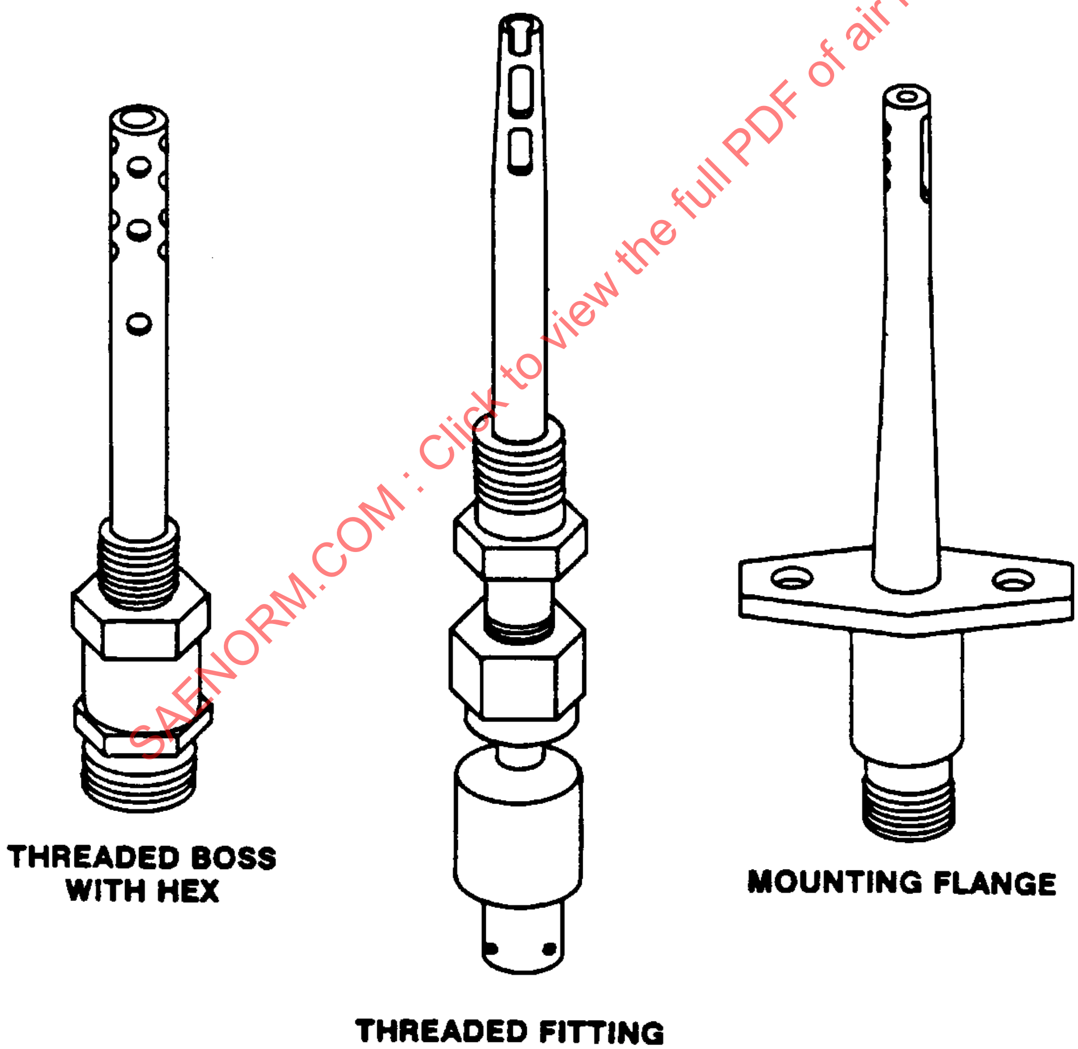


Figure 4 - Means of attachment to engine mounting surface

5.2.3.1 Mounting Flange

When flange mounting a temperature sensor the probes are welded or brazed to the flange for positive support. The flanges are bolted or secured by nuts and studs to mounting bosses located on the engine case. This arrangement permits removal of the probes for service, test and replacement, if necessary. Various flange configurations may be adopted to suit the space envelope, access to fasteners and to aid rapid installation.

Two-hole flanges are sometimes not considered sufficient for mounting where there is a high vibration environment or where there is concern about causing Foreign Object Damage (FOD) to the engine. In this event, other flange mounts may be chosen with either three or four holes provided for mounting studs or bolts.

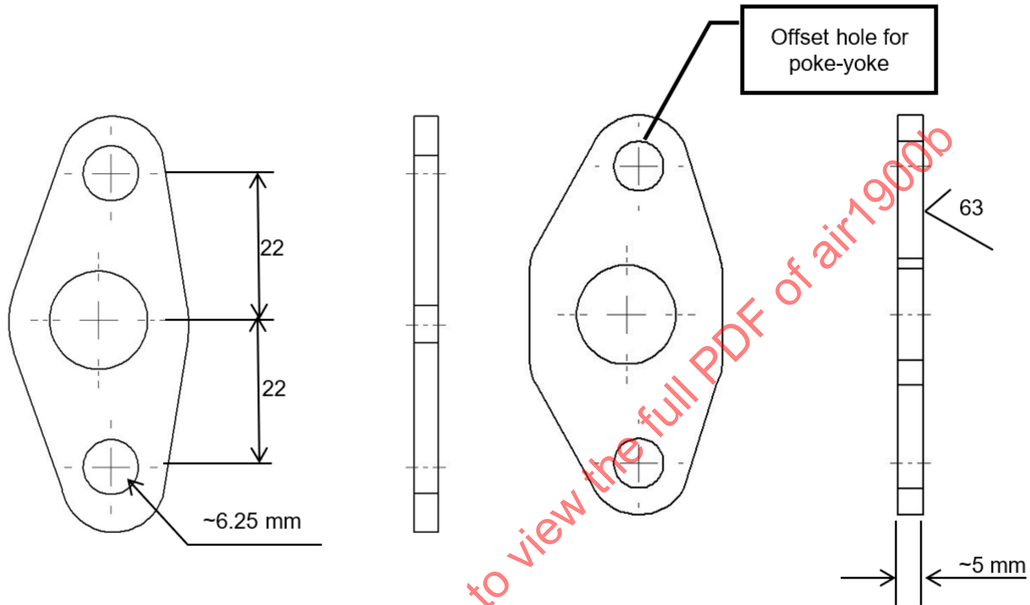


Figure 5 - Two-hole flange mounting

NOTE: All dimensions are for reference to act as a guide. Flanges should be dimensioned according to the particular environmental conditions and space envelope.

Figure 5 illustrates the standard size flange mounts with bolt holes. "a" applies when the terminal mounting shell is round, and "b" when the shell is square or rectangular.

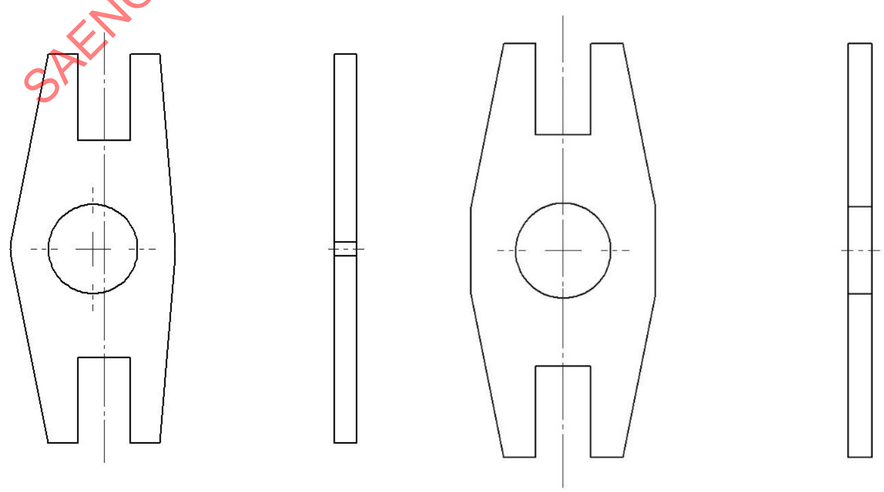


Figure 6 - Slotted flange mounting

NOTE: Flanges should be dimensioned according to the particular environmental conditions and space envelope.

Figure 6 shows slotted flanges for use with rectangular shouldered studs, providing for the use of lock nuts which eliminates the need for safety wire.

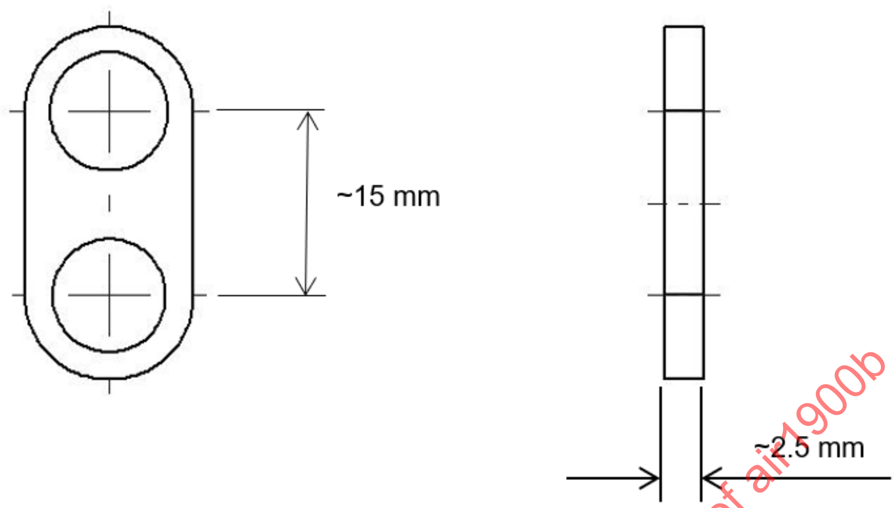


Figure 7 - Single hole flange mounting

NOTE: All dimensions are for reference to act as a guide. Flanges should be dimensioned according to the particular environmental conditions and space envelope.

Figure 7 shows the miniaturized flange suitable for applications where short, small diameter probes are used.

In general, the following notes could be considered when utilizing a miniaturized flange:

a. Flange faces to be flat within 0.10 mm.

b. Surface texture USAS B46.1 unless otherwise specified surfaces to be $^{3.2}\surd$. However, sealing faces to be better than $^{1.6}\surd$.

c. Break sharp edges 0.05 to 0.25 mm, unless otherwise specified.

d. Stamping rollover (deformation at edge of stamping due to shearing action of die) to be 0.12 mm maximum.

e. Tolerances: Linear dimension ±0.25 mm, unless otherwise stated.

5.2.3.1.1 Advantages of Flange Mounting

a. Low cost in large quantities, since they are readily produced by stamping or multi-axis CNC machining.

b. Use of flange mount, with hole offset, facilitates orientation of probes (when probes are separable from harness).

5.2.3.2 Mounting Boss

Boss mounting is often used in areas of limited space or where a leak tight seal is required and the orientation of the probe is not important. The sleeve is welded or brazed to the probe for positive support and to provide a sealing surface, which is secured between the nut and the mounting boss. The nut is usually further secured by wire locking.

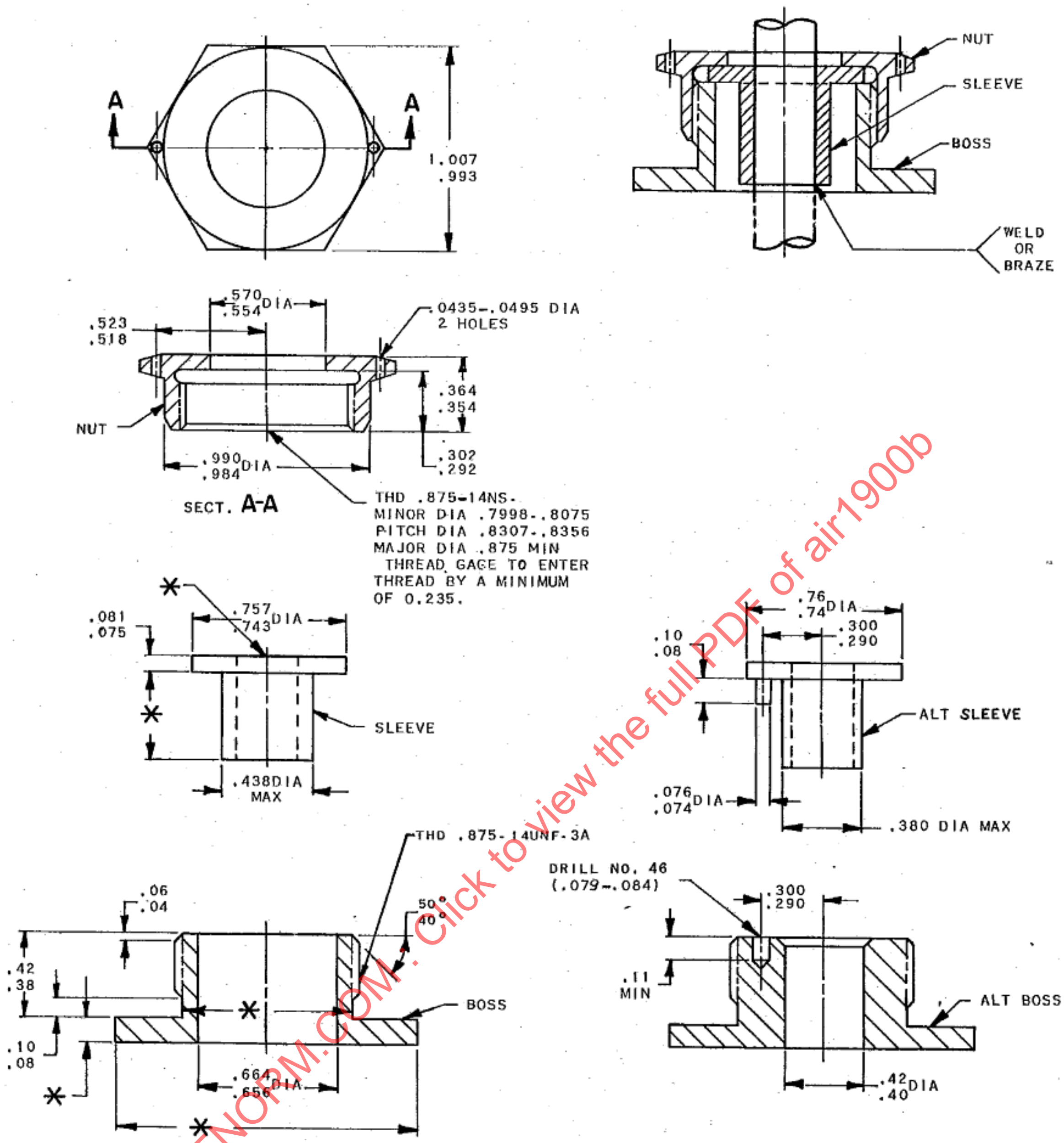


Figure 8 - Boss mounting

NOTE: All dimensions are for reference to act as a guide. Flanges should be dimensioned according to the particular environmental conditions and space envelope.

5.2.4 Sealing

Depending upon the medium and the location chosen for measurements in the engine, it is usually necessary to ensure against leakage from one location to another. For example, it will be necessary to prevent oil leakage around a sensor being used to measure oil temperature. To ensure against leakage, the sensor is usually designed with a threaded boss, such as the configuration suggested in Figure 8, with a sealing gasket or with a precision machined metal to metal face seal, where both the mounting surface and mounting flange have a very tight flatness and surface finish tolerance. Sealing difficulty may be experienced if the internal pressure is greater than 4 bar.

5.2.5 Potential Flow Distortion

Gas flow through an engine should not be disturbed by a sensor placed in the air flow path. To prevent this, the sensor is either designed to be nonintrusive, as in the case of a sensor mounted flush to the inside wall of a duct or tube, or it is designed to shed minimal wakes. If insertion in the flow is necessary, the sensor can be inserted into an engine strut or guide vane with inlet and exit ports provided. This is often done to measure EGT. Another way is to provide a sensor configuration whose configuration is an airfoil itself. For intrusive probe designs, the vortex shedding frequencies should be determined, and their effects considered.

5.2.6 Temperature Distribution Around Probe

Temperatures are often beyond the capabilities of electrical connectors or cables to survive. This means, if proper mounting is accomplished, care must be taken to ensure against excessive temperatures for certain sensor components. Not only will the ambient temperatures create difficulties, but heat can be conducted from the measured medium to the temperature sensitive components. This can happen especially in the hotter sections of the engine, including the HP compressor, HP and LP turbine areas. This is often achieved by extending the length of mineral insulated cable (MIC) to a cool zone, where it can safely interface with the less temperature resistant electrical connectors and cables. However, care must be taken to provide adequate support to the MIC.

Not only must the probe components be protected, but care must be taken to thermally isolate the temperature sensing end from the connector end. This will reduce conduction errors and provide better measurements.

5.3 Signal Transmission

In many cases, a temperature sensor is physically separated by some distance from its signal conditioner. For example, signals from a thermocouple harness used to measure EGT will generally be needed in the cockpit for display purposes. This means electrical signals will need to be transmitted over cables or lead wires. Design considerations will depend upon the sensor type, the environment in which the sensor is located and the end use.

5.3.1 RTDs

Platinum (Pt) and nickel (Ni) sensors have nearly identical needs for signal transmission. Signals from these sensors are generally processed by variations of the basic Wheatstone Bridge, to be discussed in more detail in 5.4. The main considerations for RTDs are lead resistance, lead connection, and electrical shielding.

5.3.1.1 Lead Resistance

Copper is the most common lead wire used for RTD signal transmission. Like all metals, copper lead wires possess an inherent electrical resistance, expressed in ohms/m. Electrical resistance is a function of the material, the ambient temperature and the cross-sectional area (gauge) of the wire. For example, Table 6 exhibits nominal resistances as a function of various copper wires.

Table 6 - Nominal DC resistance of selected lead wires[1]
(Ω/1000 feet [304.8 m] at 20 °C)

Wire Size (AWG/kcmil)	No. of Wires/Size (AWG or inches)	Strand Class	Nominal Area (cmils)	Silver Plated	Nickel Plated	Tin Plated
1	817/30	K	81700	0.134	0.137	0.144
1	259/0.018	H	83916	0.134	0.137	0.129
2	665/30	K	66500	0.165	0.168	0.177
2	259/0.016	H	66304	0.165	0.168	0.164
2	133/0.0223	H	66140	0.165	0.168	0.164
3	133/0.0199	H	52669	0.165	0.168	0.205
4	133/25	H	42615	0.249	0.259	0.264
5	133/0.0158	H	33202	0.249	0.259	0.325
6	133/27	H	26818	0.393	0.409	0.417
8	19/0.0295	C	16535	0.628	0.689	0.640
8	37/0.0211	D	16473	0.630	0.692	0.655
8	133/29	H	16983	0.616	0.642	0.654
10	7/0.0385	B	10376	1.00	1.10	1.02
10	19/0.0234	C	10404	1.00	1.10	1.03
10	37/26	D	9354	1.13	1.18	1.20
12	7/0.0305	B	6512	1.59	1.75	1.65
12	19/25	C	6088	1.71	1.78	1.81
12	19/0.0185	C	6503	1.60	1.75	1.70
12	37/28	D	5874	1.80	1.87	1.91
12	65/30	K	6500	1.80	1.87	1.61
14	7/0.0242	B	4099	2.53	2.69	2.63
14	19/27	C	3831	2.70	2.81	2.86
14	19/0.0147	C	4105	2.62	2.65	2.78
14	37/0.0105	D	4079	2.62	2.65	2.59
14	41/30	K	4100	2.62	2.65	2.58
16	7/0.0192	B	2580	4.02	4.28	4.27
16	19/29	C	2426	4.23	4.41	4.49
16	19/0.0117	C	2600	4.14	4.20	4.39
16	26/30	K	2600	4.14	4.20	4.07
18	7/0.0152	B	1617	6.58	6.67	6.99
18	7/26	B	1769	5.86	6.10	6.22
18	16/30	K	1600	5.86	6.10	6.61
18	19/30	C	1900	5.38	5.60	5.77
18	19/0.0092	C	1608	6.69	6.82	7.18
20	7/.28	B	1111	9.27	9.65	9.84
20	10/30	K	1000	—	—	10.58
20	19/32	C	1216	8.53	9.07	9.15
22	7/30	B	700	14.60	15.20	15.60
22	19/34	C	754	13.70	14.60	14.70
24	7/34	B	448	23.10	24.60	24.80
24	19/36	C	475	21.50	22.90	23.10
25	7/0.0067	B	314	33.00	34.80	36.40
26	7/34	B	277	37.10	39.50	39.80
26	19/38	C	304	33.30	36.60	35.70
28	7/36	B	175	58.40	62.10	66.50
28	19/40	C	182	54.60	60.00	58.60
30	7/38	B	112	90.30	99.20	96.20
30	19/42	C	118	82.70	94.00	88.80

[1] Source: Anixter (2013), pp. 93-04.

The signal processor (bridge) will receive an RTD signal affected by resistance from both the RTD and the leads. To compensate for the lead resistance, a three- or four-wire system is often chosen. As is shown in 5.4, the three-wire system almost, and the four-wire system completely, enables the bridge to compensate for the lead resistance. In the event that only two leads are used, the signal processor must account for the added lead resistance.

5.3.1.2 Lead Connection

Whenever possible, sensors should be attached to wiring harnesses through standard electrical connectors. This has two main advantages over sensors with cables permanently attached:

a. Should failures occur in either the sensor or cable, it will be necessary to replace only the failed part, leading to lower costs.

b. The sensor can be more easily designed with a hermetic seal.

If, however, hermetic connectors are not possible, then provision must be made to ensure moisture does not migrate through the cable and into the sensor itself. Moisture within the sensor or within the leads themselves can either degrade insulation resistance or cause a short circuit. In either event, the resulting measurement may be unreliable.

5.3.1.3 Electrical Shielding

Electromagnetic interference (EMI) is generally not a problem for an RTD unless unwanted signals induce currents via lead wires which can cause dielectric breakdown within the sensor itself.

However, unwanted EMI will be a problem for the signal processor if proper shielding of the cabling is not used. Figure 9 exhibits a recommended method for proper grounding of an externally shielded cable. The sensor end should be grounded, and the shield should be directly connected to that ground.

Additional care must be taken to protect the signal processor from extraneous radio frequency (RF) radiation.

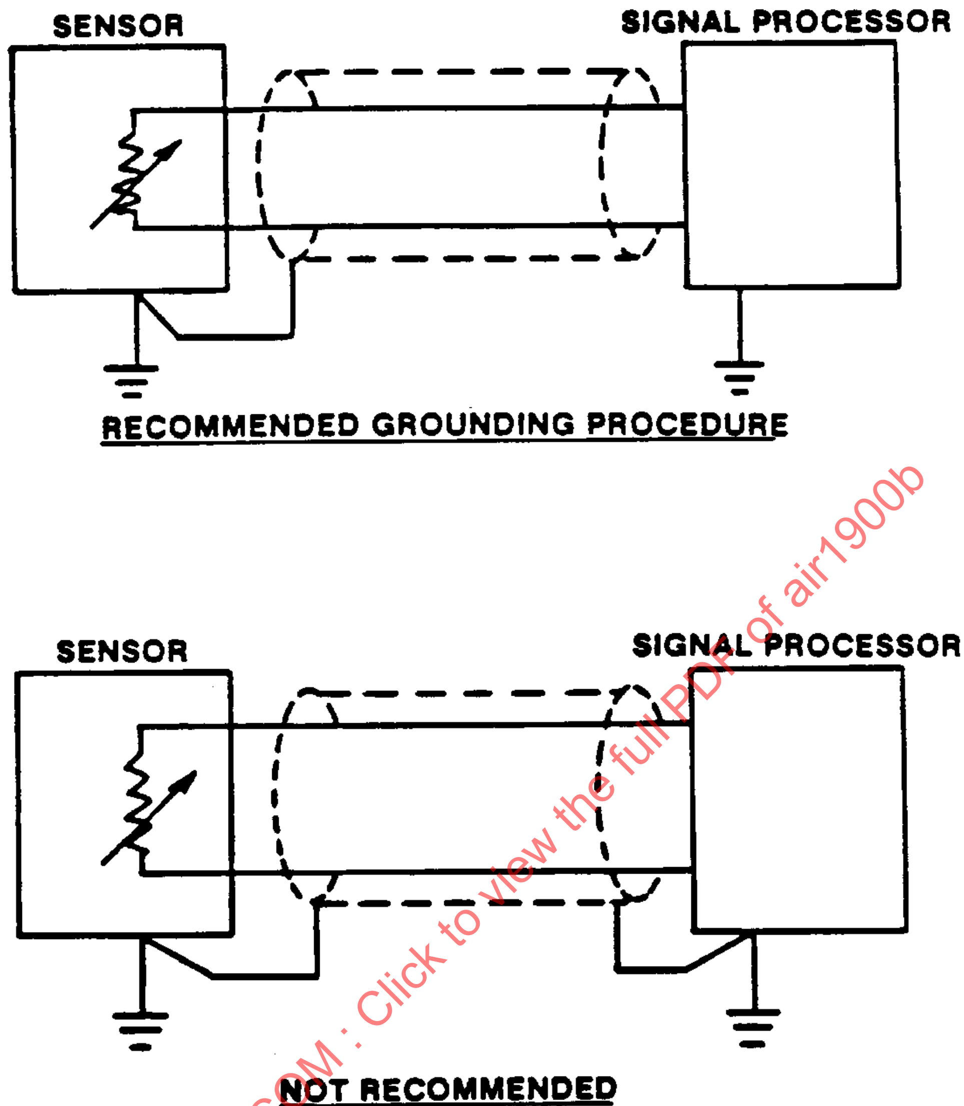


Figure 9 - RTD shielded cable-grounding options

5.3.2 Thermocouples

Signals can be transmitted from a thermocouple over the thermocouple wires themselves or through extension lead wires. Extension lead wires are attached between the thermocouple measurement end (hot junction), and the reference junction (cold junction). The central considerations for lead wires are related to extension lead materials, temperature gradients, connectors, and electrical shielding.

5.3.2.1 Extension Lead Wires

Extension leads may be used for several reasons, such as:

a. Introducing lead wires can more easily be adapted to the mounting surface.

b. Exchanging expensive thermoelectric wire for less costly extension wire.

Lead wires fall into two categories:

- Category 1: Alloys the same as the attached thermocouple wires.
- Category 2: Alloys different from the thermocouple wire.

Extension wires for types K, S, and T thermocouples are shown in Table 7.

There are several types of errors that may be introduced by the lead wires themselves. These errors include:

c. Differences in thermal EMF between thermocouples and extension lead wires.

d. Differences in temperature between the two thermo element-extension wire junctions.

e. Reversed polarity at the junctions.

f. Connector material having thermal EMF characteristics different from the lead wires.

More details on these errors can be obtained from STP470B-EB.

Care is to be taken in recommending changes from T/C grade materials.

Table 7 - Extension wires for thermocouples

Thermocouple Type	Extension Wire Type	Alloy Type Positive	Alloy Type Negative	Temperature Range (°C)	Temperature Range (°F)
K	KX	Ni-Cr	Ni-Al	0 to 200	32 to 400
T	TX	Cu	Constantan	-60 to 100	-75 to 200
S	SX	Cu	Cu-Ni	0 to 200	32 to 400

5.3.2.2 Temperature Gradients

Thermoelectric circuits can be made insensitive to temperature gradients within the extension lead wires as discussed in Trenkle et al. (1973). The main concern is that if an extension lead wire is attached to either of the thermocouple wires, the junctions at either end should be at the same temperature.

5.3.2.3 Connectors

Connectors and switches for thermocouples must not produce EMFs that would contaminate the temperature signal from the thermocouple. Spurious EMF can be caused by material incompatibility, excessive cold work (in which the calibration characteristics differ markedly from the thermocouple wires), and by temperature gradients within the connector.

5.3.2.4 Electrical Shielding

Spurious EMF must not be allowed to distort the thermocouple signal. Unshielded thermocouple leads can give rise to EMF in the presence of an intense electromagnetic field.

Ground loops must be avoided in a thermocouple circuit. For example, if different ground potentials exist between the measuring junction and the reference junction, and a ground loop exists, then a current may flow through the thermocouple leads and/or wire. Because the wire has an inherent resistance, this will give rise to a potential that will distort the original thermocouple signal.

Vendor catalogues on thermocouple connectors should be consulted for more detailed information.

5.3.3 Optical Pyrometers

The transmission of signals from an optical pyrometer will consist of two parts (examples are shown in Figure 10):

a. The transmission of radiance from the lens assembly to the photo-electric detector.

b. The transmission of an electrical signal from the pre-amplifier to the signal processor.

In the case of transmission of radiant energy, there are two different means of conveying energy. In the first case, radiant energy can be focused directly on the photoelectric detector. In the second case, radiant energy is transmitted from the lens assembly through a fiber optic cable to the detector/pre-amp assembly some distance away.

The transmission of radiant energy directly onto a detector does not present any special problems. However, due to the high ambient temperatures and high vibration levels adjacent to the engine casing it is normal to locate the sensing electronics away from this environment. Fiber optic cable lead outs provide a means to transmit the energy away from the hostile environment. The following discussion will focus on the transmission of radiant energy via a fiber optic cable as well as to discuss the considerations associated with transmitting current from the pre-amplifier to the signal processor.

5.3.3.1 Type of Fiber-Optic Cable

Fiber-optic cables can either be single fiber cables or fiber bundle cables. Single fiber cables typically offer greater efficiency (in radiant energy per square centimeter) over the cross-sectional area of the cable, possibly higher temperature capability, and better fault isolation (if the cable is broken, no signal is transmitted to the detector). Fiber bundles, on the other hand, offer the advantage of somewhat greater reliability; i.e., if one fiber is broken, there is redundancy in the system. Furthermore, fiber bundles are generally more widely available, hence less expensive.

5.3.3.2 Transmissivity

Transmissivity is defined as the percentage of radiant energy received by the lens that impacts the photoelectric detector. Transmissivity is a primary consideration in choosing a fiber optic cable. Typically in the 60% range, it is important to acquire the largest transmissivity possible in order to maximize output current from pre-amplifier assembly.

5.3.3.3 Temperature Limits

For purposes of mounting the cable, it is desirable to ensure the cable will survive maximum temperatures between 400 to 500 °C (approximately 750 to 900 °F). This is because locations aft of the turbine case may not receive cooling bypass air. Furthermore, modern engines operate at increasingly higher TET temperatures. This means the turbine case will experience temperatures up to 500 °C (approximately 900 °F).

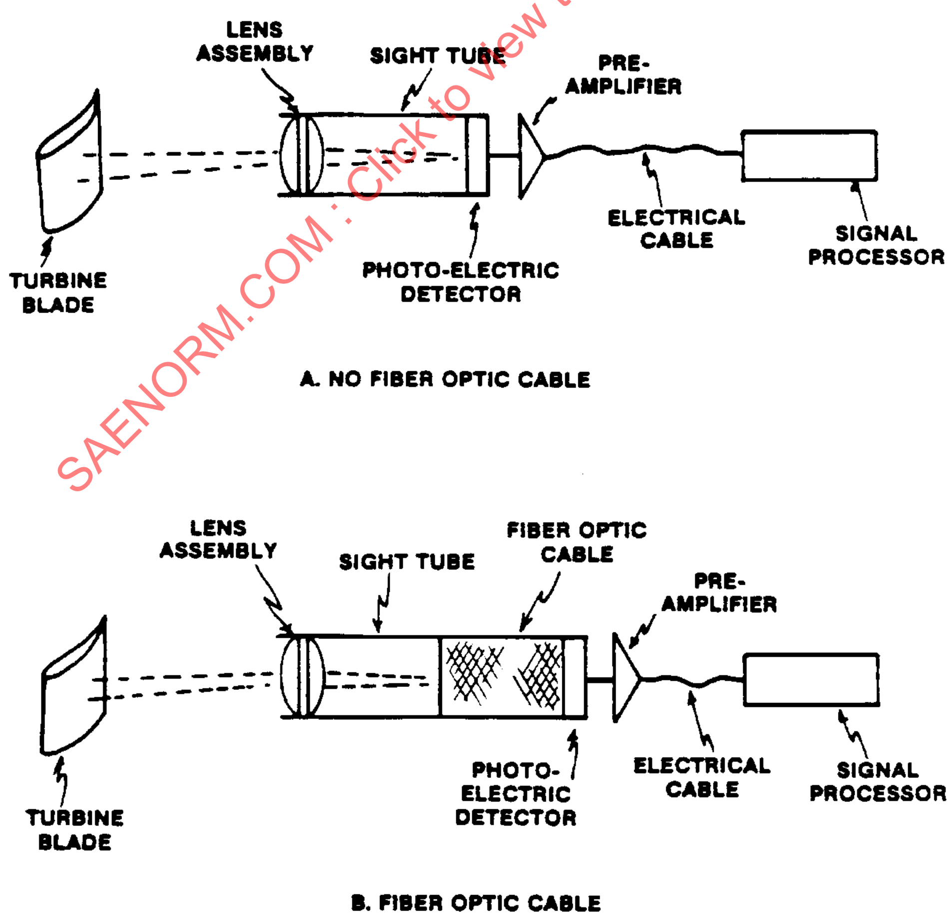


Figure 10 - Transmission of radiant energy

5.4 Signal Processing

The task of processing signals from RTDs, thermocouples, optical pyrometers, optical fiber thermometers, and gas-filled bulbs can range from a simple Wheatstone Bridge for an RTD to complex electronic devices for processing radiance signals from optical pyrometers. The following discussions will focus on the key considerations.

5.4.1 RTDs

Variations on the basic Wheatstone Bridge (refer to Trenkle et al., 1973) are used to condition the signals from an RTD. For most applications, the bridge is excited with a constant voltage power source (28 VDC). However, there are also bridges excited by constant, current sources. They will have different impacts on probe self-heating. The following considerations are important in the design of a bridge circuit: nonlinearities, self-heating errors of the probe, temperature sensitivity, and supply voltage. Self-heating errors are discussed in 7.1.1.2.5.

5.4.1.1 Nonlinearities

The bridge output voltage is always a nonlinear function of the probe resistance, and the probe resistance is a nonlinear function of temperature (especially for nickel RTDs). This means bridge output voltage will be a nonlinear function of temperature. However, in the case of nickel RTDs, nonlinearities in the probe tend to compensate the nonlinearities of the bridge. Increased linearization of a bridge with nickel RTDs can be accomplished by placing a selected fixed resistor in parallel with the probe.

In the case of platinum RTDs, the nonlinearities of the probe and the bridge tend to be additive. The total nonlinearity can be kept small by minimizing probe self-heating. In most aircraft applications, the bridge is excited by a constant voltage (28 VDC) source. The result is that probe self-heating is inversely proportional to probe resistance. In the case of constant voltage excitation, bridge nonlinearities can be kept small by selecting probes with high resistance (e.g., greater than 500 Ω).

In the case of constant current bridges, however, probe self-heating is directly proportional to probe resistance. This means selection of small resistance sensors is necessary to minimize self-heating and thereby nonlinearities.

5.4.1.2 Temperature Sensitivity

Given proper choice of bridge resistors and lead wires, changes in environmental temperature should not have an appreciable effect on bridge output. For example, Manganin wire resistors and copper leads will leave the bridge insensitive to temperature. However, the use of constantan along with copper should be avoided since the combination will cause thermoelectric effects with temperature.

5.4.1.3 Supply Voltage

The bridge supply voltage should be regulated closely, since voltage changes can cause output errors.

5.4.2 Thermocouples

Signals from thermocouples are processed for display in the cockpit and for input to the engine control unit (ECU). Direct display processors are often moving coil indicators, whereas processors in the ECU are generally analog to digital convertors. Two types of convertors are generally available: the integrating type and the successive approximation type. General considerations include the temperatures of the reference junction and electrical noise interference.

5.4.2.1 Reference Junction

Correcting or compensating a thermocouple for the cold junction temperature is usually accomplished using a “floating” reference junction, shown schematically in Figure 11. The junction is a standard uniform temperature reference (UTR) box with multi-channel capacity. The temperature in the UTR, called the reference temperature, is allowed to “float” but is measured through the use of an RTD or thermistor in the UTR. Therefore, the output voltage from the thermocouple is compensated by the addition of voltage corresponding to the reference temperature.

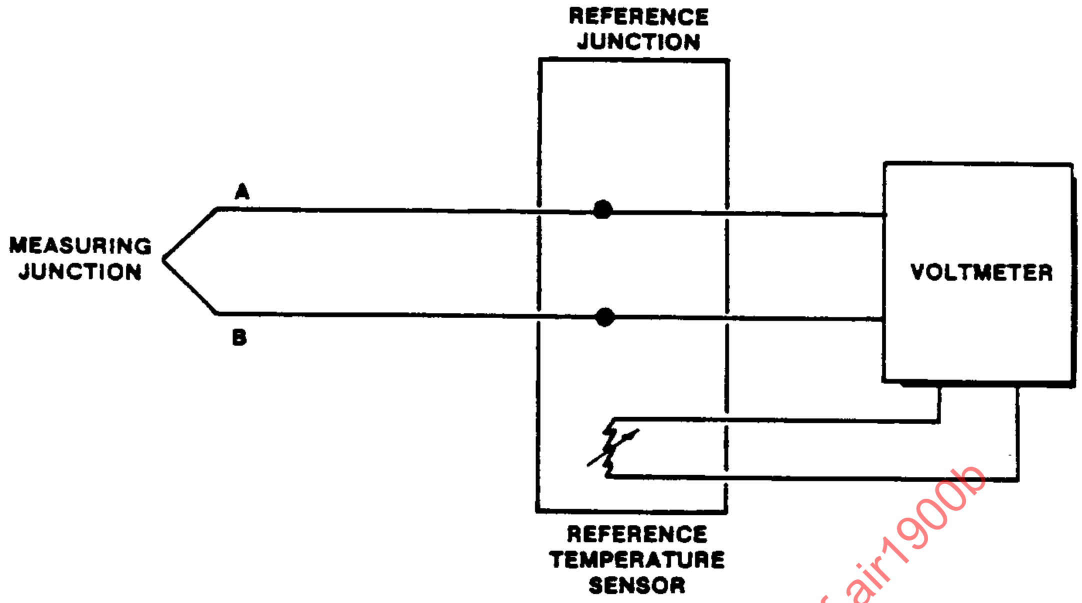


Figure 11 - Floating reference junction for thermocouples

5.4.2.2 Electrical Noise

The signal from a type K thermocouple is approximately 40 µV/°C (20 µV/°F). Furthermore, the resolution of many signal processing instruments must be kept small (2 µV maximum) to guarantee high accuracy in the entire temperature measuring system. Of the two types of digital voltmeters, the integrating type is generally less susceptible to noise than the successive approximation type. More information can be obtained from AIR46.

5.4.3 Optical Pyrometers

Optical pyrometers can be used for development, control, diagnostics, or condition monitoring. This means that signals may be processed for input to either the engine control unit, to a dedicated, on-board data acquisition unit (for flight instrumentation), or to a ground-based data acquisition unit (for development, diagnostics, or ground-based condition-monitoring systems). Electrical signals are in the form of DC voltage and they range in magnitude from a few millivolts at the lower operating temperatures (600 °C) to several volts at the higher operating temperatures (1450 to 1500 °C).

5.4.3.1 Typical Signal

The measurement of turbine blade temperature (TBT) is difficult for several reasons. To begin with, the target is remote and moving at high speed. Secondly, the optical signal from the passing blades (expressed in watts per square centimeter per micron) must be converted through a detector/pre-amplifier to an electrical signal (usually expressed in volts). The resulting electrical signal is a nonlinear function of temperature. Moreover, the higher the temperature, the more accurate the electrical signals. Finally, the electrical signal is weak and must be separated from several other extraneous signals. These extraneous signals result from emissions from the gas itself, emission from hot particles passing in view of the lens and reflected radiation from the combustor. A sample output pattern is shown in Figure 12.

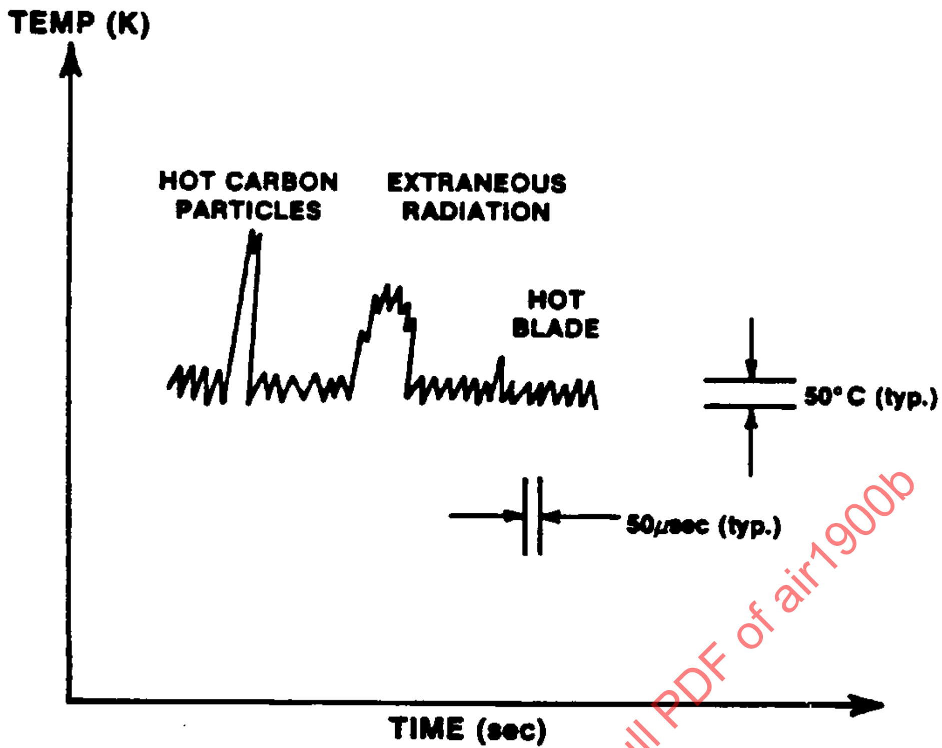


Figure 12 - Typical radiation pattern from optical pyrometers

5.4.3.2 Desired Outputs

The raw output from an optical pyrometer typically has a low signal to noise ratio. The signal typically contains extraneous radiation which can range from short 10μs bursts with amplitude no larger than peak blade radiance to peak brightness over 100 times the blade radiance and lasting for several microseconds.

The types of signals desired depend strongly upon the function of the pyrometer in the engine. They are given as follows.

5.4.3.2.1 Average Peak Blade Temperature

This type of signal is often used as a control signal to limit the maximum TBT. In the presence of extraneous radiation, it will not usually be possible to detect individual overheated blades. The electrical bandwidth is usually much lower than for a diagnostics/condition monitoring pyrometer.

5.4.3.2.2 Minimum Picking Temperature

Extraneous radiation always contributes positively to the TBT signal. This means that if the positive contribution can be eliminated, the remaining (called minimum picking) signal could be used for blade profiling purposes. This type of signal is appropriate for development, diagnostics, or condition monitoring purposes.

5.4.3.3 Electrical Bandwidth

The electrical bandwidth will depend strongly on the function of the pyrometer. Generally speaking, for control purposes, the bandwidth can be low (on the order of 0 to 20 kHz). However, for purposes of development and diagnostics, the bandwidth must be larger.

For purposes of blade profiling (to assess blade cooling designs for example), it is recommended that the optical target (spot size) be selected to be approximately one-fifth the viewable blade width and the electronic bandwidth be selected to be maximum blade passing speed divided by the target diameter. This would mean it may sometimes be necessary to establish a bandwidth as high as 125 to 150 kHz. A pyrometer, to be used for condition monitoring might thus require an electronic bandwidth somewhere between 15 kHz and 150 kHz, depending upon the temperature that is required.

5.4.4 Gas-Filled Thermometers

The processing of signals from gas-filled thermometers is usually not accomplished since there is generally no electrical signal involved. Instead, the mechanical position of the gas-filled reservoir is amplified and sent to the various mechanical servos in the ECU.

5.5 Shared Signals

Signals from various sources on the engine are often shared by subsystems with varying purposes. For example, a signal used by the ECU to control fuel flow may also be used for cockpit display. In a similar manner, signals used for control (e.g., T_2) may be selected for input to an on-board, condition-monitoring system. While this may not be unusual, there are considerations that must be made in order to ensure the intended accuracies of the various signals. These considerations fall into at least two areas:

a. Physical location of bifurcated signals.

b. Compatibility of electrical bandwidths.

5.5.1 Bifurcated Signals

Generally speaking, a properly designed amplifier with multiple outputs can supply signals (current or voltage) to different functions from the single output of a single sensor. However, it is not advisable to separate signals from a single sensor in advance of the signal conditioner as Figure 13 illustrates. Consideration should also be given to ensuring the excitation currents are identical among different power sources. If they are different, the sensor will experience different levels of self-heating giving rise to errors in measurement.

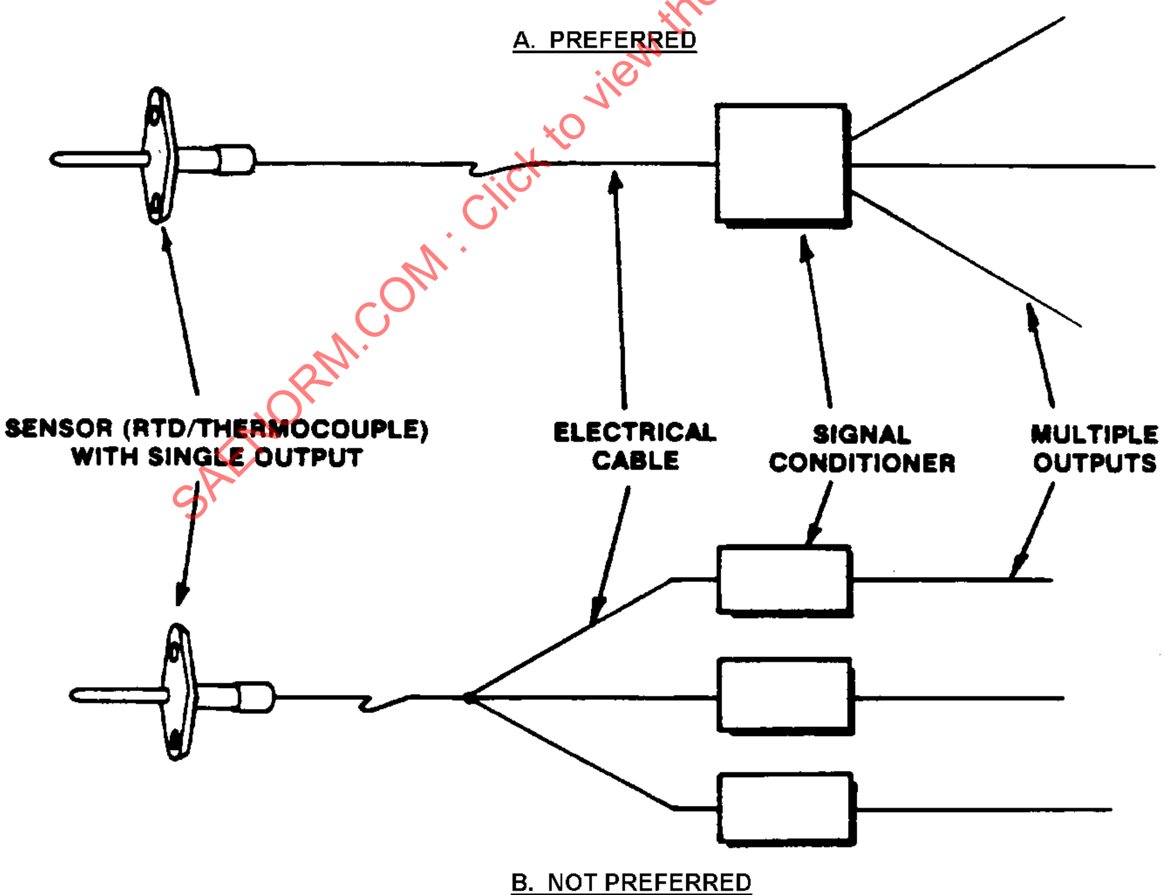


Figure 13 - Locations of signal bifurcation

5.5.2 Signal Bandwidth Compatibility

Sharing signals can be a problem if the functions intending to share a signal have widely differing data transfer or sampling needs. For example, optical pyrometer signals can range from 25 to 50 kHz to more than 150 kHz. Unless data acquisition rates between the different functions can be made compatible, it is highly probable that accuracies of the temperature devices will be compromised. For example, a diagnostics/condition monitoring function will generally require much higher bandwidths than will a control function. This means a control output at 50 kHz will probably not be sufficient for blade profiling at much higher frequencies.

Bandwidth is generally not a problem for an RTD or a thermocouple since their response times are generally much slower than the data transfer or sampling rates for most systems. For example, a typical RTD time constant is 4 to 6 seconds in air, while a 1 kHz data rate provides an upper response of 2 ms.

6. SELECTION CRITERIA

Stated in general terms, the selection of temperature systems or subsystems is made with consideration of the following:

a. Type of measurement.

b. General performance, including accuracy.

c. Costs, including hardware and maintenance.

d. Reliability and maintainability.

e. Interface considerations.

6.1 Measurement Type

The measurement type includes the consideration of whether:

a. The type of medium being measured is gas path, turbine blade, oil or fuel temperature.

b. The measurement is for engine testing or whether it is a measurement on production engines.

c. The measurement is for control, diagnostics and condition monitoring purposes, or for performance measurement.

d. The signal is to be used for instrument reading, airborne recording, or for real-time use.

e. There are individual or multiple measurements, such as point or area measurements, mean, differential, or rate-type measurements.

For those measurements where the results are to be displayed in the cockpit, the need for accuracy may not be as great as those cases where the measurement is to be used for airborne recording or real-time use. In some instances, diagnostics and condition monitoring measurements will need to be more accurate than for purposes of control. For trending, stable, repeatable measurements are needed.

6.2 Performance

There are several performance characteristics of interest, such as:

a. Temperature range.

b. Accuracy.

c. Time response.

d. Stability.

6.2.1 Temperature Range

There are two ranges of concern: the operating measurement range and the ambient or environmental ranges. Generally speaking, the environmental range will differ from the operating range and is important in determining the interface (such as connectors versus cables) and whether signal conditioning can be done locally or remotely. The various parts of a temperature measurement system may have very different ambient temperature ranges, depending on their location.

6.2.2 Accuracy

An accurate measurement is one with low measurement uncertainty. Generally speaking, uncertainty can be expressed as the sum of time-dependent error sources and those which are time- independent as follows:

$$e(t) = a(t) + b \tag{Eq. 4}$$

where:

e(t) = total measurement uncertainty, as a function of time

a(t) = time dependent error

b = time independent error

Generally speaking, the time dependent error a(t) is referred to as stability. It can be characterized as a drift in measurement. Moreover, the total measurement uncertainty can be expressed as the sum of random errors and systematic errors. Systematic errors are predictable errors. These are often called bias errors, dependent upon the engine operating condition. The random errors are not predictable and contribute to a band of uncertainty about the systematic error. Random errors will include some portion of the signal conditioning errors. More discussion follows in Section 7.

6.2.3 Time Constant

The primary time constant of a sensor is generally expressed as the time taken by the sensor to respond to 63.2% $(1-e^{(-1)})$ of a step change in temperature. The importance of time constant depends upon the function and type of measurement. It is typically desirable to minimize the time constant to achieve rapid response of the system, particularly for control purposes. Low response rate sensors can be used during steady-state conditions to measure engine performance trends, such as EGT.

6.2.4 Stability

As explained in 6.2.2, the measurement is subject to drift over time. The amount of drift allowable depends upon the overall level of accuracy required of the sensor as well as the type of measurement being made.

6.3 Costs

The cost of a system is often complex and difficult to estimate. Costs often include but are not necessarily limited to the following:

a. Unit cost, purchased from the vendor, for production engines.

b. Nonrecurring development cost.

c. Qualification costs including data costs.

d. Flight testing costs.

e. Product support costs.

f. Spares costs.

g. Other administrative costs.

While initial costs of a system or subsystem may be low, the total life cycle cost per unit may be high. This may occur, for example, when failure rates are high and spares costs are excessive.

6.4 Reliability/Maintainability

The selection of a temperature system often depends upon the reliability of the system itself. This can be measured in a number of different ways, including:

- Mean time between overhauls (MTBOs).
- Mean time between failures (MTBFs).
- Mean time between unscheduled removals (MTBURs).

It is necessary to define the different failure modes, such as:

a. Intermittent reading.

b. Open circuit.

c. Out of tolerance condition, determined by some reference.

d. Other—dependent upon data acquisition.

Maintainability may also be a determining factor in the choice of a temperature system. For example, the extent to which a system conforms to “on-condition” maintenance may be important. Additionally, accessibility of the probe or other parts of the system may be important in its selection. For example, if a location for mounting is not available, alternative measurements may be required in lieu of the direct measurement.

6.5 Interface Considerations

Interface refers to the electrical and physical connections that must be made to attach the sensor at its location. Consideration should be given to the following:

a. Mounting holes and brackets.

b. Vibration isolators.

c. Connectors and cables.

d. Shielding.

e. Signal conditioning.

f. Electrical uses of the signal, such as engine control units (ECUs), engine monitoring units (EMUs), air data computers (ADCs), multiplexers (MUXs), and data buses.

g. Modular design aspects.

h. Quick disconnect.

i. Testability.

j. Need for cooling (air/fluid).

7. ACCURACY

All practical measurements are accompanied by measurement uncertainties. Generally speaking, a measurement uncertainty or error is the sum of a systematic or predictable component and of a random or unpredictable component. Systematic components are predictable using any number of engine flight conditions. As such, the errors can be compensated by appropriate signal processing. Random errors, on the other hand, are not predictable, and hence, they must be regarded as residual errors after compensation for systematic components. An accurate measurement is one with low errors while a repeatable measurement is one with low random (but not necessarily low systematic) errors.

While it is possible to utilize sensors that are repeatable for the functions of control and cockpit display, accurate sensors are needed for diagnostics and condition monitoring. For performance monitoring, repeatability is more important. Hence, there may be a risk in sharing signals with control sensors unless the accuracy requirements for condition monitoring are met. It should be noted that single gas path sensors only provide an estimate of the average gas path temperature.

7.1 Error Types

7.1.1 RTDs and Thermocouples

Temperature measurement errors may be:

a. Meteorological errors.

b. Position errors.

c. Temperature lag error.

d. Instrument error.

e. Lead wire errors.

f. Indicator errors.

7.1.1.1 Meteorological Errors

In the event a measurement is being made in the inlet or bypass duct of an engine, the effects of moisture and of snow or ice can be quite pronounced. Water droplets can impinge directly on the sensing element, if care is not taken to inertially separate droplets or moisture from the temperature sensing element. Continuous airflow past the element will generally cause an evaporative process to take place which means the establishment of temperature equilibrium lower than that prevailing in dry air. This is the so-called "wet bulb temperature" effect and can cause considerable measurement errors. The magnitude of this error depends on several factors. These factors include relative humidity, flow rate, static temperature, difference between water temperature and static temperature, etc. The unpredictable magnitude of this error means that it must be treated as a random error.

7.1.1.2 Position Errors

To measure the temperature at a given location, the sensor and the measured medium must come into thermal equilibrium with one another. Due to the need to make measurements practical and reliable, something less than true equilibrium between sensor and medium is achieved. This means the measurement involves less than ideal heat transfer between sensor and medium. It may be ascribed to the physical location (i.e., position) of the sensor or to the configuration of the sensor itself. For example, a probe whose sensing element is immersed directly in the airstream will perform differently from a probe whose sensing element is placed elsewhere in the probe with airflow directed to it.

Position errors fall into the following categories:

a. Probe location error.

b. Velocity error.

c. Conduction error.

d. Radiation error.

e. Self-heating error.

f. De-icing heat error.

7.1.1.2.1 Probe Location Error

Three different types of location error may occur. They include (1) the error due to differences in flow rates between the probe and the medium, (2) the error due to differences between the actual thermodynamic station and the desired thermodynamic station, and (3) attitude errors.

7.1.1.2.1.1 Flow Rate Differences

This error arises because the local flow rate at the probe is different from the actual flow rate in the medium. For example, total temperature (T_t) is the sum of static air temperature (T_s) and the adiabatic temperature rise (ΔT_k) as follows:

$$T_t = T_s + \Delta T_k \quad \text{(Eq. 5)}$$

Furthermore, adiabatic temperature rise is related to T_s through the Mach number as follows:

$$\Delta T_k = T_s\left(\frac{\gamma - 1}{2}\right)M^2 \quad \text{(Eq. 6)}$$

where:

T_s = given in absolute units (k)

γ = ratio of specific heats C_p/C_v

In an ideal sense, the sum of static and adiabatic temperatures inside a closed system such as an engine inlet should remain constant, unless heat transfer changes one or both components. However, the flow rate inside a flow boundary layer is much slower than in inviscid airflow. Moreover, the static temperature cannot be measured well because of convection phenomena. This means the measurement of total temperature from inside a flow boundary layer will result in a measurement error which is referred to here as position error.

7.1.1.2.1.2 Actual Versus Desired Thermodynamic Station

Position errors also occur when, for example, an attempt is made to measure T_{12} (first compressor front face tip section total temperature) by locating the probe at the T_{13} location (see 4.2.1). In twin-spool turbofans, this position is behind the fan. Some adiabatic compression takes place between the T_{12} and T_{13} stations. However, the increase in total temperature between the two locations cannot simply be subtracted from T_{13} to estimate T_{12}. This is because convection and radiation effects occur within the turbulent flow pattern at station 13.

7.1.1.2.1.3 Attitude Errors

Position errors can also include attitude errors that arise because of changes in the direction of flow. This, in turn, gives rise to an angle of attack or angle of sideslip effect, causing a shift in the recovery of adiabatic temperature rise, the subject of which is covered in the next subsection.

7.1.1.2.2 Probe Velocity Error

Even under conditions where probe location errors are minimized or eliminated, complete capture (or recovery) of the sum of static plus adiabatic temperature rise is impossible. This arises mainly in the measurement of gas path temperatures.

The proportion of the adiabatic temperature rise ΔT_k that is recovered by the probe is called the recovery factor r. It is defined as follows:

$$r = \frac{T_i - T_s}{T_t - T_s} \qquad \text{(Eq. 7)}$$

where:

Ti = indicated temperature

It is also shown in Figure 14.

Furthermore, the temperature velocity error E_v is given as the difference between true total temperature and indicated temperature.

$$E_v = T_t - T_i = \Delta T_k(1 - r) \qquad \text{(Eq. 8)}$$

Since T_t is not known, a substitute for T_t must be made in terms of known quantities. First, T_t is found in terms of T_i as follows: Let $\eta = 1 - T_i/T_t$ to express the fraction of total temperature not recovered through T_i. Next, T_t is expressible as:

$$T_i = T_i /(1 - \eta) \qquad \text{(Eq. 9)}$$

This means:

$$E_v = T_i \frac{\eta}{1 - \eta} \qquad \text{(Eq. 10)}$$

However, when η is small, E_v is given approximately by:

$$E_v = \eta T_i \qquad \text{(Eq. 11)}$$

More details are given for thermocouples in AIR46.

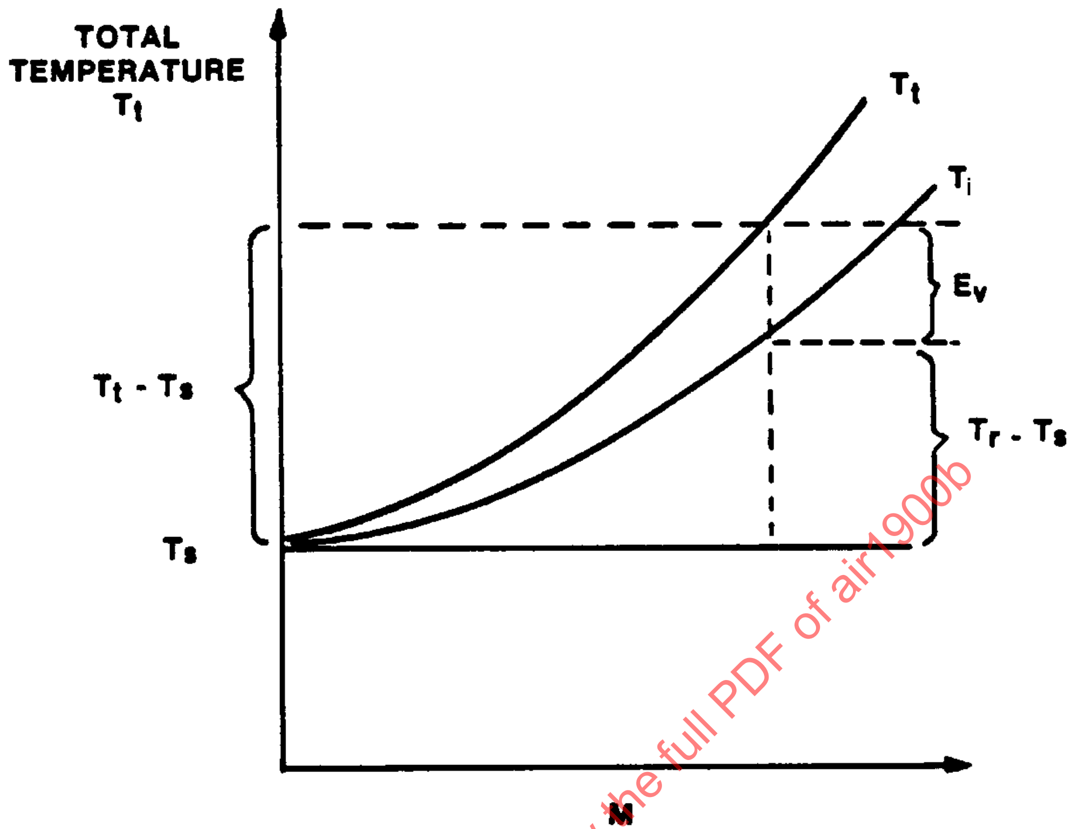


Figure 14 - Total temperature as function of Mach number

7.1.1.2.3 Conduction Error

This error is caused by heat transfer to (from) the sensing element from (to) the mounting surfaces and the electrical leads. This error is a function of the flow rate past the sensing element as well as the ratio of length to diameter of the probe (L/D) and the temperature difference. AIR46 shows the effect on conduction error of both flow rate and L/D in Figure 15.