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AEROSPACE INFORMATION REPORT

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GUIDE TO TEMPERATURE MONITORING IN AIRCRAFT GAS TURBINE ENGINES

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF TABLES

1. SCOPE:

This Aerospace Information Report (AIR) provides an overview of temperature measurement for engine monitoring systems in various areas of aircraft gas turbine engines while focusing on current usage and methods, systems, selection criteria, and types of hardware. This document emphasizes temperature monitoring for diagnostics and condition monitoring purposes.

2. PURPOSE:

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

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 AIR 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 make certain temperature measurements on the aircraft physically apart from 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 AIR will not address the theory of these phenomena. The reader is referred to Reference 18 for more in-depth information.

4. CURRENT USAGE:

The measurement of temperature is dependent on the state of both the current technology available to the user and 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 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 (Ref. AIR1873). Signals dedicated to monitoring are usually not actively utilized to control or correct other variables in an engine. However, signals used for control are sometimes used for condition monitoring. Temperature measurements made in various locations of the engine during the development phase are included in this function.

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: Internal engine temperatures are critical to the determination of engine performance. Engine performance can be measured in a number of ways, including corrected fan speed (N_1/θ), engine pressure ratio (EPR), or specific fuel consumption (SFC). Two of these measures, N_1/θ and SFC depend strongly on temperature measurements.

4.2 Media:

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

a. Gas paths
b. Turbine blades
c. Liquids, including oil and fuel

4.2.1 Gas Path:

4.2.1.1 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 will be discussed in the following paragraphs. The stations and their designation are described in 4.4.1 and illustrated in Figure 3.

4.2.1.1.1 T1, T12, and T2 Locations: The reasons for making these measurements are generally related to control. 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 T2x and T3 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 (T1, T12, or T2) temperature to reference (sea level) ambient temperature.

In many civil (commercial) applications, T1 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 T2x and T3: These temperatures are often selected for diagnostics and condition monitoring purposes. They can be used to identify trends, track efficiencies of low (T2x) and high (T3) pressure compressors through examination of their discharge temperatures in order to establish relationships between temperatures in the engine (between T1 and T2x for example) under various engine operating conditions.

4.2.1.1.3 T4x, T5, and T7: These temperatures are used for all purposes, including control, diagnostics, condition monitoring, cockpit display, and for performance measurement.

4.2.1.2 Temperature Range: The temperature ranges for each measurement are given by thermodynamic station in Table 1. 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). For high performance engines, maximum TET exceeds 1150°C (2100°F, 2560°R or 1423 K), 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.

TABLE 1 - Normal Operating Temperature Ranges

Station	High (°C)	Low/Medium (°C)
T1/T12/T2	-55 to +175	-55 to +125
T2x	-55 to +260	-55 to +200
T3	0 to +650	0 to +500
T4x	260 to >1150	260 to <1150
T5/T7	260 to +600	260 to +500

In general, there is a trend toward higher core temperatures, particularly T3, T4x, T5, and T7. 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.

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

Accuracies are provided in Table 2 and discussed further in related SAE documents cited in the bibliography (such as ARP1587 and AIR1873).

TABLE 2 - Accuracy Requirements

Temperature	Control (°C)	Diagnostics/ Condition Monitoring	Cockpit Display (°C)	Performance Measurement (°C)
T1	±0.5	°C	±1.0	±0.5
T12	±2.0	°C	NA	±1.0
T2	±2.0	°C	NA	±1.0
T2x	±2.0	TBD °C	NA	TBD
T3	NA	°C	NA	TBD
T4x	TBD	°C	±10.0	TBD
T5/T7	±2.5[1]	°C	±10.0	±10.0

[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 is measured to assure blade temperature limits are not exceeded. Exceedance of established maximum allowable temperature will significantly reduce the creep life of a part (see AIR1872). The purposes of the measurement include control, diagnostics, and condition monitoring.

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

4.2.2.3 Temperature Range: The operating temperature range is from +650 to +1500°C.

4.2.2.4 Accuracy: Accuracy requirements are meaningful only at the temperature design point selected. This may be anywhere over the operating range of temperatures. At the design point, the accuracy will typically be ±9°C.

4.2.3 Oil Temperature:

4.2.3.1 Purpose: The purpose of this measurement is for condition monitoring, diagnostics or cockpit display.

4.2.3.2 Location: The location of the temperature sensor will be before the oil cooler, see 4.4.3.

4.2.3.3 Temperature Range: The temperature range is from -55 to +150°C.

4.2.3.4 Accuracy: The accuracy for the condition monitoring and diagnostic purposes should be ±3.5°C. It should be within ±3.5°C for cockpit display.

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 (RTD)
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: Resistance temperature devices (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 increases with increasing 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.

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

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

where T = temperature (°C)
R_T = resistance at T degrees
R_O = resistance at the ice point
α = sensitivity coefficient, varies between .00385 and .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 $T \geq 0$

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 vs 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 1. Note MIL-T-7990B is defined for temperatures up to 300°C, beyond the normal operating range for nickel.

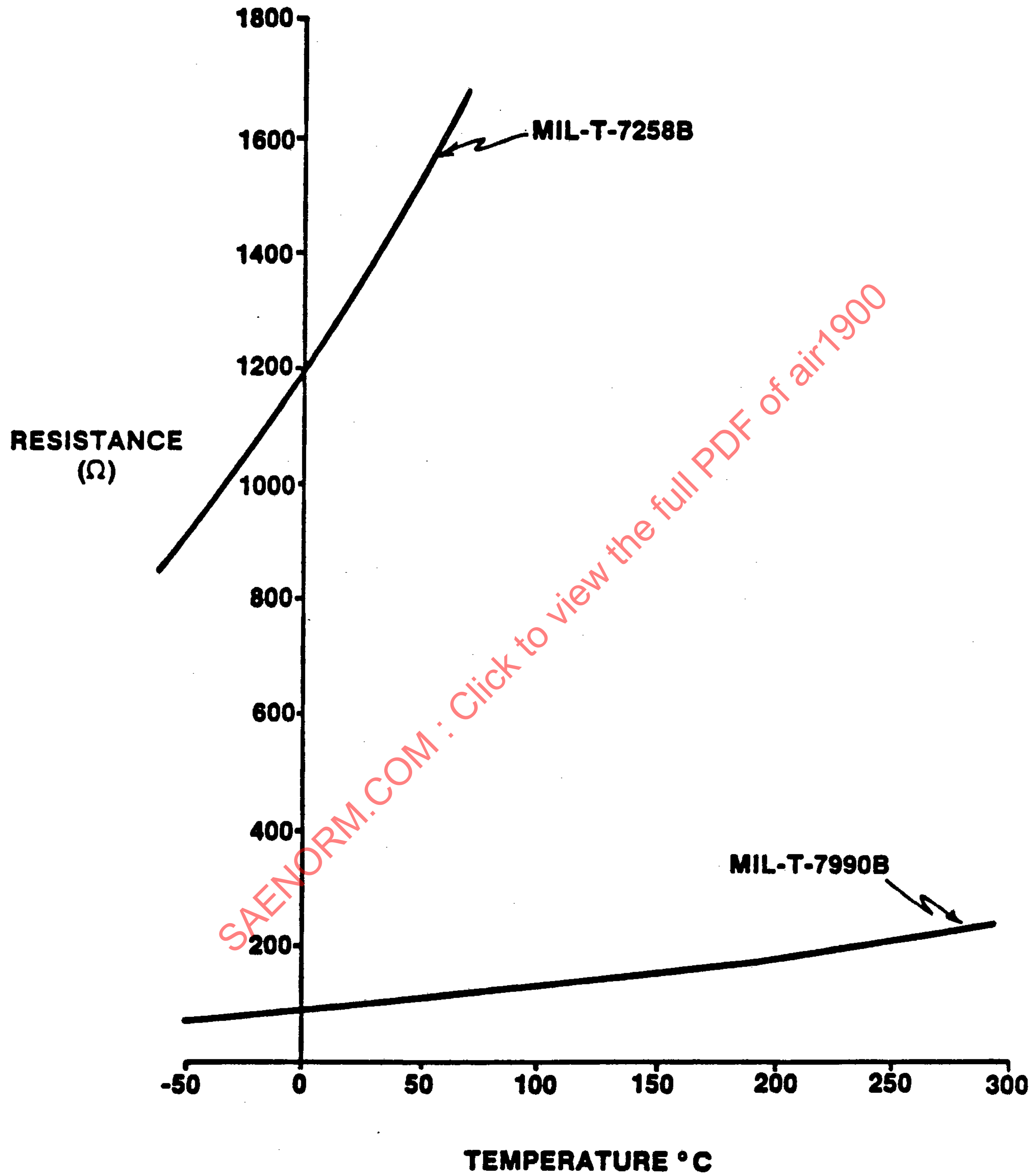


FIGURE 1 - R Versus T Two Nickel Sensors

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, including the following:

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 thermoelements chosen.

There does seem to be a trend away from thermocouples for many of the compressor section measurements. Furthermore, turbine blade temperatures (TBT) are beginning to be measured by optical pyrometers for high performance military engines. At this time, the TBT measurements are being made exclusively by thermocouples for civil aircraft 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 AIR is not intended to be a detailed reference on thermocouples. It is recommended that AIR46 and AIR65 be consulted for more in-depth discussion. An explanation of the theory of thermocouples is given in Reference 17.

4.3.2.1 Types of Thermocouples: There are several types of thermocouples used on aircraft. These are shown in Table 3, along with their performance characteristics. Of these, type K and type E thermocouples are the most commonly used on aircraft gas turbine engines.

4.3.2.2 Temperature Range: The temperature ranges shown in Table 3 are given for bare wire thermocouples. The maximum temperature will provide only a short life. To obtain a reasonable sensor life, these maximum temperatures should be lowered 100 to 150°C for the wire sizes (16 to 18 gauge) typically used in turbine engine instrumentation.

4.3.2.3 Thermal-emf Relationships: The emf-temperature relationships are given in Figure 2 for several different thermocouples. Even though the outputs are nonlinear, they can be considered linear over short (10 to 20°C) temperature spans.

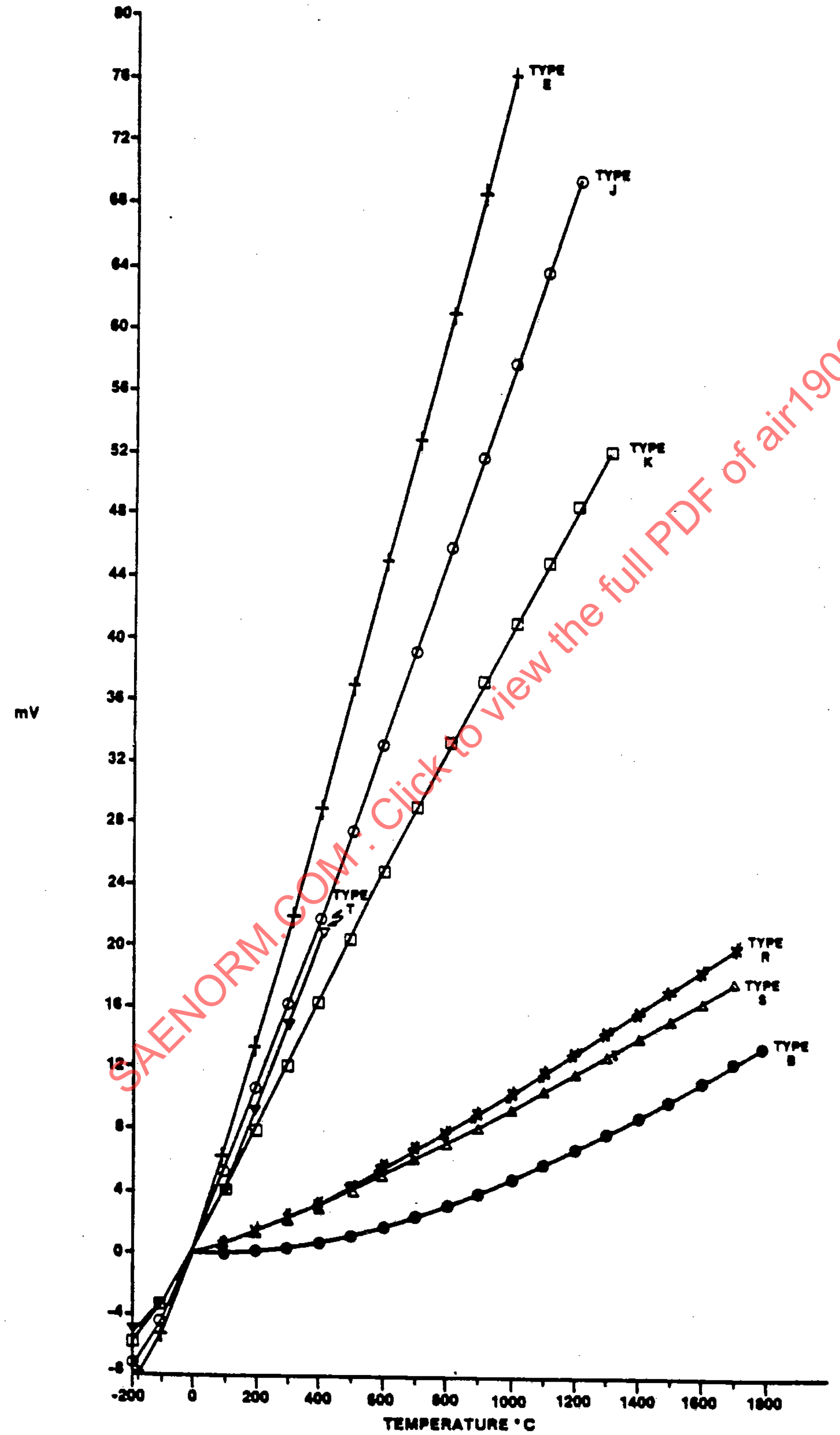
4.3.3 Optical Pyrometers: Optical pyrometers operate on the principle that an object will radiate energy at various wavelengths, the intensity of which is proportional to a function of temperature. By focusing the emitted light onto a photoelectric sensitive material, an electrical signal can be generated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

TABLE 3 - 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 - 900	±1.67-316 ±0.27% from 316-871	±1.25-316 ±0.21% from 316-871
J	Iron/Constantan	0.054	0 - 875	±2.22-277 ±0.42% from 277-760	±1.11-277 ±0.21% from 277-760
T	Copper/Constantan	0.045	-270 - 400	±1.11% from -101 -59; ±0.83, -59-93; ±0.42% 93-371	±0.55%, -101-59 ±0.42, -59-93 ±0.21%, 93-371
K	Nickel - 10% Chromium/ Nickel - 5% Al & Si	0.0396	-200 - 1260	±2.22, 0-277 ±0.42%, 277-1260	±1.11, 0-277 ±0.21%, 277-1260
R	Platinum - 13% Rhodium/Platinum	0.0115	-50 - 1600	±1.39, 0-538 ±0.14%, 538-1482	NA
S	Platinum - 10% Rhodium/Platinum	0.0102	-50 - 1540	±1.39, 0-538 ±0.14%, 538-1482	NA
B	Platinum - 30% Rhodium/Platinum - 6% Rhodium	0.0077	0 - 1800	±0.28%, 0-1705	NA

[1]ANSI C96.1 standard.
[2]Reference 17, STP470B, Manual on the Use of Thermocouples in Temperature Measurement.
[3]Per ANSI C96.1 standard. % applies to temperature being measured.

NOTE: Suggest max. S.S. 950-1000°C



Ref: NBS Monograph 125

FIGURE 2 - Output (mV) Versus Temperature for Various Thermocouples

4.3.3 (Continued):

Unlike other temperature technologies, the optical pyrometer does not come into contact with the temperature 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 Reference 25.

As mentioned previously, optical pyrometers are used in high performance military engines to measure TBT directly. In civil engine usage, however, thermocouples are still being utilized to infer TBT.

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 hydromechanically 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 servoactuators 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 4 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 bulbs are currently limited to gas path (air) temperatures.

TABLE 4 - Media Applications of Each Sensor Type

Sensor Type	Media: Gas Path	Media: Turbine Blade Temperature	Media: Liquids
RTD	X		X
Thermocouple	X	X	X
Optical Pyrometer		X	
Gas-Filled Bulb	X		

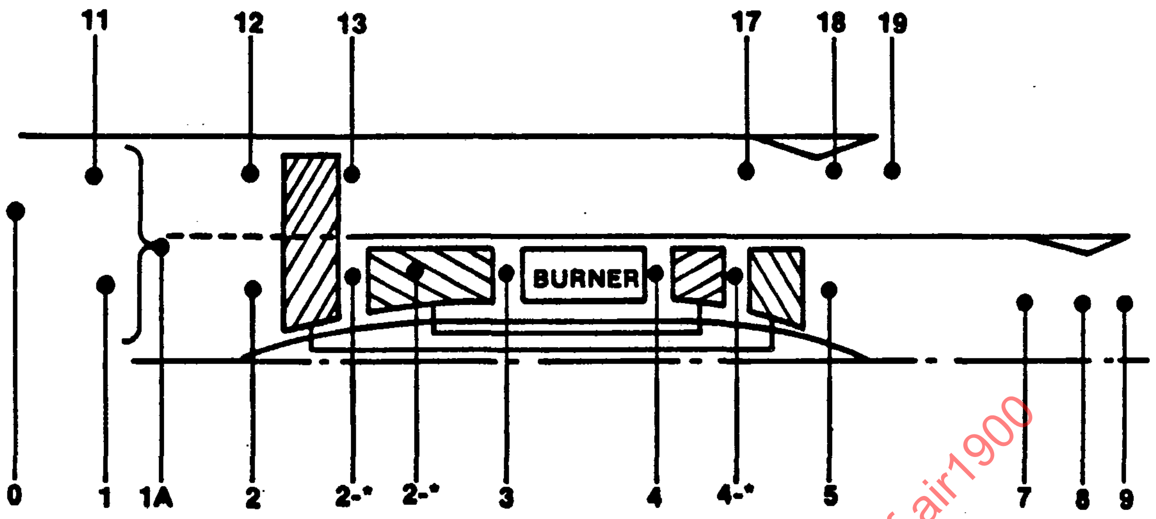
4.4 Measurement Locations:

4.4.1 Gas Path: The following thermodynamic stations are often chosen for making measurements:

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

Reference 8 describes gas turbine engine performance station identifications and nomenclature, and Reference 5 provides temperature measuring devices nomenclature.

Figure 3 illustrates the thermodynamic stations for a twin-spool turbofan engine.



*Intermediate stations are assigned a numeric or alpha identification, such as $T_{2.2}$.

FIGURE 3 - Thermodynamic Stations for Twin-Spool Turbofan (Reference (ARP755A)

4.4.1 (Continued):

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.

4.4.2 Turbine Blade Temperature (TBT): 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, convective cooling, conduction, and radiation from the blades.

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.

4.4.3 Oil: Measurement of the oil temperature is usually accomplished by use of a probe immersed directly into the medium. Locations may vary but measurements are often located downstream of the scavenge pumps and upstream of the oil cooler. This subject is discussed in Reference 13.

4.4.4 Fuel Temperature: Measurement of fuel temperature is generally accomplished by the insertion of a probe directly into the medium. Locations may vary, but measurements are often located downstream of the fuel heater and upstream of the fuel filter.

5. SYSTEM CONSIDERATIONS:

Proper design of a temperature monitoring system will account for each subsystem element. These 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 4.4.1).

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 high pressure (HP) turbine discharge temperature

T_5 = Low pressure (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

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 20 000 Hz. Vibration inputs can be random or sinusoidal. When the actual vibration specification is in doubt, MIL-STD-810 should probably 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. Reference 3 provides a recommended thermocouple mount and Reference 4 describes recommended flange designs for two hole flanges. 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.

5.2.4 Sealing: Depending upon 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 4.

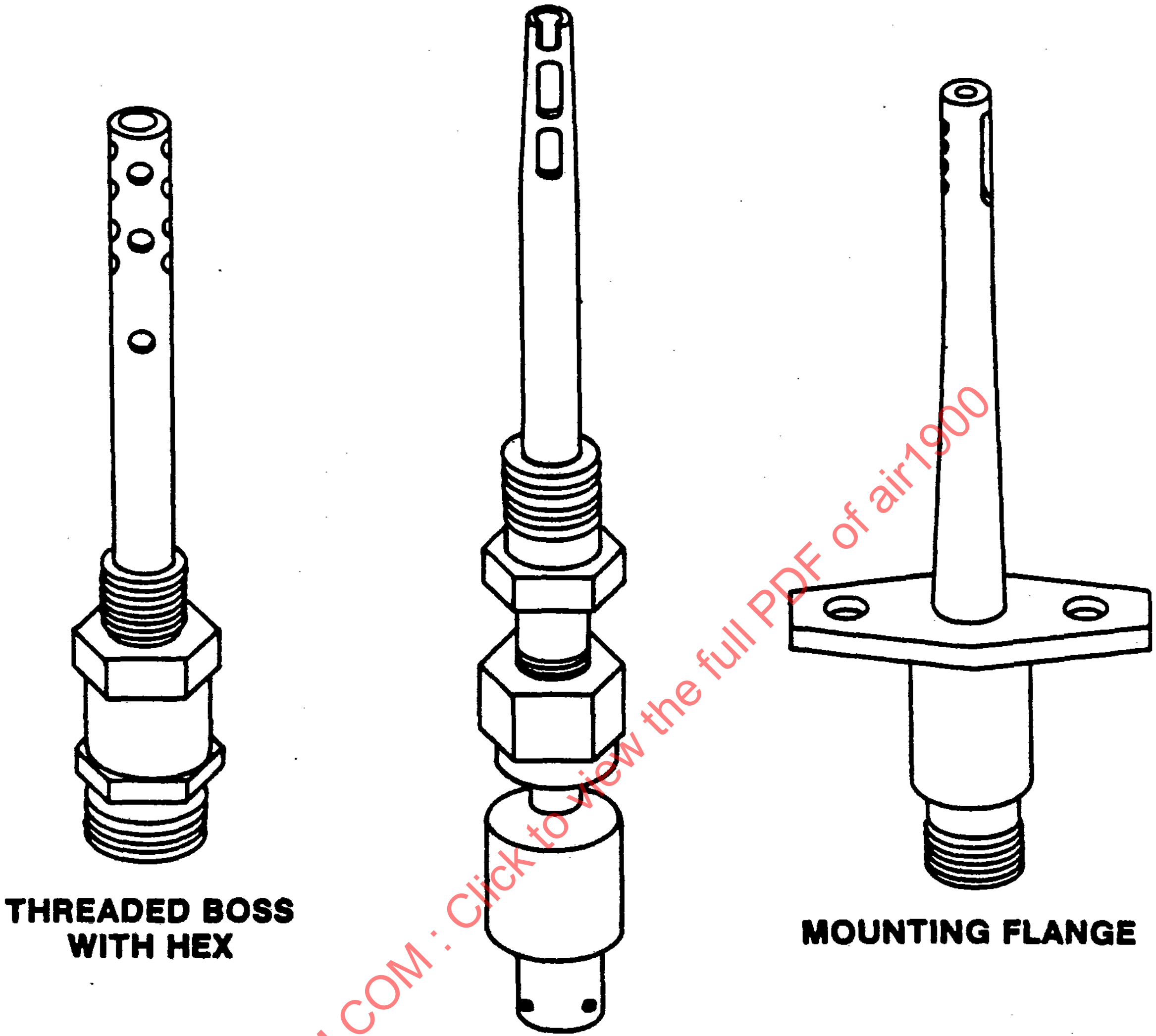


FIGURE 4 - Means of Attachment to Engine Mounting Surface

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.

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.

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

5.3 Signal Transmission:

In many cases, a temperature sensor will be 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 leadwires. 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 leadwire used for RTD signal transmission. Like all metals, copper leadwires possess an inherent electrical resistance, expressed in ohms/1000 feet or meters. Electrical resistance is a function of the material, the ambient temperature and the cross-sectional area (gauge) of the wire. For example, Table 5 exhibits maximum resistances as a function of various copper wires.

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 will be 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.

TABLE 5 - Maximum Resistance of Selected Leadwires[1]
(Ω/1000 ft (304.8 m) at 20°C)

AWG	Tin-Plated Copper	Silver-Plated Copper	Nickel Plated Copper	Silver-Plated High Strength Copper Alloy
30	107.0	101.0	109.0	116.0
28	67.6	62.9	68.3	72.2
26	39.3	36.2	40.1	41.5
24	24.9	23.2	25.1	26.6
22	15.5	14.6	15.5	16.8
20	9.70	9.05	9.79	10.4
18	6.08	5.80	6.08	6.65
16	4.76	4.54	4.76	5.23
14	2.99	2.87	3.00	3.30
12	1.58	1.48	1.59	1.70
10	1.27	1.20	1.27	1.38
8	0.700	0.661	0.680	0.760
6	0.436	0.419	0.428	0.483
4	0.274	0.263	0.269	0.302
2	0.179	0.169	0.174	0.194
0	0.114	0.105	0.109	0.123

[1]Reference 16, pp. 2-13.

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, cause a short circuit or both may happen. In either event, the resulting measurement will 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 leadwires 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 5 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.

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

5.3.2.1 Extension Leadwires: Extension leads may be used for several reasons, including the facts that:

a. Introducing leadwires can more easily be adapted to the mounting surface
b. Exchanging expensive thermoelectric wire for less costly extension wire

Leadwires fall into two categories:

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

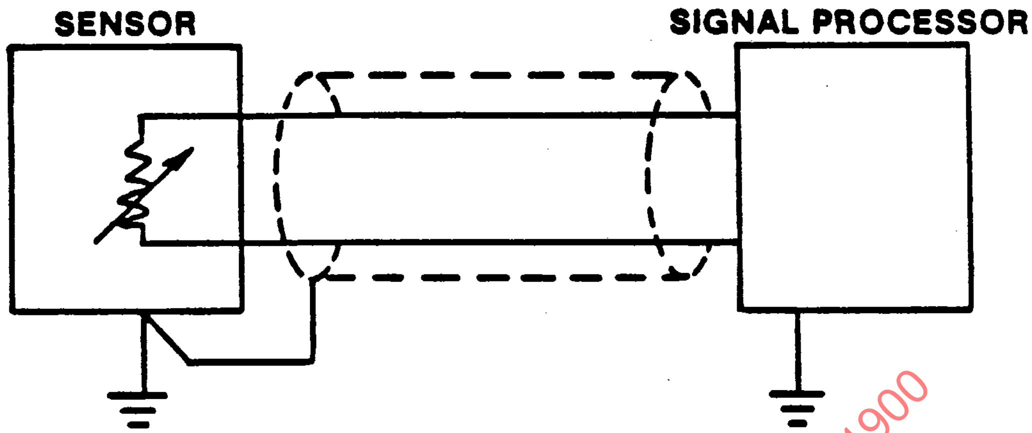
Extension wires for types K, S, and T thermocouples are shown in Table 6.

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

a. Differences in thermal emf between thermocouples and extension leadwires
b. Differences in temperature between the two thermoelement-extension wire junctions
c. Reversed polarity at the junctions
d. Connector material having thermal emf characteristics different from the leadwires

More details on these errors can be obtained from Reference 17.

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



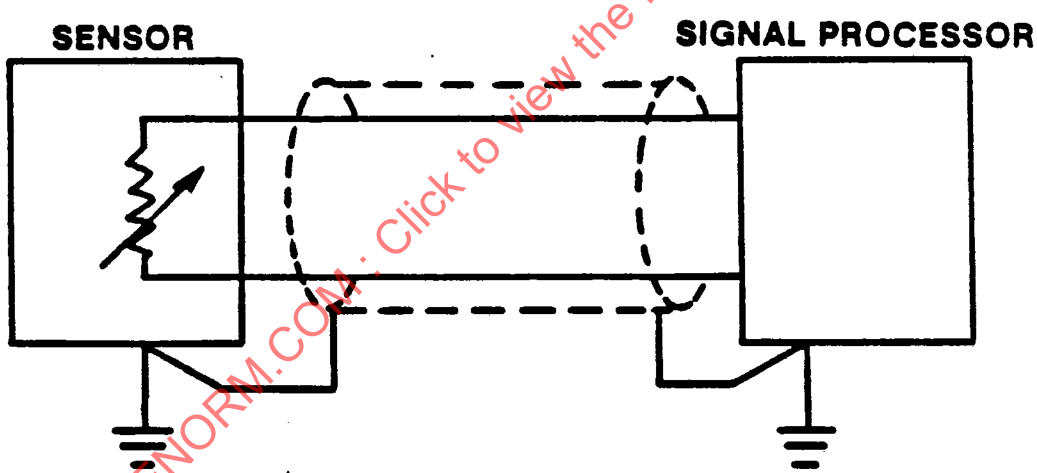


FIGURE 5 - RTD Shielded Cable-Grounding Options

TABLE 6 - 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 - 200	32 - 400
T	TX	Cu	Constantan	-60 - 100	-75 - 200
S	SX	Cu	Cu-Ni	0 - 200	32 - 400

5.3.2.2 Temperature Gradients: Thermoelectric circuits can be made insensitive to temperature gradients within the extension leadwires as discussed in Reference 15. The main concern is that if an extension leadwire 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.

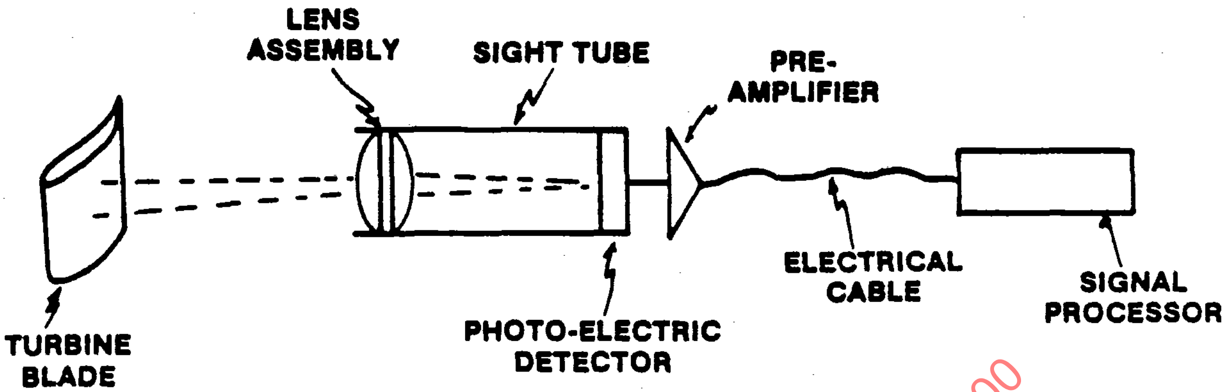
Vendor catalogs on thermocouple connectors should be consulted for more detailed information.

5.3.3 Optical Pyrometers: The transmission of signals from an optical pyrometer will consist of two parts (examples are shown in Figure 6):

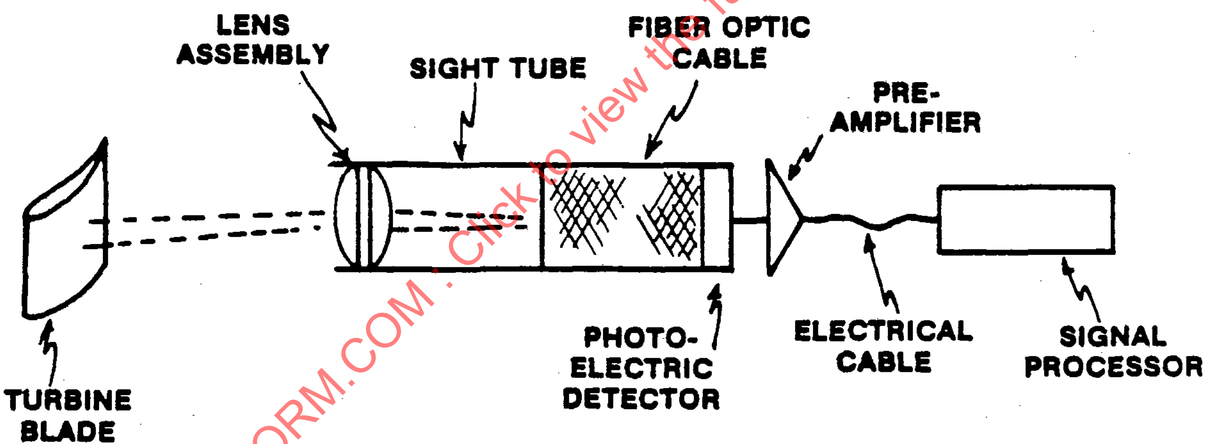
a. The transmission of radiance from the lens assembly to the photo-electric detector
b. The transmission of current from the pre-amplifier to the signal processor

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. Therefore, 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-amp to the signal processor.



A. NO FIBER OPTIC CABLE



B. FIBER OPTIC CABLE

FIGURE 6 - Transmission of Radiant Energy

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 will be transmitted to the detector). Fiber bundles, on the other hand, offer the advantages 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 insure the cable will survive maximum temperatures between 400 to 500°C (approximately 800 to 1000°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 1000°F).

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 (see Reference 15) are used to condition the signals from an RTD. For most applications, the bridge is excited with a constant voltage power source (28 V DC). 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 will be excited by a constant voltage (28 V DC) source. This means 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 will be necessary to minimize self-heating and thereby nonlinearities.

5.4.1.2 Temperature Sensitivity: Given proper choice of bridge resistors and leadwires, 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 through the use of a "floating" reference junction, shown schematically in Figure 7. The junction is a standard "Uniform Temperature Reference" box with multichannel 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.

5.4.2.2 Electrical Noise: The signal from a type K thermocouple is approximately 40μV/°C (20μV/°F). Furthermore, the resolution of many signal processing instruments must be kept small (±1 to 2μV) in order 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 Reference 1.

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 for ground-based condition-monitoring systems). Electrical signals are in the form of DC current and they range in magnitude from a few nanoamps at the lower operating temperatures (600°C) to several microamps at the higher operating temperatures (1450 to 1500°C).

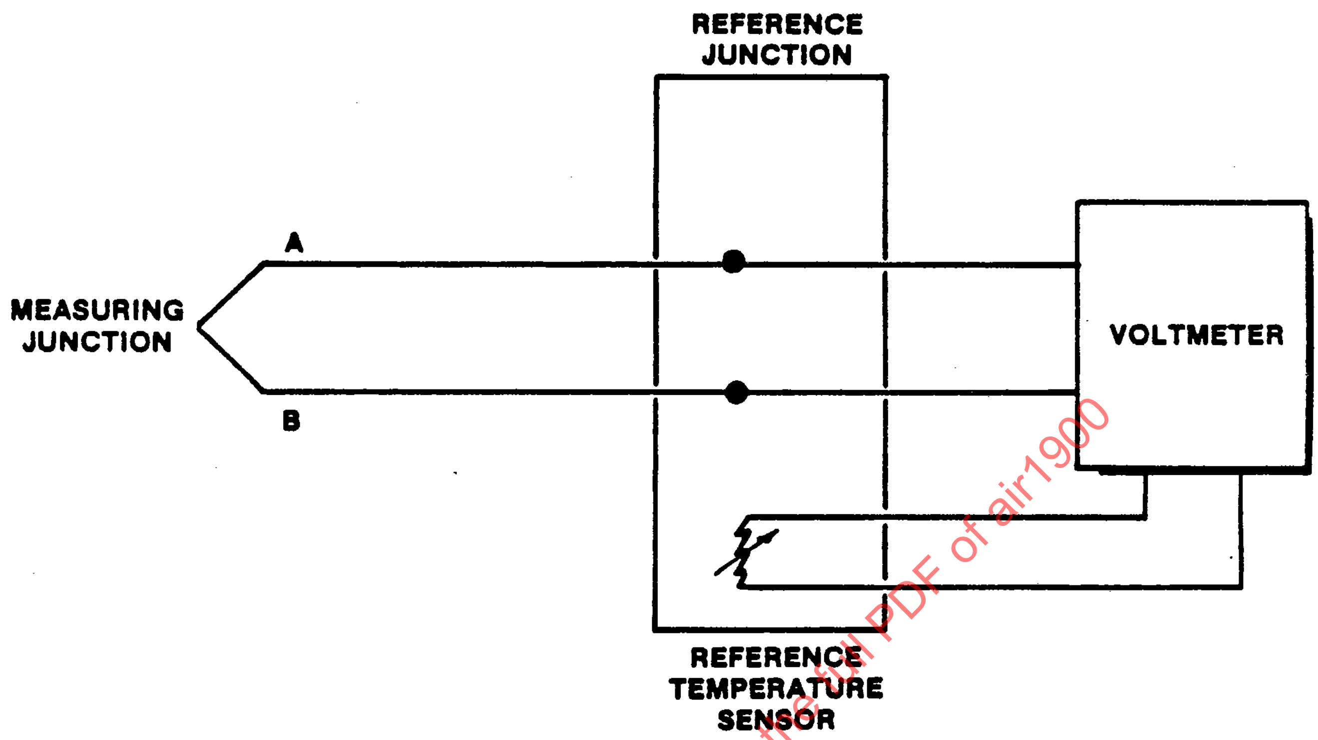


FIGURE 7 - Floating Reference Junction for Thermocouples

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/preamp to an electrical signal (usually expressed in nanoamps). 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 8.

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 10 µs bursts with amplitude no larger than peak blade radiance to peak brightnesses 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:

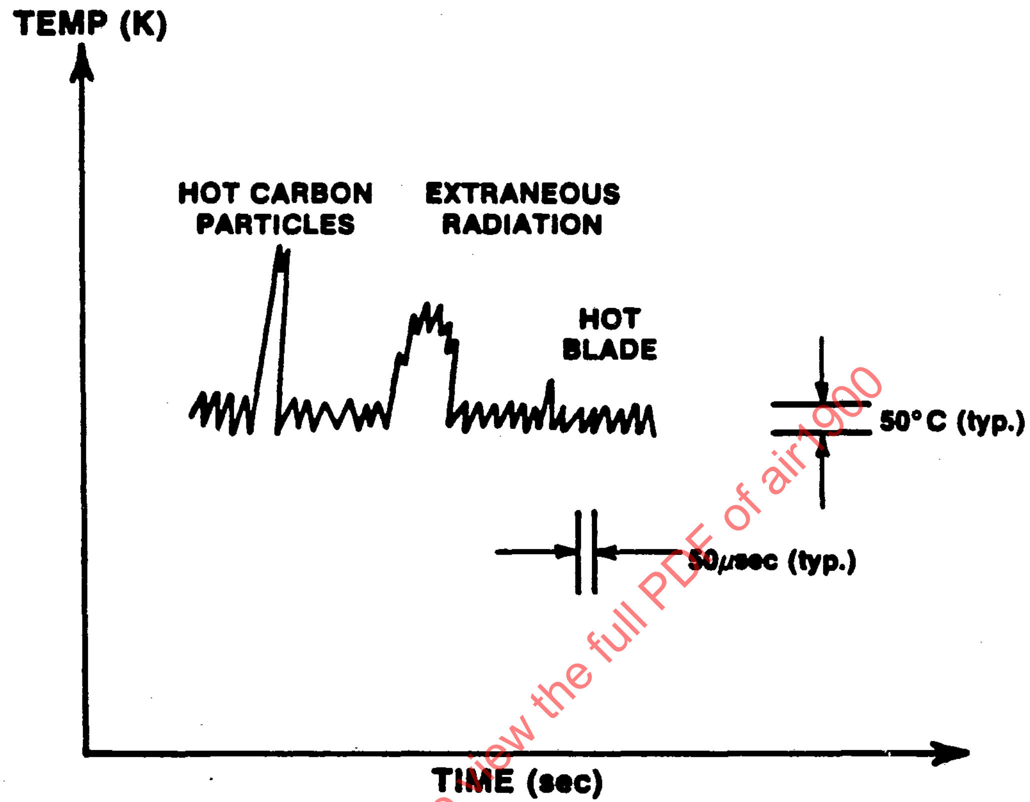


FIGURE 8 - Typical Radiation Pattern From Optical Pyrometers

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. Extraneous radiation is usually ignored and, in general, it will not 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 40 to 50 kHz). However, for purposes of development and diagnostics, the bandwidth must be larger.

For purposes of blade profiling (in order 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

5.4.3.3 (Continued):

necessary to establish a bandwidth as high as 125 to 150 kHz. This suggests a pyrometer to be used for condition monitoring may require an electronic bandwidth somewhere between 50 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 impulse is sent from a reservoir to various mechanical actuators 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 insure 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 will be able to 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 9 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.

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 will be 4 to 6 s in air, while a 1 kHz data rate provides an upper response of 2 ms.

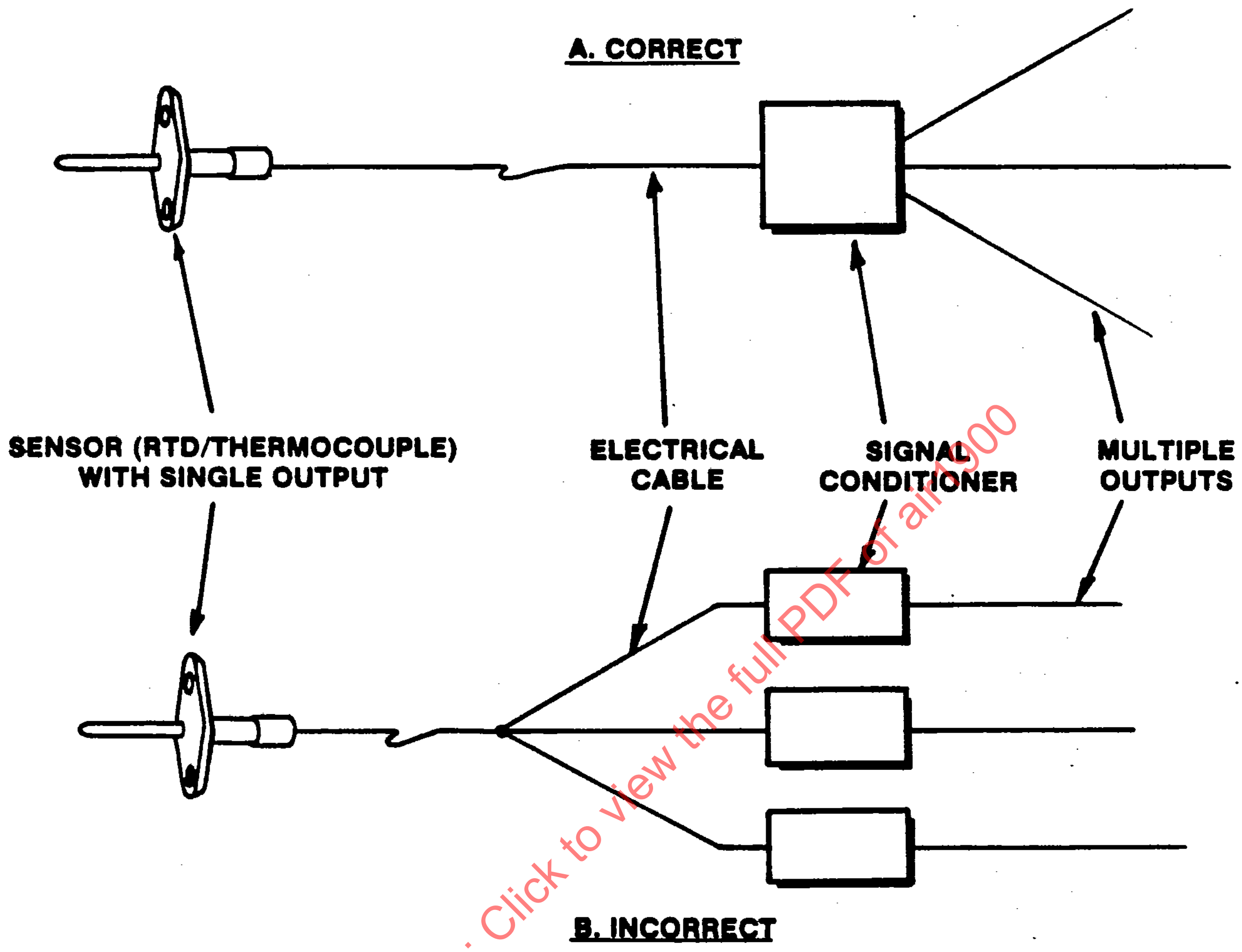


FIGURE 9 - Locations of Signal Bifurcation

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, and
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 temp
b. The measurement is for engine testing or whether it will be a measurement on production engines
c. The measurement is for control, diagnostics and condition monitoring purposes, display, or for performance measurement
d. The signal is to be used for instrument reading, airborne recording, or for real-time use
e. There will be 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. Moreover, in some instances, diagnostics and condition monitoring measurements will need to be more accurate than for purposes of control.

6.2 Performance:

There are several performance variables of interest. These include:

a. Temperature range
b. Accuracy
c. Time response
d. Stability

6.2.1 Temperature Range: There are two ranges of concern: the ambient or environmental ranges and the operating measurement range. Generally speaking, the environmental range will be wider than the operating range and will be important in determining the interface (such as connectors versus cables) and whether signal conditioning can be done locally or remotely.

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

$$e(t) = a(t) + b \qquad \text{(Eq.2)}$$

where $e(t)$ = the total measurement error, as a function of time
$a(t)$ = time dependent error
b = time independent error

6.2.2 (Continued):

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 error 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 time constant of a sensor is generally expressed as the time taken by the sensor to respond to 63.2% 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 assure repeatable measurements in a sampled system, particularly in control applications.

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 cost per unit may be high. This may occur, for example, when failure rates are high and spare 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 (MTBO)
Mean time between failures (MTBF)
Mean time between unscheduled removals (MTBUR)

6.4 (Continued):

It will be necessary to define precisely what a failure consists of. It may comprise several meanings:

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 desired 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 ECUs, air data computers (ADC), multiplexers (MUX), and data buses
g. Modular design aspects
h. Quick disconnect
i. Testability

7. ACCURACY:

All practical measurements are accompanied by error components. Generally speaking, an error is the sum of a systematic or predictable component and of a random or unpredictable component. Systematic components are predictable using any of a 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 systematic components are accounted for. 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 posssible 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. Leadwire 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 a 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 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: In order 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. Deicing 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:

$$T_t = T_s + \Delta T_k \tag{Eq.3}$$

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

$$\Delta T_k = T_s \left(\frac{\gamma-1}{2}\right) M^2 \tag{Eq.4}$$

where T_s is given in absolute units

γ is the 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 of these components. However, the flow rate inside a flow boundary layer is much slower than in nonviscid air flow. 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 we choose to call 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 4.4.1). 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 will be 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:

$$r = \frac{T_r - T_s}{T_t - T_s} \qquad \text{(Eq.5)}$$

where T_r is the recovered temperature

It is also shown in Figure 10.

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

$$E_v = T_t - T_r = \Delta T_k\ (1-r) \qquad \text{(Eq.6)}$$

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_r as follows: Let $\eta = 1 - T_r/T_t$ to express the fraction of total temperaure not recovered through T_r. Next, T_t is expressible as:

$$T_t = T_r/(1-\eta) \qquad \text{(Eq.7)}$$

This means:

$$E_v = T_r \frac{\eta}{1-\eta} \qquad \text{(Eq.8)}$$

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

$$E_v = \eta T_r \qquad \text{(Eq.9)}$$

More details are given for thermocouples in ARP65.

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. AIR65 shows the effect on conduction error of both flow rate and L/D in Figure 11.

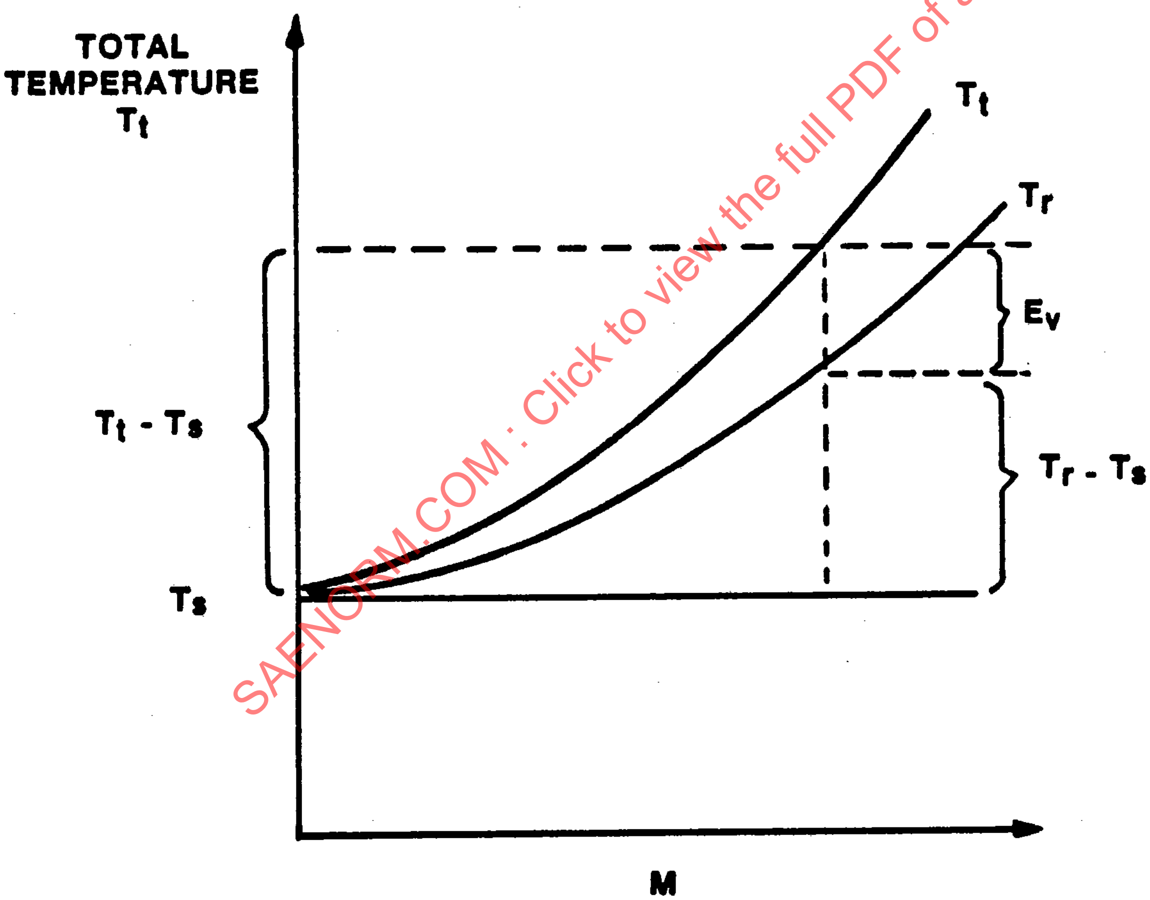


FIGURE 10 - Total Temperature as Function of Mach Number

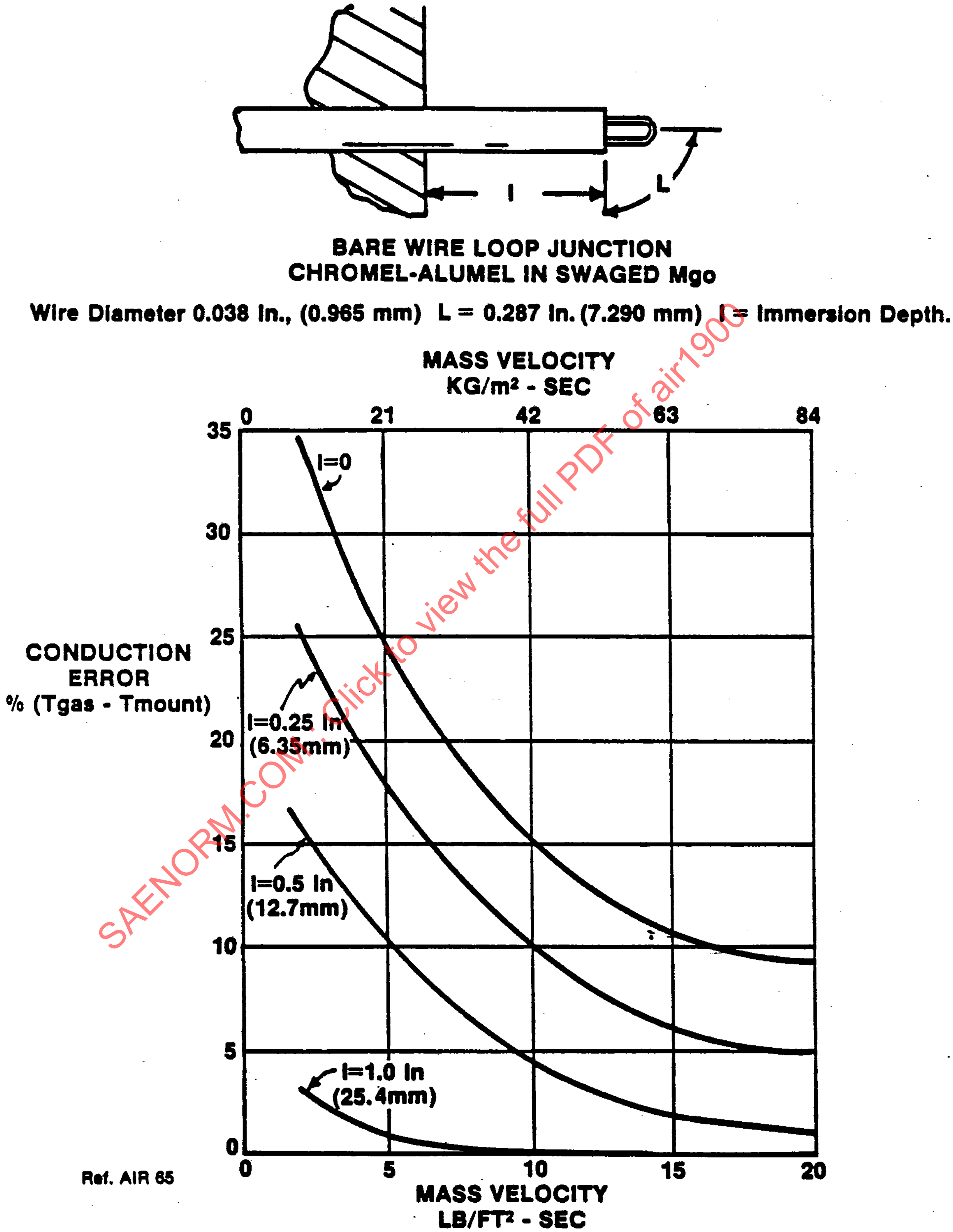


FIGURE 11 - Conduction Error as Function of Mass Flow for Various Immersion Depths

7.1.1.2.4 Radiation Error: This error arises because of the tendency of a body at higher temperature to transfer heat to another body at lower temperature. This is commonly realized by heating the sensor from surrounding areas at higher temperatures. The magnitude of this error is difficult to quantify. However, ARP65 discusses this problem for thermocouples in some detail. Means for minimizing such errors will be discussed in 7.2.

7.1.1.2.5 Self-Heating Error: This error is encountered only in resistance thermometers. This is due to the fact that a current must flow through the sensing element in order to determine its resistance, a function of temperature. The power disipated is given by

$$P = I^2R \text{ WATTS} \qquad \text{(Eq.10)}$$

This error is influenced by excitation current (the smaller the better), total pressure, Mach number, total temperature, and the probe design. Generally speaking, this error can be minimized by maintaining a low excitation current. In any event, it is a systematic error, always acting to increase measured temperature.

7.1.1.2.6 Deicing Heat Error: This error is unique to those temperature probes that are heated to remain ice-free. Hence, they are mainly limited to engine inlet total temperature probes. The deicing heat effects depend largely upon inlet mass flows with larger flows contributing to lower deicing heat. A typical error curve is shown in Figure 12.

7.1.1.3 Temperature Lag Error: The temperature lag error occurs whenever the sensed medium (air or liquid) temperature changes more rapidly than the sensor can respond to (see 6.2.3). Generally speaking, the time constant for RTDs and thermocouples is a function of the mass of the sensor itself. In other words, the larger the mass surrounding the sensing elements, the longer the time constant. The time constant results from the process of attaining equilibrium between the phenomena of convection, conduction, and radiation. This means whenever these processes slow down, the time constant will be larger. Consequently, the temperature lag error will be correspondingly larger.

7.1.1.4 Instrument Errors: This error type is inherent to the sensor and is independent of the application in which the sensor is used. These errors comprise these categories: calibration, repeatability, hysteresis, and interchangeability.

7.1.1.4.1 Calibration Error: This error is interpreted as an uncertainty in the resistance (in the case of an RTD) or the voltage (in the case of a thermocouple) output of a sensor at a reference (calibration) temperature. For example, RTDs and thermocouples are often calibrated at 0°C. Furthermore, the resistance (or millivolt) outputs will be subject to an uncertainty to a level specified by the supplier. This error is independent of the sensor manufacture but is dependent on the calibration equipment, medium, and operator.

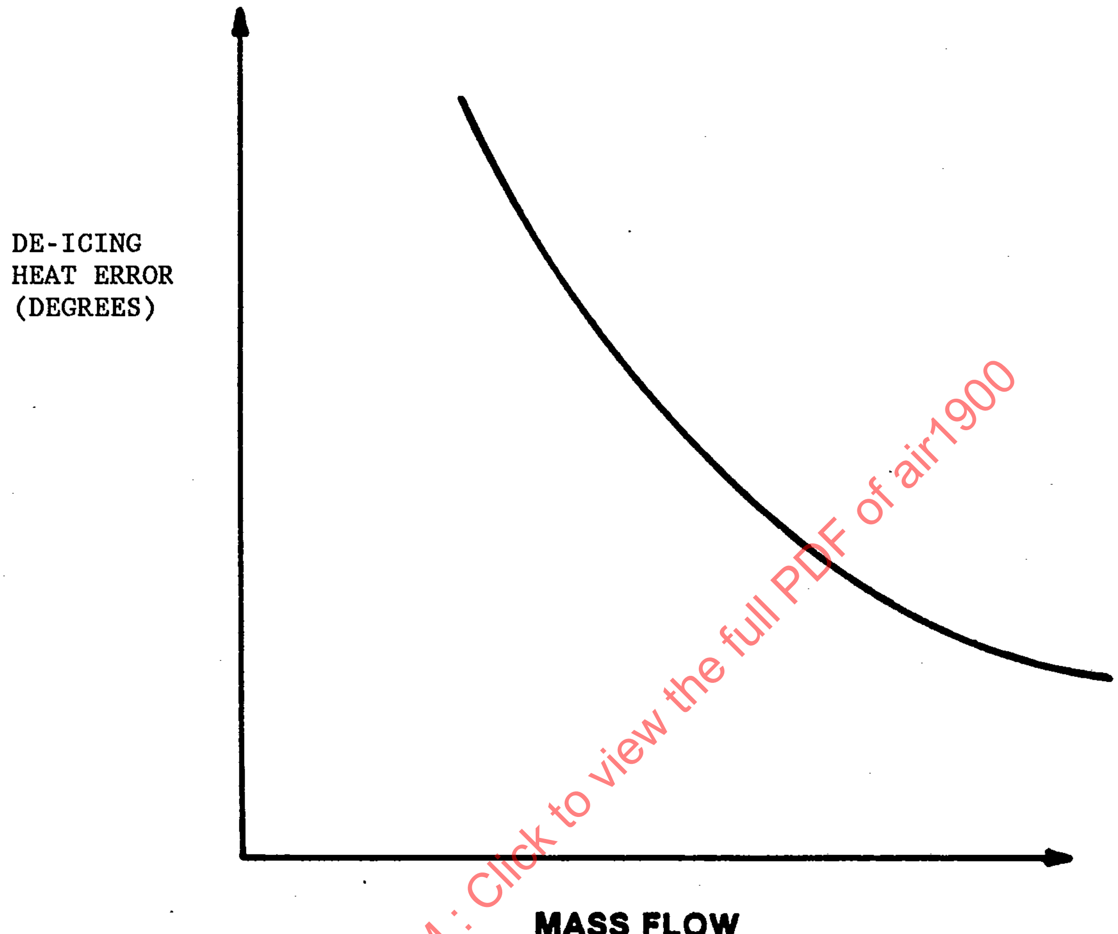


FIGURE 12 - Deicing Heat Error as Function of Inlet Mass Flows

7.1.1.4.2 Repeatability Error: This error arises as a result of the sensor manufacture. In the case of RTDs, thermal cycling will often cause the calibrated resistance to shift due to internal stresses and strains on the element wire. This error is often interpreted at a single temperature (such as the ice point).

7.1.1.4.3 Hysteresis Error: This error is also dependent on sensor manufacture and arises in RTDs because of internal stresses and strains on the element wire. It most often arises during thermal cycling and can be interpreted as a difference between the actual resistance at a selected temperature and the expected resistance (from an interpolation scheme) at the same temperature. Figure 13 shows an example of this type of error in addition to the repeatability error.

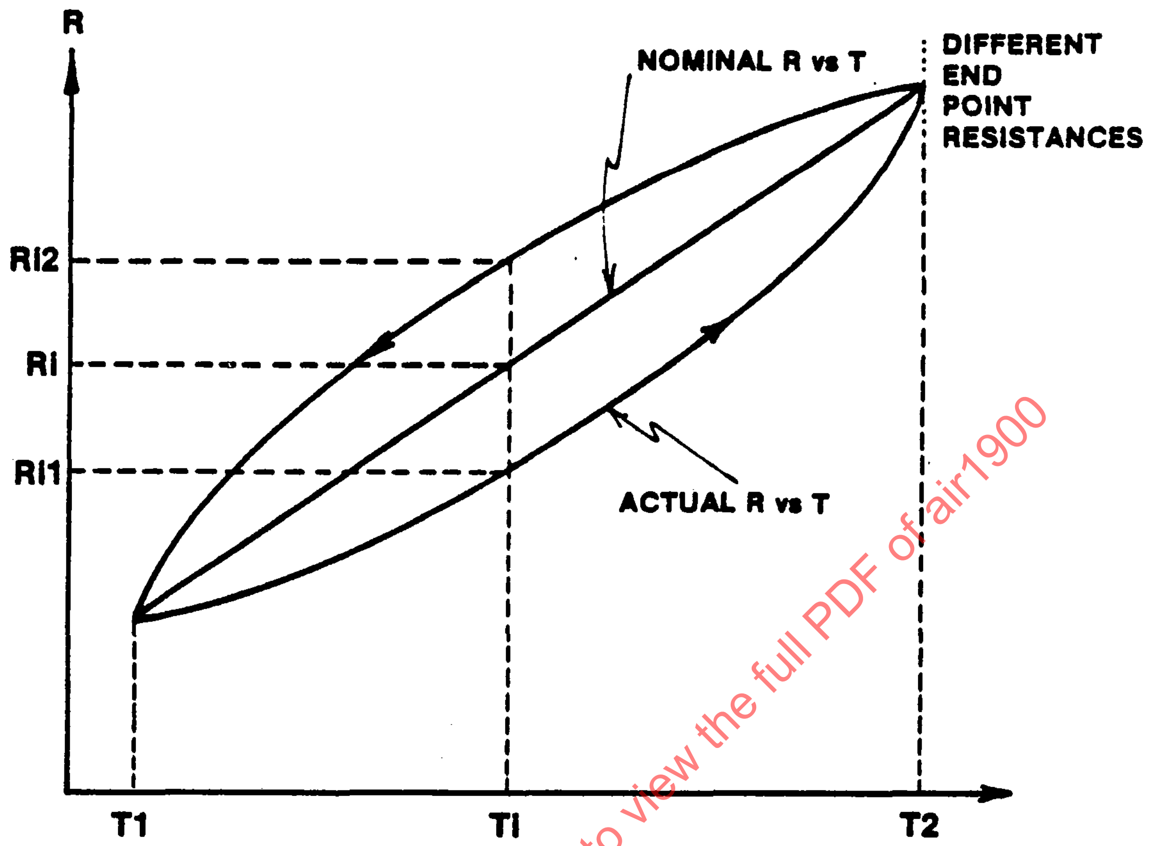


FIGURE 13 - Repeatability and Thermal Hysteresis Errors in RTDs

7.1.1.4.4 Interchangeability Error: This error refers to the ability to substitute one sensor for another in a temperature application without affecting overall system accuracy. This error is expressed as a tolerance band about the nominal R versus T curve (in the case of an RTD) or about the nominal voltage versus T curve (in the case of a thermocouple).

7.1.1.5 Leadwire Errors: Leadwire errors arise in the case of an RTD whenever the resistance of the leadwire cannot be separated by the Wheatstone Bridge from the resistance of the sensing element wire. This error can generally be eliminated by introducing 3 or 4 wire leads instead of two. Other sources for RTD leadwire errors can arise whenever the leads experience stress or strain due to vibration, for example. RTD leadwires are generally insensitive to parasitic voltages due to EMI.

Leadwire errors in thermocouples can arise in a number of different ways. Thermal emf can arise at points of connection between thermocouple wires and other leadwires, especially where adjacent temperatures are not the same (Reference 18). Additionally, EMI can cause errors in the temperature reading if the thermocouple is not properly shielded.

7.1.1.6 Indicator Error: This type of error arises independently of the sensor and the application. It is inherent to the design and application of the indicator. Since our purpose is to concentrate more on the sensor, no detail will be provided on this type of error.

7.1.2 Optical Pyrometers: Temperature measurement errors from optical pyrometers can be of six generic types:

a. Spurious radiation
b. Emissivity
c. Detector/electronics
d. Spot size
e. Interpolation
f. Instrument error

7.1.2.1 Spurious Radiation: This type of error arises in the presence of hot carbon particles, from gas emissions and from reflection of combustion flame off objects adjacent to blades.

7.1.2.1.1 Hot Carbon Particles: Particles from incomplete combustion, metal abrasion, and ingested particles can pass between lens and the targeted spot. Additionally, these particles will generally be at a higher temperature than the target. These particles will consequently give off radiation which, if not corrected, will cause an error in blade temperature measurement.

7.1.2.1.2 Reflection: Depending upon the orientation of the pyrometer lens head assembly relative to the combustor, the pyrometer can be subject to considerable errors arising from the reflection of the combustor flame off components adjacent to the target. The combustor flame can be as high as 2000°C, whereas the blade temperature will be much lower. Since the reflected component will contribute positively to the radiation received by the pyrometer, there can be a substantial error associated with this phenomenon.

7.1.2.1.3 Gas Emissions: The hot gas from the combustor will itself emit a radiation different from that of the targeted blade. Since the gas will generally be at a higher temperature than the blade, it will contribute to the temperature reading of the target, depending upon the response bandwidth of the photodetector.

7.1.2.2 Emissivity: The radiation from a blade will be proportional to some function of the wavelength and the absolute temperature. The constant of proportionality is often referred to as the emissivity ε. This constant is, however, time dependent. Since reflectivity of a component decreases over time due to oxidation, abrasion and other surface changes, the emissivity will also change over time. It may be expressed as follows:

$$\varepsilon(t) = 1 - \rho(t) \qquad \text{(Eq.11)}$$

where $\rho(t)$ = reflectivity of the target at time t

7.1.2.3 Detector/Amplifier: This error contribution occurs because of detector temperature variations and amplifier noise.

7.1.2.3.1 Detector Temperature Sensitivity: For most aircraft gas turbine applications, optical pyrometers use a silicon photodiode as the detector. The silicon photodiode is, however, sensitive to temperature. Because of this, the detector output will depend not only on the target temperature but also on its own temperature. Unless the contribution it adds is accounted for, a considerable error in temperature measurement can result.

7.1.2.3.2 Amplifier Noise: Amplifier noise increases with increasing bandwidth. This becomes more significant with decreasing target temperature. With higher amplifier noise, the signal-to-noise ratio is lower. This means a larger error in temperature due to this component, if the signal cannot be separated from the noise component.

7.1.2.4 Spot Size: The target or spot size determines the amount of radiation collected at the detector, given the focal length and lens diameter. In turn, the higher the radiation, the higher the signal to noise ratio. However, the spot size may need to be much smaller than the width of a turbine blade in order to identify the blade temperature profile. The larger the ratio of spot size to blade width, the greater the error between the actual blade temperature and the recorded temperatures.

7.1.2.5 Interpolation: The total emitted radiation from the blade will, according to Planck's Law of Radiation, be a function of wavelength and the fourth power of absolute temperature. However, because the actual radiation will be processed by a silicon photodiode, the photodiode output will be a different function of wavelength and absolute temperature. This function will be nonlinear and empirically determined. Because it is only an approximation to the true radiation function, errors will result.

7.1.2.6 Instrument Errors: This error type is inherent to the sensor and is independent of the application in which the sensor is used. These errors comprise three categories: calibration, repeatability, and interchangeability.

7.1.2.6.1 Calibration: Calibration errors arise through several different sources. These include an assumed blackbody error, resulting in a measured temperature different from the actual temperature; operator errors; and indicator/recorder errors.

7.1.2.6.2 Repeatability: This error results from sensor manufacture and is caused by thermal cycling of the associated electronics. The calibrated output in nanoamps, for example, will have a tendency to shift due to aging effects and to changes in bias.