91-0300

Criteria for the Selection of Thermocouples Versus RTD's in Industrial Applications

D. Bediones and T.P. Wang, Thermo Electric Co., Inc.

Individual Paper Preprint
from the

ANAHEIM • OCTOBER 28–31, 1991
ISA/91
INTERNATIONAL
CONFERENCE & EXHIBITION

INSTRUMENT SOCIETY OF AMERICA

1054-0032/91/001-011/$0 + .50pp

CRITERIA FOR THE SELECTION OF THERMOCOUPLES VERSUS RTD'S IN INDUSTRIAL APPLICATIONS

D. BEDIONES
Supervisor of Calibration Laboratory
Thermo Electric CO., Inc.
Saddle Brook , N.J. 07662

T.P. WANG
Director of Research Thermometry and QA
Thermo Electric Co., Inc.
Saddle Brook , N. J. 07662

KEY WORDS

Temperature, Thermocouples, RTD's, Calibration, Initial tolerance, Reproducibility, Stability.

ABSTRACT

A thorough understanding of the properties, advantages and limitations of a sensor is a pre-requisite in choosing the right one for the measurement and control of temperature. In this paper, the pertinent features of thermocouples and RTD's are described and compared. Criteria for the selection of a temperature sensor are presented and followed by two case studies.

INTRODUCTION

Thermocouple and Resistance Temperature Detectors (RTD's) are the two most wildly used sensors for temperature measurement and control in scientific and process industries. This paper reviews and compares their specific types, specification, temperature range of application, accuracy and stability of calibration of these two temperature sensors in more detail than a previous paper (1). Criteria for selection of the appropriate sensor for a process are discussed.

PRINCIPLE OF THERMOCOUPLE OPERATION

Thermocouple is a sensor that operates on established electromotive force versus temperature relationship. The basic construction of a thermocouple consist of two dissimilar metals joined at one end usually by welding. The joined end of the thermocouple is placed in the area the temperature of which is to be measured. The other ends are connected to a voltmeter or a potentiometer. The thermal emf generated in the circuit is directly proportional to the temperature difference between the hot and the cold junction of the thermocouple. By setting the reference cold junction at 0°C and measuring the emf generated in the circuit we can determine the the temperature of the hot junction. The desirable feature of thermocouples are wide operating range, good accuracy, availability, sturdiness and low cost.

THERMOCOUPLE MATERIAL AND TEMPERATURE RANGE OF OPERATION

Thermocouple material can be grouped into two basic categories: Standardized and non-standardized. The description of the non-standardized thermocouples may be found in literature (2).The standardized thermocouples are listed in Table I (3) . Types J, K, T, E and N are base metal thermocouples. Types R,S and B are precious metal thermocouples. The composition of positive and negative thermoelements for each thermocouples are listed together with recommended maximum operating temperature and atmospheric conditions. The temperature range of operation and recommended service for thermocouple are shown on Figure I .

Types J and K are the most widely used thermocouples in industrial applications. The primary advantage of Type J thermocouple is that it can be used in both oxidizing and reducing atmospheres up 760 °C . Type K thermocouples are made from high nickel alloys and can be used up to 1260°C in an oxidizing atmosphere. However, reducing atmospheres are commonly used in heat treatment to prevent oxidation of parts. Type K thermocouples should not be use in reducing atmosphere such as hydrogen, dissociated ammonia, carbon monoxide in which small amount of oxygen is present. The partial pressure of oxygen in reducing atmospheres is very low. Under that condition and at temperature range from 800 and 1000 °C , the positive K thermoelement would form a greenisn chromic oxide commonly known as "green rot" . This would decrease the emf of KP. Type K thermocouple as a whole would read as much as 55 °C lower than the actual reading. Type T thermocouples are used primarily at cryogenic temperatures. They can be used up to 350°C. Type E thermocouples are used in thermopile applications because of its large thermoelectric power.

TABLE I

STANDARDIZED THERMOCOUPLES

TYPE	THERMO ELEMENTS	TYPICAL ALLOY	BASE COMPOSITION	APPLICATIONS ATMOSPHERE	MAX. TEMP°C (°F)
J	JP	IRON	FE	OXIDIZING &	760
	JN	CONSTANTAN(J)	44Ni/55Cu	REDUCING	(1400)
K	KP	CHROMEL*	90Ni/9Cr	OXIDIZING &	1260
	KN	ALUMEL*	94Ni/Al,Mn,Fe	INERT	(2360)
T	TP	COPPER	OFHC Cu	OXIDIZING	370
	TN	CONSTANTAN(T)	44Ni/55Cu	REDUCING	(700)
E	EP	CHROMEL*	90Ni/9Cr	OXIDIZING &	870
	EN	CONSTANTAN(T)	44Ni/55Cu	INERT	(1600)
N	NP	NICROSIL	Ni/14.2Cr/1.4Si	OXIDIZING	1260
	NN	NISIL**	Ni/4.4si/.15Mg	INERT	(2300)
R	RP	Pt/Rh	87Pt/13Rh	OXIDIZING &	1480
	RN	Pt	Pt	INERT	(2700)
S	SP	Pt/Rh	90Pt/10Rh	OXIDIZING	1480
	SN	Pt	Pt	INERT	(2700)
B	BP	Pt/Rh	70Pt/30Rh	OXIDIZING,INERT	1700
	BN	Pt/Rh	94Pt/6Rh	& VACUUM	(3100)

*CHROMEL, ALUMEL, CONSTANTAN-TRADE NAME FOR HOSKINS; TOPHEL, NIAL & CUPRON TRADE NAMES FOR CAR TECH; T1,T2, ADVANCE-TRADE NAMES FOR HARRISON ALLOYS
**NISIL, PATENTED ALLOY , CAR TECH

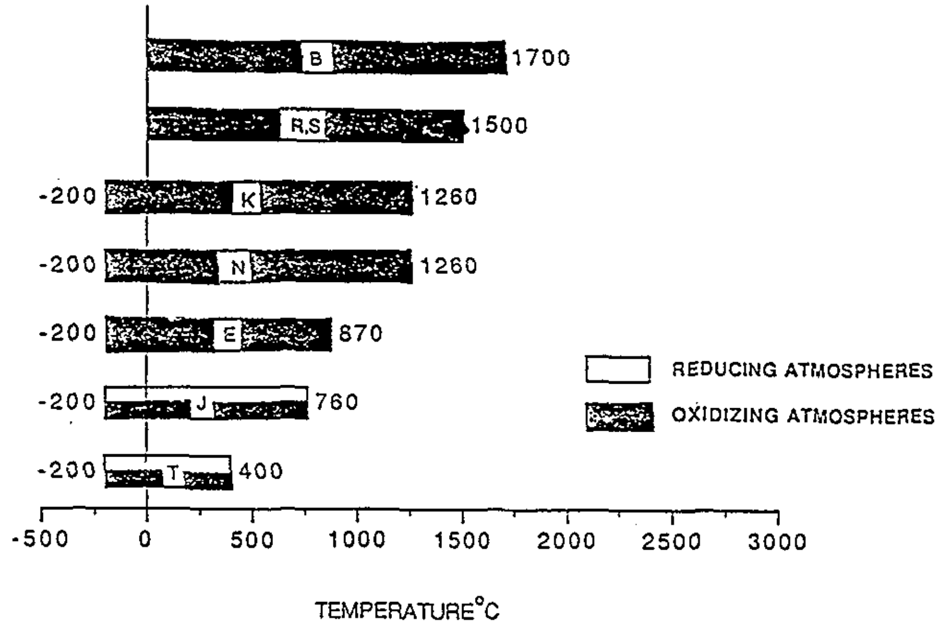

FIG. 1 TEMPERATURE RANGE OF OPERATION AND RECOMMENDED SERVICE OF THERMOCOUPLES

In the precious metal group, Type R and S thermocouples may be used up to 1400°C (2700°F). These thermocouples can be used in both oxidizing and inert atmospheres. Type B thermocouple can be used in oxidizing and inert atmospheres as well as in vacuum up to 1700°C (3092°F). None of these thermocouples should be used in reducing atmospheres, Otherwise, contamination of the thermoelements would occur, resulting in large changes of calibration, early failure or both.

THERMOCOUPLE CONSTRUCTION

Thermocouples are manufactured for a wide variety of temperature applications. There are three basic types of construction. Each particular type of thermocouple must be selected to meet specific temperature requirements. No particular thermocouple would meet the entire range of application.

<u>Bare Wire:</u> Consists of positive and negative conductors usually welded to formed an exposed measuring junction. Alumina or mullite (70% Al_2O_3,30% SiO_2) thermocouple protection tubes are commonly used as insulation.

<u>Insulated Thermocouples with Plastic, Glass and Ceramic Fiber Insulation.</u> Base metal thermocouples can be insulated with various types of insulation. At present, extruded plastic are used for low temperature applications. Glass insulation for mid-temperature range and ceramic fiber insulation for high temperature application. Insulation offers improved temperature and good chemical resistance. Insulated thermocouples are color coded for easy identification of the type of thermocouples and for separation of positive and negative thermoelements.

<u>Metal Sheathed Mineral Insulated thermocouples</u>: Construction consists of positive and negative thermocouple wires embedded in ce:amic insulation protected by metallic sheath. The most commonly used insulation material are MgO and Al_2O_3. Inconel 600 and stainless steel are the most frequently used sheath material. There are three types of measuring junction for metal sheathed thermocouples.

Exposed Junction: The junction extends beyond the metal sheath. It offers fast thermal response but not suitable for harsh environment such as corrosive atmospheres.

Grounded Junction: The junction is within the sheath. The measuring junction becomes an integral part of the sheath. Thermoelements are completely protected from harsh environment. Fast response but not as fast as exposed junction.

Ungrounded Junction: Slowest response time among the three junction. Conductors are welded together to form a junction which is isolated from external sheath and has the advantage of generating a signal that is completely isolated.

THERMOCOUPLE SPECIFICATIONS

The initial calibration tolerance of standardized thermocouples are tabulated in ANSI MC 96.1 (4). The initial calibration tolerance represent the manufacturing limits of the initial accuracy of these standardized thermocouples prior to usage.

The initial calibration tolerance of Types J, K and N thermocouples are ploted in Fig.2 . Their tolerances are the same except in their maximum temperature: J thermocouple is 750 °C (1400°F) while that of K and N is 1250 °C (2300 °F). For standard grade, the initial calibration tolerance is ± 2.2 °C (4 °F) or ±0.75 % of temperature, whichever is greater. For the special (premium) grade the tolerance is ± 1.1 °C (±2 °F), or ±0.4 % of temperature, whichever is greater.

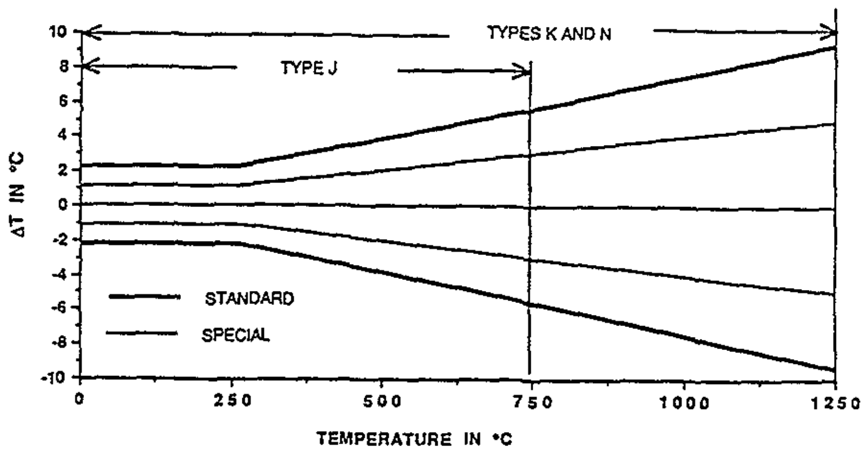

FIG. 2 INITIAL CALIBRATION TOLERANCE FOR J,K & N THERMOCOUPLES PER ANSI MC 96.1-82

The initial calibration OF type T thermocouple is shown in Figure 3 in both cryogenic and intermediate temperature ranges. Above 0°C, its tolerance for standard grade ±1°C or ± 0.75% of temperature , whichever is greater. The tolerance for special (premium) grade is ± 0.5° C or ±0.4 % of temperature, whichever is greater. Below 0° C , the tolerance for standard grade is ± 1.°C or ±1.5 % of temperature, whichever is greater. The suggested range for special grade is ±0.5 ° C or ±0.8 % of temperature, whichever is greater.

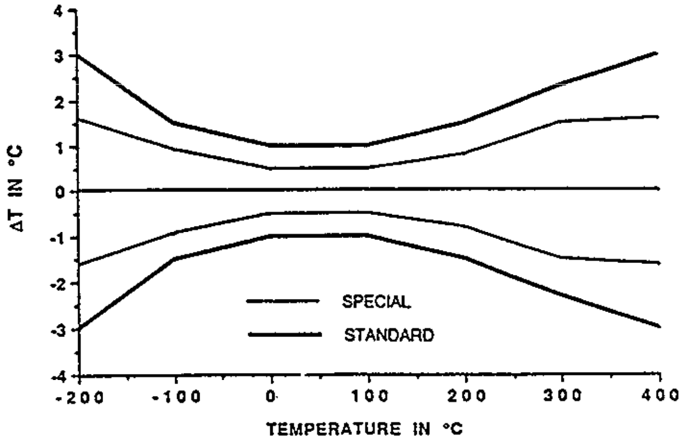

FIG. 3 INITIAL CALIBRATION TOLERANCE FOR TYPE T THERMOCOUPLE

The initial calibration tolerance of types R and S thermocouples are shown in Figure 4 . The tolerance for its standard grade is ±1.5 ° C or +0.25 % of temperature, whichever is greater. The tolerance for special (premium) grade or reference grade is ±0.6° C or±0.1% of temperature, whichever is greater.

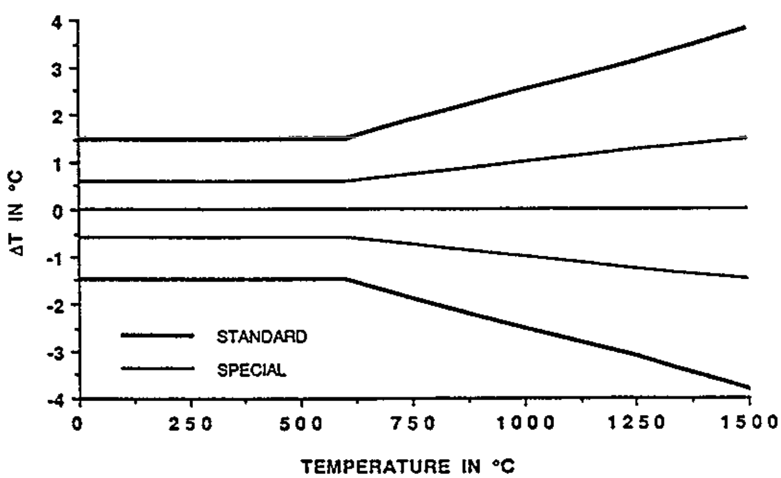

FIG. 4 INITIAL CALIBRATION TOLERANCE OF TYPE R AND S THERMOCOUPLES

PRINCIPLE OF OPERATION OF RTD's

RTD's operates on established resistance versus temperature relationship of its resistance element. The resistance of the element (metal or alloy) increases and decreases with a temperature change in a predictable and repeatable manner. In comparison with thermocouples, RTD have a narrower operating range and slower heat response. However, RTD's are more accurate and stable than thermocouples within the same operating range.

RESISTANCE MATERIAL FOR RTD's

Material used as resistance elements for RTD's are platinum, nickel, copper, a nickel-iron alloy and some semi-conductors. Platinum is the most commonly used resistance element. Basically, there are two grades of platinum resistance element: one with a temperature coefficient of resistance, alpha 0.00385 Ω/Ω/°C, 0 to 100 °C range and one with an alpha of 0.00392 Ω/Ω/°C and slightly above at the same temperature range. The alpha 0.00385 material is generally used for industrial grade RTD's. The higher purity platinum with an alpha of 0.00392 Ω/Ω/°C, is usually used for standard platinum resistance thermometer, SPRT. Most of the resistance element is supplied as wire wound resistor. Recently, thin film resistance element is also use.

RTD CONSTRUCTION

The basic construction of RTD's consists of the resistance element elements, the protection sheath, the extension leads and connector. As stated before, platinum is the most widely used resistance material. Stainless steels and Inconel are commonly used as sheath. For low temperature application (250 °C and below), Teflon coated insulated nickel copper wire are used. For higher temperature the lead wire is made of fiber glass insulated nickel copper alloy.

There are three standard configurations: Two wire, three wire and four wire. In the 2 wire configuration, the resistance of lead wire is added directly to the resistance of the platinum or the resistance element. In the 3 wire configuration, the third wire is added to the circuit to compensate for the resistance of the lead wire. The 4 wire configuration, with two voltage and two current leads, is basically a Kelvin bridge setup in which the resistance of the lead wires does not have any effect on the resistance of the RTD element.

OPERATING TEMPERATURE RANGE OF RTD's

The operating range of RTD's is shown on Fig. 5. Low temperature RTD's with low temperature leads, can be operated from -200°C to +250°C. High temperature RTD's can be operated up to 650°C. Some specially constructed SPRT's can be operated up to 850°C.

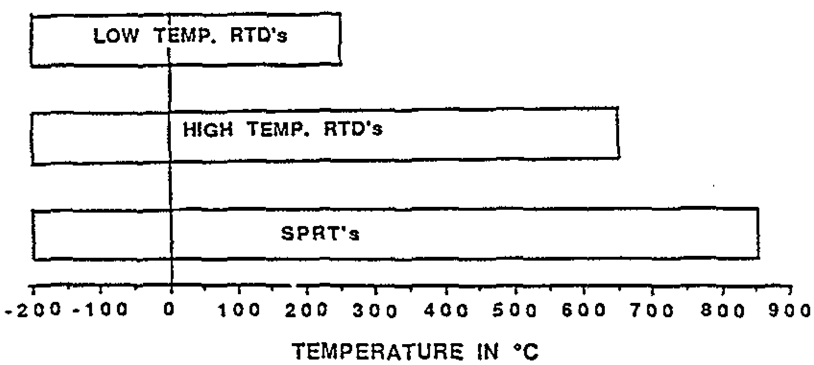

FIG. 5 OPERATING TEMPERATURE RANGE OF RTD's

RTD SPECIFICATION

The initial calibration tolerance of platinum RTD's with an alpha of 0.00385 Ω/Ω/°C in accordance with ASTM E1137 (5) is plotted in FIG. 6. The tolerance on this ASTM specification is slightly tighter than IEC (International Specification) which is use in Europe and most of the rest of the world (6). The maximum operating temperature listed in the specification is 650°C. In the IEC specification, the class B resistance platinum thermometers are listed as having maximum operating temperature of 850°C.

COMPARISON OF INITIAL CALIBRATION TOLERANCE OF RTD's VERSUS THERMOCOUPLES

The initial tolerance of platinum resistance thermometer (Pt. RTD's) with an alpha value of 0.00385 Ω/Ω/°C versus thermocouple is listed in the Table II. In 0°C to 200°C, the initial accuracy of RTD's is superior to that of the thermocouples. Above 200°C, the advantage no longer exists, especially when compared with precious metal thermocouples. At the maximum ASTM recommended temperature at 650°C, the initial accuracy of RTD lie's between that of Type J, K, N and the precious metal thermocouple.

TABLE II

COMPARISON TABLE FOR THE TOLERANCES* OF PRTD & TYPE T, J, K, R & S THERMOCOUPLES

	PRTD ALPHA 0.00385		ISA THERMOCOUPLES					
	PRTD ALPHA 0.00385		TYPE T		TYPE J, K, & N**		R & S	
TEMP. IN°C	Gr. A	Gr. B	SP.	Std.	Sp.	Std.	Sp.	Std.
-200	0.47	1.1	1.6	3.0	-	-	-	-
-100	0.30	0.67	0.8	1.5	-	-	-	-
0	0.13	0.25	0.5	1.0	1.1	2.2	0.6	1.5
100	0.30	0.67	0.5	1.0	1.1	2.2	0.6	1.5
200	0.47	1.1	0.8	1.5	1.1	2.2	0.6	1.5
300	0.64	1.5	1.5	2.3	1.2	2.3	0.6	1.5
400	0.81	1.9	1.6	3.0	1.6	3.0	0.6	1.5
500	0.98	2.4			2.0	3.8	0.6	1.5
600	1.15	2.8			2.4	4.5	0.6	1.5
650	1.24	3.0			2.6	4.9	0.6	1.6
700					2.8	4.9	0.7	1.8
800					3.2	6.0	0.8	2.0
900					3.6	6.8	0.9	2.3
1000					4.0	7.5	1.0	2.5
1100					4.4	8.3	1.1	2.8
1200					4.8	9.0	1.2	3.0
1300					5.2	9.8	1.3	3.3

*Tolerance in ± °C

**Type J Recommended maximum temperature 760°C
Types K and N Recommended maximum temperature 1260°C

OVERALL COMPARISON OF THERMOCOUPLES VERSUS RTD's

The overall comparison between thermocouples and RTD's is summarized in the Table III. The signal output of thermocouple is measure in terms of millivolts, which is rather small when compared with the resistance change in ohms of a 100 ohm industrial RTD's. Thermocouples are affected by electrical noise . Insulated thermocouple should be properly shielded and instrumentation appropriately grounded to eliminate the effect of electrical noise. The overall operating temperature range of thermocouples is wider than that of RTD's. However, with RTD's we can measure temperature to 0.001°C while thermocouples measurement seldom go beyond 0.05°C (0.1°F). At ambient or moderate (<200°C) temperature, RTD's are more stable than thermocouples.

Thermocouples are tip sensitive while RTD's are stem sensitive. With exposed thermocouple junction, the response time is less then 1 second. The response time of an 1/4" OD RTD could reach as much as 5 seconds. The response time of a metal sheathed thermocouple with a grounded junction is 1.7 second versus 5 seconds for an RTD's with a 1/4 OD probe. The cost of thermocouple range from a few dollars for a base metal thermocouple to several hundred of dollars for a platinum thermocouple. An industrial RTD cost about $75 while a standard platinum resistance thermometer (SPRT) could cost up to $3000 not including calibration (NIST charges close to $2000). By comparison, it is easier to manufacture thermocouples than RTD's. Thermocouples are more rugged and not subject to vibration as in the case of RTD's.

TABLE III

FEATURES OF THERMOCOUPLES VERSUS RTD's

	THERMOCOUPLES	RTD's
Signal Output	Low	High
Overall Temperature Range	-200 to 2300 °C	-200 to 850°C
Temperature Sensitivity in °C	0.025	0.001
Accuracy and stability at Operating Range		Better
Tip Sensitivity	Yes	No
Response Time	1.7 sec.*	5.0 sec.**
Cost per unit	$ 15 to $500	$75 to $3000 (SPRT)
Fabrication	Easy	
Rugged	Yes	No

*.250" OD Probe,grounded junction **.250 OD Probe

CRITERIA FOR SELECTION OF A TEMPERATURE SENSOR

The criteria for the selection of a temperature sensor are listed in Table IV. In order to select an appropriate sensor for specific process or measurement, one should consider not only the individual factor such as time, temperature, environment etc, but also the overall application requirements. For specific application, we may not need the best and most expensive sensor. We may only need a sensor which is slightly more than completely meeting all requirement for particular temperature application, particularly the maximum temperature range of operation and environmental restriction are usually the important factors for consideration for the selecting the most appropriate sensor for specific application. The required accuracy of temperature measurement control and stability throughout the process, the response time and sturdiness of the sensor are also important factor. Last but not least, the overall cost of the thermal process in relation to the increased value of the product after the thermal operation should be carefully considered.

TABLE IV

CRITERIA FOR THE SELECTION OF TEMPERATURE SENSOR

Application Requirement

Temperature

Maximum Temperature
Total Range of Operation

Time of Operation

Environmental restraints
protection vs Environment

Accuracy

Stability of calibration

Response Time

Sturdiness

Cost

CASE STUDIES

The following examples illustrates the choice of the right temperature sensor for particular requirements.

CASE (1) CALIBRATION OF TYPE T THERMOCUPLES FOR CRYOGENIC APPLICATION

In manufacturing metal sheathed thermocouples for cryogenic application one must use special process and pre-select the bare wire in order to meet costumers calibration requirements. A specially selected 14 gauge copper and constantan bare wire was manufactured into Type T metal sheathed thermocouples. Thirty Type T thermocouples were calibrated at -196°C (-320°F). As shown on Fig. 7, all thermocouples met the ANSI MC 96.1 recommended special limits of ±1.6°C (2.9°F) at liquid nitrogen temperature.

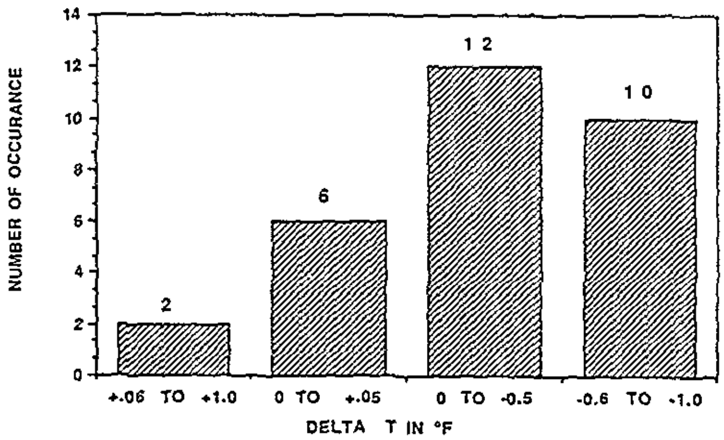

FIG. 7 30 TYPE T T/C CALIBRATED AT -320 °F FOR CRYOGENIC APPLICATION

CASE (2) CALIBRATION OF THREE 4 WIRE RTD AT TRIPLE POINT OF WATER AND AT 200°C

In some applications, extreme initial accuracy and stability of calibration of the temperature sensor is required at moderate temperature range 0°C to 200°C. In this case, RTD is the choice over thermocouple, *at these temperature range the ASTM specification for grade A* RTD is ± 0.13 °C at 0°C and ± 0.47 °C at 200°C. As shown in Fig. 8 , the initial deviations of three 100 Ω platinum RTD's -0.05 to -0.12 at 0°C (measured at triple point water +0.01°C and corrected at 0.00°C) and -.014 °C to -0.14 °C are within the ASTM Grade A specification

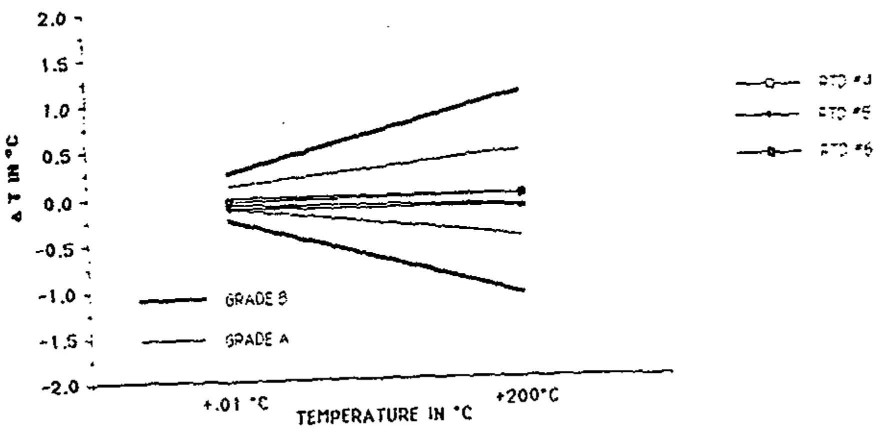

FIG. 8 CALIBRATION OF THREE 4 WIRE RTD AT TRIPLE POINT OF WATER & 200 °C

SUMMARY AND CONCLUSIONS

(1) The principle of operations material, construction, specification, operating temperature range, stability and response time of thermocouples are describe in comparison with those of RTD's.

(2) In brief, thermocouples can be operated at wider temperature range, with faster response time, and are easier to fabricate, more rugged, less subject to vibration and are generally lower in cost than RTD's. On the other hand, RTD's have higher signal output, are more accurate and stable at moderate temperature than thermocouples.

(3) In choosing the right temperature sensor for a particular process, one must consider the overall requirement of the process, compared and weigh all advantages and limitations of each and every features of thermocouples and RTD's in order to derive the final selection.

ACKNOWLEDGEMENT

The authors wish to thank D. Frank for his permission to publish this paper.

REFERENCES

(1) Wang T.P. "Thermocouple vs Resistance Temperature Detectors", Chemical Engineering Progress p. 14, June,1989

(2) ASTM STP 470 B, Manual on the Use of Thermocouples in Temperature Measurement, p. 35, 1987

(3) Ibid

(4) ANSI MC 96.1, Temperature Measurement of Thermocouples, p. 15, 1982

(5)ASTM Book of Standards, E-1137-87, Standardized Specification for Industrial Platinum Resistance Thermometers, p. 379 ,1990

(6) International Electrotechnical Commission (IEC) Standard Publication 751,Industrial Platinum Resistance Thermometer Sensors,1983