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Recent Advances In Temperature Sensors

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RECENT ADVANCES IN TEMPERATURE SENSORS

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KEYWORDS

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ABSTRACT

This paper describes the features and performance data of three new temperature sensors of interest to power and process industries: stabilized metal sheathed K and E thermocouples, high temperature RTD's and LIST sensors, Linear Integrated Sensor Transmitter. The calibration of nine stabilized Type K metal sheathed thermocouples were proven to be unchanged after an extended period at 538°C in actual environment and the use of these stabilized thermocouples could help a utility generating station with four 500 megawatt steam turbines realize savings of fuel cost of \$200,000 annually. 6,000 hour laboratory stability data at 538°C and 300 hour data at 1260°C (K only) are presented. For high temperature RTD's, over 1 year of continuous performance data of over fifty 100 ohm RTD's at three major utilities monitored by users and compared with previous sensors were described. Long term laboratory stability data of these 3-wire and 4-wire RTD's at 538°C are presented. The LIST sensor is a new smart RTD developed by this Company. It is an accurate and stable RTD with a transmitter which outputs 4 to 20 mA. It is available in both low temperature and high temperature ranges. As an integrated sensor and transmitter, the LIST provides superior accuracy and economic advantages over separate sensor/transmitter assembly.

INTRODUCTION

Temperature is one of the most important process variables in sciences and industries. In many instances, the quality of the process and products depends on how accurate temperature is measured and controlled, particularly the more sophisticated products or processing. Therefore, if the measurement or control is poor, we may end up with rework or scrap. Of course, neither one is cost effective.

There are various types of temperature sensors to fit different ranges and applications. Behind thermocouples, RTD's (Resistance Temperature Detectors) are the most popular sensors used in the measurement and control of temperature today. While different types of thermocouples can be used in a wider temperature range, from near absolute zero (-273°C) to over 2000°C versus -196°C to +850°C for RTD's, and thermocouples are faster in heat response and less subject to vibration than RTD's, RTD's are more accurate and stable than thermocouples at ambient to moderate temperature.

For the power industry, the temperature of most interest is 538°C (1000°F). Thermocouples, Types K or E, are the sensors for generators using fossil fuel (coal) where vibration is prevalent. The positive shift of up to 5°C when K or E thermocouples are well known. RTD's are more generally used in nuclear plants where the test temperatures are generally lower than 400°C (750°F) and vibrations are less. In this paper, laboratory and field stability test results are presented for stabilized K and E thermocouples and RTD's temperature at 538°C (1000°F).

No sensor measures temperature directly. One measures an output which is temperature dependent. In order to obtain most accurate temperature measurement, the dependent variable has to bear a definite and reproducible

relationship with the independent variable, temperature. For thermocouples, the dependent variable is voltage. For RTD's, the dependent variable is resistance. For most accurate temperature measurement, one would like this relationship to be linear. However, neither thermocouples nor RTD's bear a strictly linear relationship with temperature over the entire range. Therefore, by using a diode or a transmitter in connection with a temperature sensor, one obtains linearization of the output, hence, more accuracy. LIST sensor is a sensor with a RTD and a transmitter built into a single unit. The accuracy and stability of LIST sensors up to 400°C (752°F) are described in this paper.

STABILIZED TYPE K AND E THERMOCOUPLES

The hysteresis effect of heating and cooling the Type K thermocouples to a high temperature has been reported by Sibley et al.⁽¹⁾ The theoretical interpretation of the about +5°C change of the couple, which is essentially attributed to KP, the Type K positive thermoelement, was explained by Wang et al.⁽²⁾ The first stabilized Type K thermocouples in the form of ceramic fiber insulated wire was first mass produced for McDonnell Douglas in 1990. The calibration of this stabilized K thermocouple wire was the same regardless of heating rate from ambient to 1100°C (2000°F). It makes no difference if heating rate is fast, 20 minutes later, or slow, 16 hours.⁽³⁾

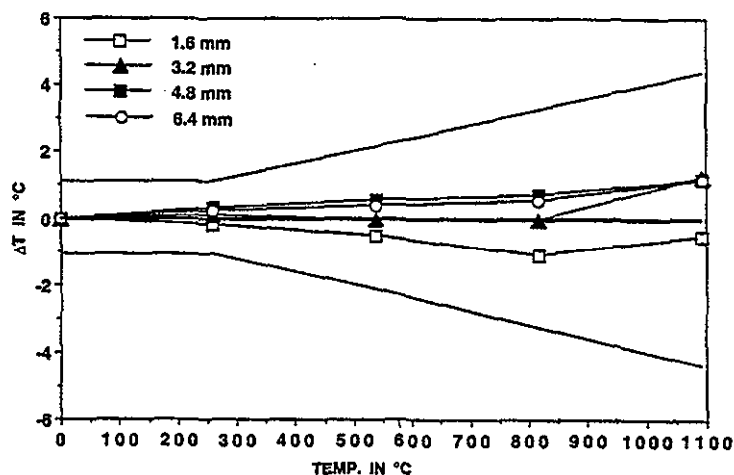


FIG. 1 ACCURACY OF 1.6 mm, 3.2 mm, 4.8 mm, 6.4 mm O.D. STABILIZED TYPE K METAL SHEATH THERMOCOUPLES

Accuracy of Metal Sheathed Stabilized Type K and Type E Thermocouples

About one year ago, the metal sheathed mineral insulated Type K and Type E thermocouples were developed, mass produced and inventory stocked. The accuracy of various sizes meet the premium (special tolerance) of initial values of EMF versus temperature, e.g., Type K $\pm 1.1^\circ\text{C}$ or $\pm 0.4\%$ of temperature whichever is greater (0° to 1260°C) as specified in ASTM E-230-93⁽⁵⁾. See Fig. 1. Note that the calibrations of the four sizes, 6.4 mm (.250"), 4.8 mm (.187"), 3.2 mm (.125") and 1.6 mm (.062") type K thermocouples made from the same original wire match are essentially the same. The Type E thermocouples follow the same trend. This is unlike the nonstabilized wire where the EMF becomes more negative as the sheath diameter gets smaller.

Stability of Metal Sheathed Stabilized Type K and Type E Thermocouples at 538°C (1000°F) and 1260°C (2300°F)

Laboratory stability tests at 538°C (1000°F) was conducted on 6.4 mm (.250") and 3.2 mm (.125") diameter Type K and Type E Ceramo* thermocouples for a total of 3400 hours (4.7 months). The test results are shown in Fig. 2. The calibration of both Type K and Type E Ceramos are essentially unchanged since the changes in all four cases were well within the uncertainty of calibration of $\pm 1.1^\circ\text{C}$.

* Ceramo - Tradename for metal sheathed mineral insulated thermocouple, Thermo Electric

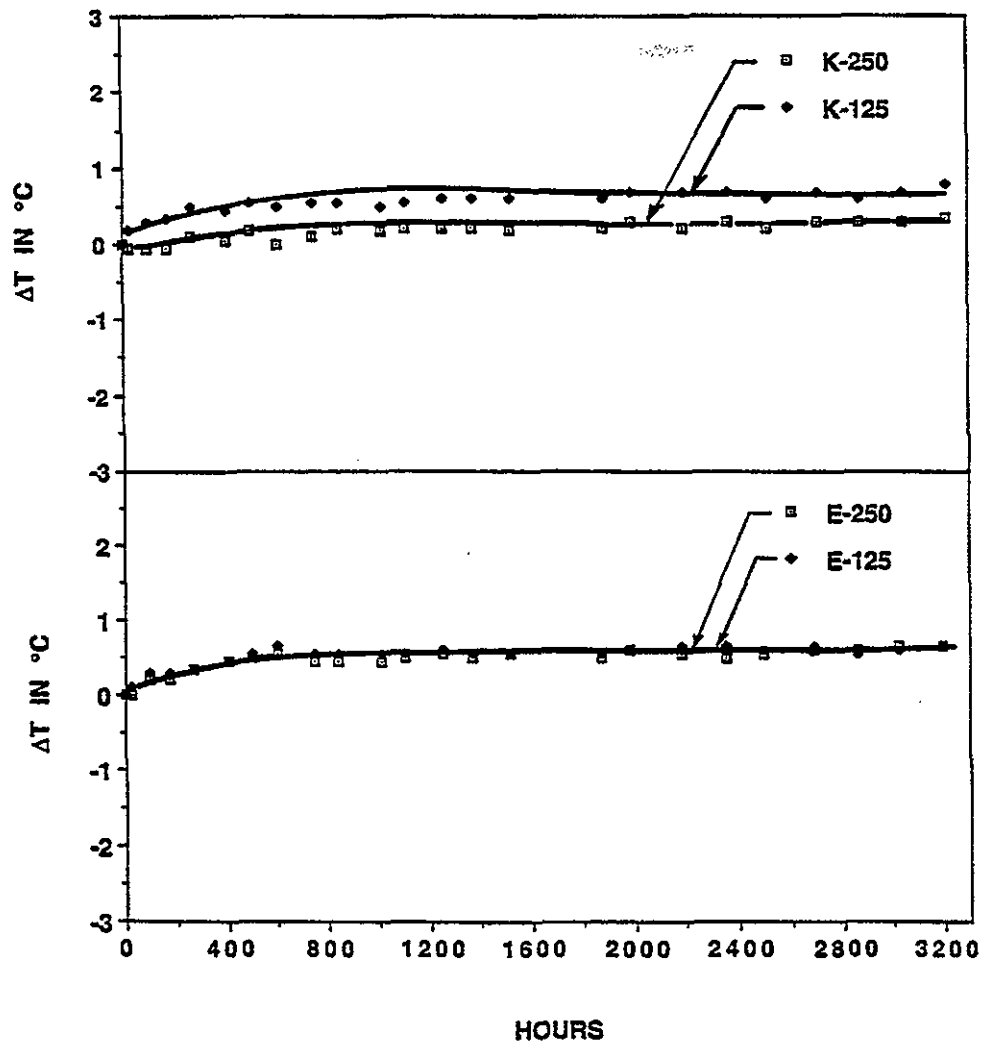


FIG. 2 STABILITY TEST OF STABILIZED TYPE K AND E METAL SHEATHED THERMOCOUPLES AT 538°C (1000°F) IN AIR

After the above laboratory test have gone over several hundred hours, no significant shift was found. Then we submitted a total of nine 64 mm (.250") OD Type K Ceramo thermocouples to the Lampton Station of Ontario Hydro for evaluation. After a total of 90 days in actual operation, we found that (1) there was no significant calibration change in all nine stabilized Type K thermocouples, and (2) for a power generating unit like Lampton with four 500 MW generators, a 2 C lowering of steam temperature (thermocouple drifted 2°C positive) would mean an additional fuel cost of \$200,000 annually (4). The Type E are being evaluated and the aforementioned nine Type K thermocouples were put back for further tests. The results will be reported at a later date.

It may be stated that the above 200K annual savings as a result of using stabilized thermocouples are in reference to fuel cost only. It does not include the savings in maintenance shutdown in time loss or the labor cost in replacing the thermocouples for calibration. Nor does it include the expense of under compensating or overcompensating for thermocouple errors. For under compensating, it means the system is running at lower than 538°C which means additional fuel cost. For overcompensating, it means the system is running at higher temperature than 538°C. This may be detrimental to the steel components of the turbines since 538°C is the maximum recommended operating temperature.

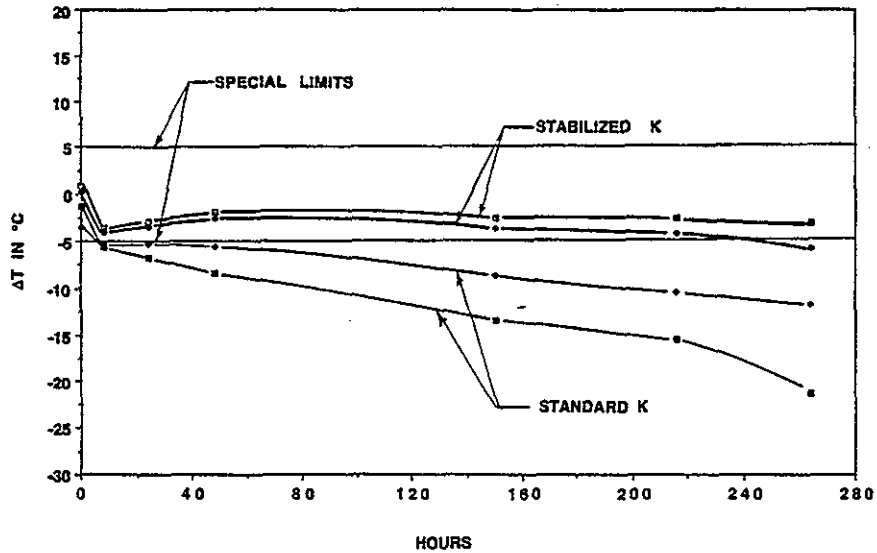


FIG. 3 STABILITY TEST OF 3.2 mm O.D. STABILIZED K AND STANDARD CERAMO THERMOOCOUPLES IN AIR AT 1260°C

The metal sheathed stabilized K thermocouples are more stable than the unstabilized version of the same sheath material, not only at 538°C, but also at the limit of Type K thermocouples, 1260 C (2300°F). Duplicate 3.2 mm (.125") diameter stabilized and nonstabilized Type K Inconel[®] sheathed thermocouples were tested at 1260°C for a total of 260 hours in air atmosphere. The test results are shown in Fig. 3. One can observe that at the limiting temperature of K, 1260°C, the stabilized K thermocouples were essentially within the premium tolerance of $\pm 5^\circ\text{C}$ ($\pm 9^\circ\text{F}$), but the nonstabilized K drifted out of this range after only 8 hours.

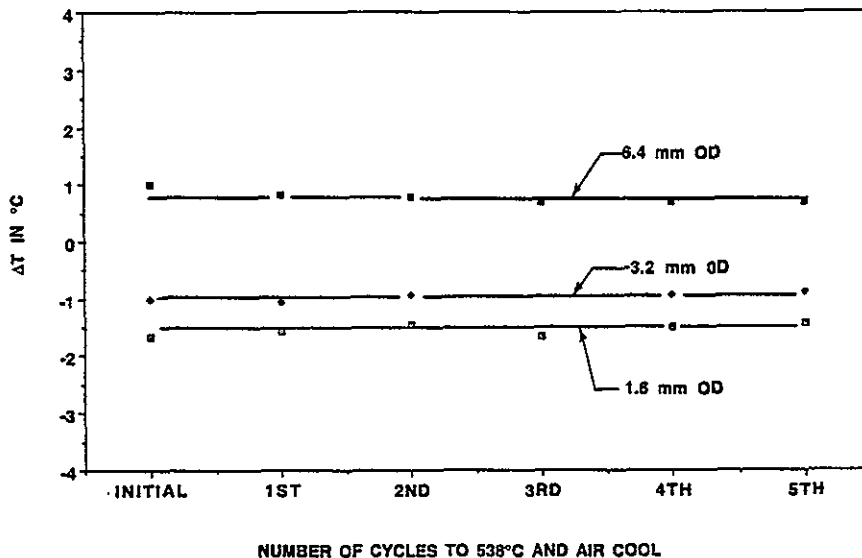


FIG. 4 EFFECT OF AIR COOLING FROM 538°C ON STABILIZED TYPE K CERAMO THERMOOCOUPLES

Effect of Heating and Cooling Rate

The effect of heating/cooling rate on the calibration of stabilized K Ceramo thermocouples are summarized as follows:

Heating

No effect, regardless of size, ambient to 1100°C (2000°F), fast or slow. This is different than the well known hysteresis effect of up to 5°C for the slow heating of unstabilized K.

Air Cooling

(1) Slow Rate

No effect regardless of size (6.4 mm to 1.6 mm) 1100°C (2000°F) to ambient. See Fig. 4.

2) Air Cool

(i) 538°C (1000°F) to ambient.

No effect regardless of size.

(ii) 1100°C (2000°F) to ambient.

Checked at 1100°C, no effect for 6.4 mm, less than -1°C for smaller sizes. No change after the first cooling cycle.

Checked at 538°C, less than -1°C for all sizes. No change after the first cooling cycle.

The above results are shown in Fig. 5. This information may be of interest to those who wish to try stabilized K.

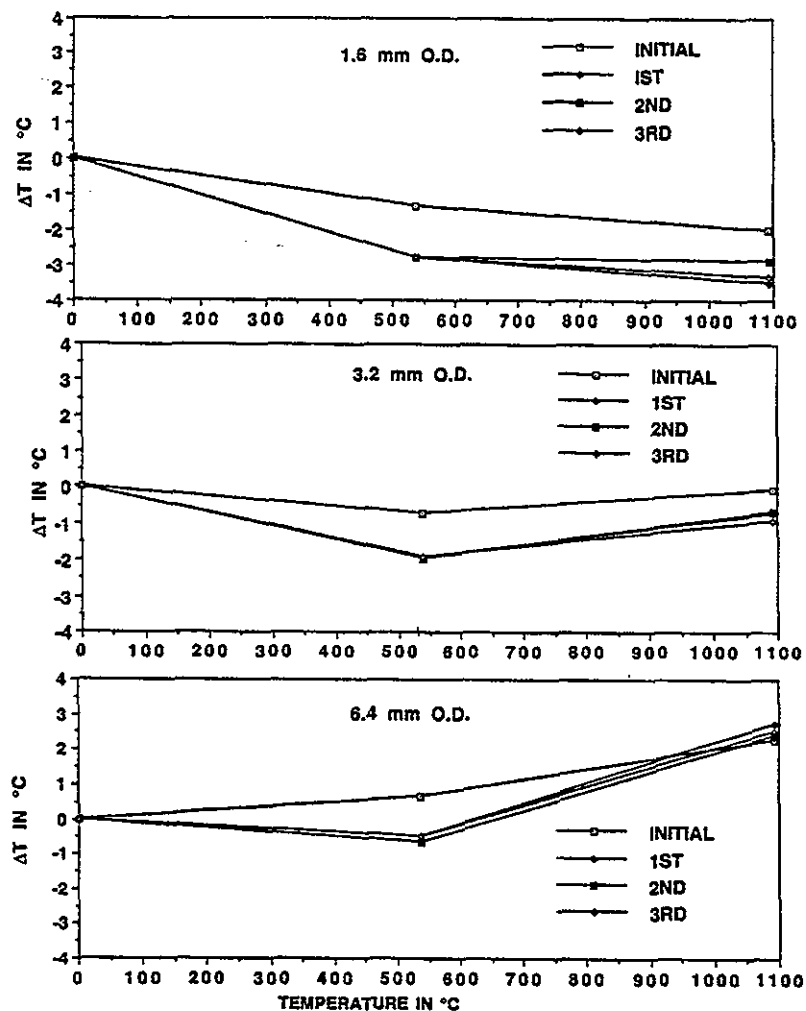


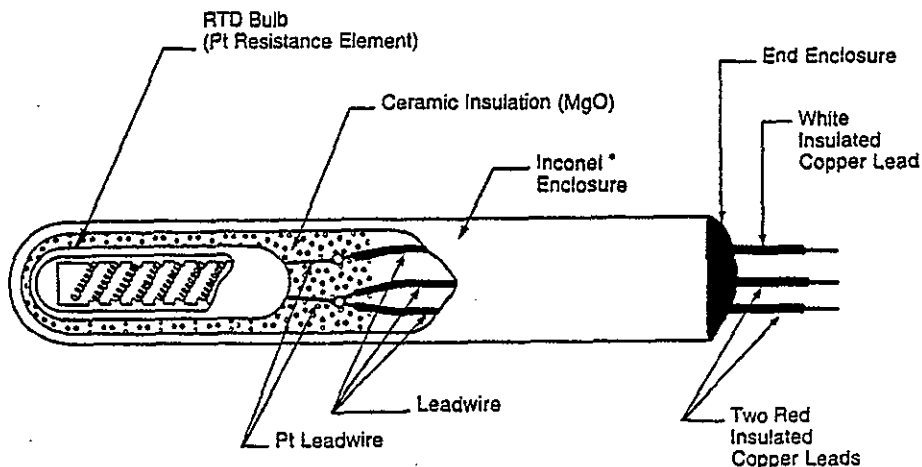
FIG. 5 EFFECT OF AIR COOLING FROM 1093°C ON STABILIZED TYPE K METAL SHEATH THERMOCOUPLES

The stabilized Type E Ceramo thermocouples should behave similar to Type K thermocouples. The reason being they share the same positive thermoelement which is known to subject to aging in the 400°C to 600°C range while neither of the negative thermoelements, Alumel* for Type K and Constantan for Type E, is known to be subject to aging.

HIGH TEMPERATURE RTD'S

The maximum operating temperature of RTD's was said to 850°C (1562°F). According to one manufacturer recently, "Few suppliers can provide a metal sheathed probe for industrial measurements that has acceptable stability when used above 600°C."⁽⁶⁾ However, according to users' comments, many did not last in operating temperatures of 538°C (1000°F) in users environments, whether in U.S. or Europe. Shepard, who retired after a long stay at Oakridge, stated that at 538°C (1000°F) for 1,000 hours the deviations of various RTD's range from +.9°C (+1.5°F) to 9°C (+15°F) at temperature.⁽⁷⁾ DeGraaff stated that after 1,000 hours at 500°C, the change was about +6°C at temperature.⁽⁸⁾ From the above, the challenge of developing a high temperature RTD's is to manufacture one that will be stable after a long time at temperature at the user's environment.

A schematic design of a high temperature RTD is shown in Fig. 6. It is a 3-wire 100 ohm RTD with platinum resistance element with an alpha value of .00385 Ω/Ω/°C. The enclosure is Inconel and the insulation is high purity magnesium oxide (MgO). Inside the enclosure, the platinum lead wire of the platinum resistance element is connected to three constantan lead wires which are connected to three insulated copper lead wires near the other end of the enclosure. The insulated copper lead wire is properly sealed to prevent contamination.



3-Wire 100 Ohm RTD

Fig. 6 SCHEMATIC DESIGN OF A 1000°F RTD

After developing the 100 ohm, 0.00385 alpha high temperature metal sheathed RTD's, our first step was to stability test them at our laboratory in air for 7,000 hours at 538°C (1000°F). The test results on a 3-wire probe and a 4-wire probe were obtained. Both of these probes were 6.4 mm OD. The resistance at the ice point at various intervals were measured and compared with the original resistance values. The ΔR readings were converted to °C as shown in Fig. 7 and 8. The changes for both are less than .03°C at the ice point. This was, of course, very stable.

* Inconel - Trademark, International Nickel Company

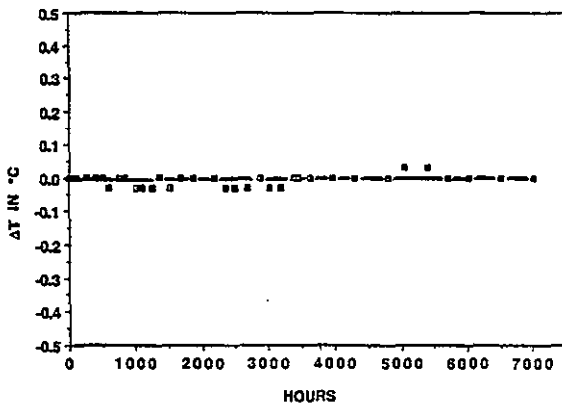


FIG. 7 7000 HRS STABILITY TEST OF 3 WIRE RTD AT 538°C (1000°F) IN AIR

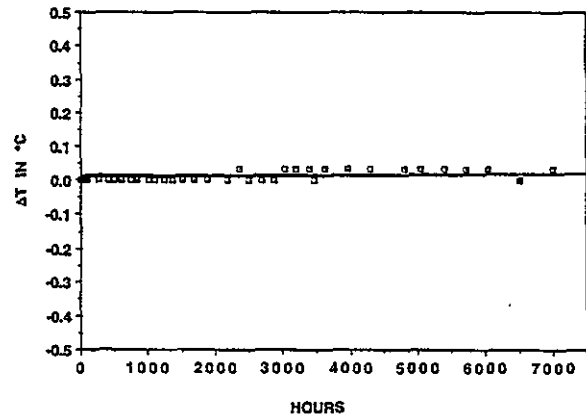


FIG. 8 7000 HRS STABILITY TEST OF 4 WIRE RTD AT 538°C (1000°F) IN AIR

Since the middle of the lab test, we started to ship some of the same sizes (and different lengths) to various users. We believe that it is great to have a QA system which was certified to meet ISO 9002. We further believe that product evaluation can only be judged by users at their sites in actual operations on sufficient number of units for a prolonged period of time and in comparison with previous units. See Table I.

TABLE I
PERFORMANCE OF TE's 1/4" O.D. 100 OHM
HIGH TEMPERATURE RTD's AT MAJOR UTILITIES

<i>Customer</i> <u>East Utility</u>	<u>Mid West Utility</u>	<u>Far West Utility</u>
<i>Product</i> Initial 20 Reorder 23	12	1 (4-wire)
<i>Application</i> (a) 300/700°F, 2 cycles/day (b) 1000° ± 50°F	950° to 1150°F	900° to 1000°F
<i>Time in Service</i> Over 20 months	Over 20 months	Used for a total of 1 year. Returned to customer after ice point check at TE. 99.99 ohms after 10 months.
<i>Performance</i> Checked periodically with temperature controller with RTD sensor One bulb failure in days. Balance on-going.	Checked to within ±1°F with dry-block calibrator One failed after 6 months. Balance on-going.	Checked vs. used Type E T/C to within ±1°F before restart and ±2°F after restart. On going.
<i>Competition</i> <u>Previous Supplier's RTD's</u> More than ten failed within days of installation. Now all his RTD's are TE RTD's as of 2/1/95 visit.	<u>Previous Supplier's RTD's</u> 1/2" O.D. 32 ohm RTD's were satisfactory. Switched design to 1/4" O.D. 100 ohm RTD's in 1993. All 1/4" O.D. 100 ohm RTD's he tried failed within 2 months until he used ours.	<u>Previous Supplier's RTD's</u> Three months
<i>Service</i> Telephone conversation with Mr. M on 4/11/95	Telephone conversation with Mr. T for 18 months with Mr. W on 4/13/95	Telephone conversation with Mr. F on 4/11/95

Westinghouse, Orlando, FL

Used two RTD's for 3 weeks in actual environment. Ongoing. RTD's from 3 major suppliers all failed in service in less than 2 hours. Ordered 25 units, after initial evaluation ordered an additional 35 units.

(4/11/95)

So far, we monitored the performance of three high temperature RTD's for four users. Three of them are major utilities across the continent, and the fourth is Westinghouse, a major manufacturer in the Southeast. The units involved were mostly double digits. Two of the four had ordered double digit additional units. A third one is contemplating ordering more. One of them, a single 4-wire RTD, was found to have a resistance of 99.990 ohms after 10 months usage from 482°C (900°F) to 538°C (1000°F). This is equivalent to $-.025^{\circ}\text{C}$ at the ice point.

The temperature in all cases was mostly 538°C, with one as high as 621°C (1150°F), and one as low as 141°C (300°F). The duration ranged from 3 weeks to 20 months. Failure of previous RTD's occurred from a 1/2 hour to 3 months, while these RTD's, except 2 early failures, lasted up to 20 months and still on-going. At Westinghouse, three major supplier's units failed from a 1/2 hour to 2 hours while our RTD's are still on-going after 3 weeks. At one location where the temperature was as high as 620°C, our units lasted 20 months as still on-going. It is interesting to know that this user got 20 months performance from previous 12.8 mm (1/2 in.) OD metal sheathed platinum RTD. But when this user switched to 6.4 mm (1/4 in.) OD 100 ohm metal sheathed platinum RTD, the most he could get was 2 months before he switched to our RTD's. The performance comparison is similar to a 150 pounder fighting on even keel with a person twice the weight.

The performance description of RTD's is important. This is because RTD is the heart of the next sensor we wish to describe, the LIST sensor.

L.I.S.T.* (Linear Integrated Sensor Transmitter)

The LIST instrument is an RTD sensor and a transmitter combined into an integral unit. See Fig. 9. The platinum ($\alpha = .00385 \Omega \text{ per } \Omega \text{ per } ^{\circ}\text{C}$) sensing element is housed inside in a 316 stainless steel enclosure, or Inconel if specially ordered, of either 6.4 mm (1/4") or 4.8 mm (3/16") in diameter. Through miniaturization, we are able to insert a 4 to 20 mA transmitter into the transition of the RTD. For a 6.4 mm LIST sensor, the top section is only 7.9 mm (5/16") in diameter and 10.2 cm (4 inches) long. The top section remains this length for the smaller 4.8 mm diameter LIST sensor also. Inside the enclosure, the three lead wires of the RTD are connected to the one end of the transmitter, and the other end of which is connected to the flexible red (+) and white (-) copper lead wire.

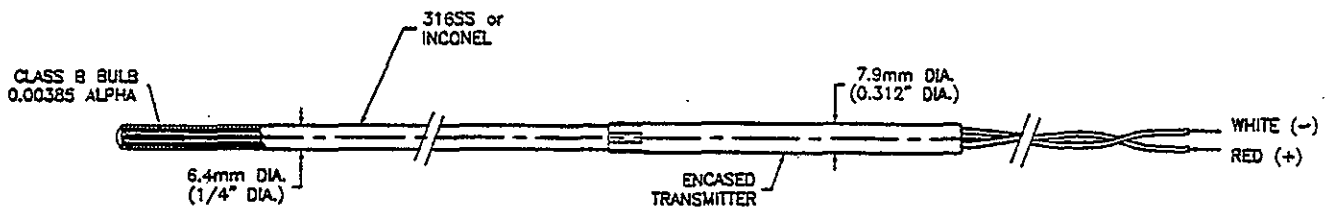


Fig. 9 - Schematic Diagram of a LIST Sensor

LIST saves money and space. Estimates range from 25% to 40% savings than the standard construction of separate RTD and transmitter of equivalent quality. Separate transmitters usually require larger connection heads or rack mounting for wall panes or box installations. With LIST, installation is just the connection of two leads from the LIST to the system. In addition to the costly labor and materials, installation errors will be less common with fewer connections. Hardware costs and their space requirements for racks, wall mountings and boxes for transmitters are eliminated.

The LIST instruments are calibrated with standards directly traceable to the NIST. This complies with ISO 9000 quality standard requirement.

*Patent pending.

Accuracy and Repeatability of LIST

Unless otherwise specified, the LIST sensors are made with RTD stems which meets ASTM class B requirements. See Fig. 10.

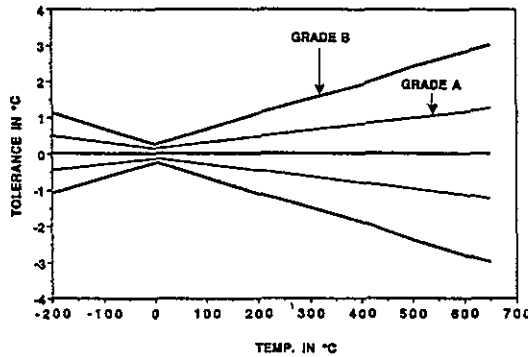


FIG. 10 TOLERANCE IN °C OF GRADE A & B RTD'S PER ASTM E1137

Five 6.4 mm RTD stems randomly selected from the Stock Room are listed as follows:

RTD Number	Ro. ohms	Δ Ro. ohms	Grade
1	99.93	-.07	B
2	99.99	-.01	A
3	99.95	-.05	A (Marginal)
4	99.98	-.02	A
5	99.95	-.05	A (Marginal)

Tolerance	A	B
	100 Ω \pm .05 Ω	100 Ω \pm .10 Ω

When they were made into 0° to 150°C range LIST sensors, they were calibrated vs. our NIST calibrated SPRT standards at test temperatures 25%, 50% and 75% of the full scale. The results are shown in the Calibration Lab Report dated April 5, 1995.

E Calibration Laboratory Test Report

Customer: PER 1000 P.O. No. 1-1
 Product name: RTD WITH CONNECTOR P.E. Lab No. 1-1
 Reference: American Institute of Chemical Engineers, Inc. (AIChE) 1984, 1-1
 Test No. 1-1
 Part 1: List of Stem and Resistance Data Transmitted to the NIST
 Part 2: List of Stem and Resistance Data Transmitted to the NIST
 Part 3: List of Stem and Resistance Data Transmitted to the NIST
 Part 4: List of Stem and Resistance Data Transmitted to the NIST
 Part 5: List of Stem and Resistance Data Transmitted to the NIST
 Part 6: List of Stem and Resistance Data Transmitted to the NIST
 Part 7: List of Stem and Resistance Data Transmitted to the NIST
 Part 8: List of Stem and Resistance Data Transmitted to the NIST
 Part 9: List of Stem and Resistance Data Transmitted to the NIST
 Part 10: List of Stem and Resistance Data Transmitted to the NIST

RANGE: 0 TO 150°C

TRANSFORMER	SCALE	TEST TEMPERATURE	ACTUAL TEMPERATURE	ACTUAL RESISTANCE
1	25	25.0	27.71	7.000
	50	75.0	75.10	13.000
	75	112.5	112.30	18.000
2	25	25.0	27.71	8.000
	50	75.0	75.10	14.000
	75	112.5	112.30	19.000
3	25	25.0	27.71	9.000
	50	75.0	75.10	15.000
	75	112.5	112.30	20.000
4	25	25.0	27.71	10.000
	50	75.0	75.10	16.000
	75	112.5	112.30	21.000
5	25	25.0	27.71	11.000
	50	75.0	75.10	17.000
	75	112.5	112.30	22.000

CALIBRATION SYSTEM IS IN COMPLIANCE WITH NIST-1137-10000 AND NIST-1137-10000
 CALIBRATION PROCEDURE PER NIST 1137-10000, TOLERANCE SCALE PER ITS 100

DATE: 4 Apr 1995 APPROVED BY: *[Signature]*
Chas. Smith, Chief Chief Calibration Cell - Lab. 1000-10

THERMO ELECTRIC 100 N. First Street, Suite 3000, New Jersey 07003-6167

The test results were repeated two more times, and are shown in Fig. 11 in terms of ΔT in $^{\circ}\text{C}$. One can easily observe that all five LIST sensors, have maintained or improved on the initial accuracy and are repeatable to within $\pm 0.05^{\circ}\text{C}$ at temperature.

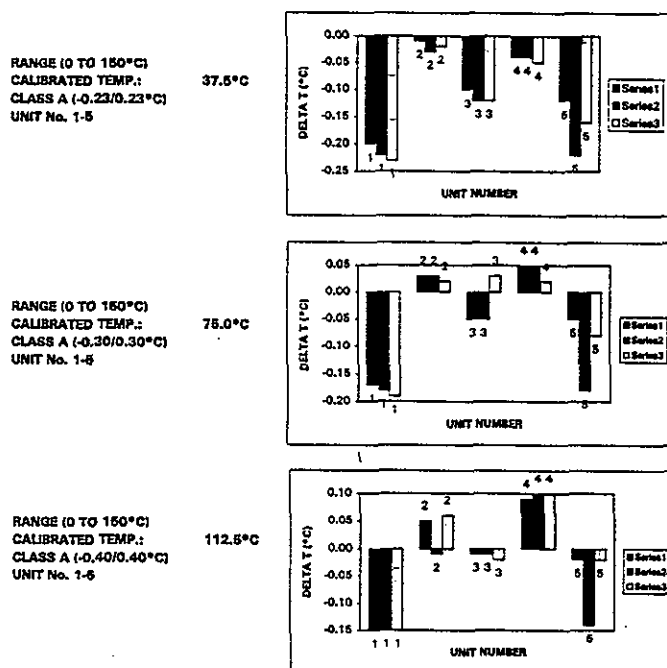


Fig. 11 INITIAL ACCURACY AND REPEATABILITY OF LIST SENSOR

PROPOSED APPLICATION OF THESE THREE SENSORS

Stabilized K and E Thermocouples

Utilities
 Aerospace
 Auto
 Heat Treat
 Chemical

High Temperature RTD's

Utilities (especially Nuclear)
 Aerospace
 Chemical

LIST Sensors

Pharmaceutical
 Food
 Chemical
 Utility
 Petro Chemical

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