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Errors introduced by the standard resistance in bridge thermometry measurements

T J P Gwilliam & S B Keene

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Natural Environment Research Council

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ABSTRACT

This is a report on a series of tests to evaluate the errors introduced into the temperature calibrations by the bridge standard resistors used at the Institute of Oceanographic Sciences. Long term stability, temperature coefficient and self heating effects are studied.

KEYWORDS

ITS90
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Errors introduced by the Standard Resistance in Bridge Thermometry Measurements.

1.0. Introduction

With the increasing need for greater accuracy in oceanographic temperature measurements, there is a growing emphasis on investigating, identifying and minimising the errors introduced during the sensor calibration process. This report describes one source of possible error with the standard resistance and discusses a method of minimising the effects of this imperfect behaviour.

2.0. General

Precision temperature measurements at the Institute of Oceanographic Sciences Deacon Laboratory, lOSDL, are carried out using well established bridge thermometry techniques involving the inductively coupled alternating current divider. The Automatic Systems Laboratory F17 series bridge in use at IOSDL is capable of measuring the ratio of two, four terminal resistors to an accuracy of better than ±1ppm of the reading. For temperature measurement applications, one of the resistors, R_t, is a platinum resistance thermometer (prt), and the second, R_s a standard reference resistor.

To carry out a temperature measurement, the first stage is to calibrate the prt against known standard temperatures. At the present time the most stringent requirement in oceanographic temperature measurement is for the World Ocean Circulation Experiment (WOCE) where an accuracy of 0.002°C. (ref.1)(ref.2)(ref.3) is specified over the range from near 0°C to 30°C To meet this specification and to satisfy the requirements of ITS 90 (International Temperature Scale 1990 ,ref. 4) the thermometer (prt) must be calibrated at the triple points of mercury (-38.8344 °C), water (0.0100 °C), and at the melting point of gallium (29.7646 °C). In addition, we also use two secondary standard triple point cells, phenoxybenzene (26.8625 °C) and ethylene carbonate (36.3135°C) to provide further calibration points. At each fixed temperature the bridge is balanced and a ratio of the prt resistance to standard resistance, which is unique to that temperature, is obtained.

At standard temperature T(std),

$$\text{Ratio} = R\,(\text{prt}) / R\,(\text{std}) \qquad \text{----eqn.1}$$

The results of a typical transfer standard calibration are shown in Table 1. Note that the reference temperatures in Table 1 include a hydrostatic head correction.

Table 1- Transfer Standard Calibration

PRT Probe ASL708 Serial Number: 238708

Standard Resistance Serial Number: 239022

Calibration Date: 2/12/91

Cell Type	Standard Temp. °C.	Bridge Ratio	Standard Res. Temp.° C.	Standard Res. Ω	PRT Res. Ω
Mercury	-38.8334	0.850 257	20.5	24.999 940	21.256 379 8
Water	0.01000	1.007 163	19.5	24.999 868	25.178 942 1
Phenoxy-benzene	26.8625	1.114 550 5	20.0	24.999 905	27.863 656 6
Gallium	29.7639	1.126 098 5	20.2	24.999 919	28.152 371 3
Ethylene Carbonate	36.3135	1.152 134	19.8	24.999 890	28.803 223 3

Using the temperature corrected absolute value of the standard resistance, the value of the prt resistance can then be deduced using eqn.1 and a polynomial equation derived that best describes the relationship between the standard temperatures and the prt values. Using this calibration equation it is then possible to derive any temperature from the bridge measurements of the prt resistance. The resolution of the bridge is equivalent to 0.25m° C and the accuracy is better than 1m°C.

The performance of the bridge as a temperature measurement device is therefore dependent on the quality of both the prt and the standard resistance used. The standard platinum resistance thermometers used for temperature measurements at IOSDL are model 5187SA, manufactured by H. Tinsley and fully meet the ITS90 specification (ref. 5) by satisfying one of the following relationships:

$$W(29.7646\ °C) \geq 1.118\,07$$

$$W(-38.8344\ °C) \leq 0.844\,235\,,$$

where $W(t_{90}) = R(t_{90}) / R(0.01\ °C.)$

For example, for the prt calibration data shown in Table 1:

$$W(29.7639°C) = 1.118\,09$$

$$W(-38.8344°C) = 0.844\,212$$

It could be argued that using eqn.1 to evaluate the prt resistance, in order to obtain temperature, is an unnecessary step and that the absolute value of the standard resistance is not a critical factor for measuring the temperature. The argument being that it is a series of ratio measurements against known temperatures that provide the calibration, and therefore any temperature can be determined if the ratio alone is known. While this is true, in practice this method of evaluating temperature carries several disadvantages that outweigh the apparent benefit of an arithmetic shortcut.

Changes in the bridge standard resistance values during the calibration process can compromise the assessment of a prt for ITS90 if it is done by a comparison of ratios. For example, if the 'Bridge Ratio' values from Table 1 were used to determine the mercury or gallium standard ratios then the results would differ from those derived using the absolute prt values. The reason for this is that the temperature of the standard resistance changed during calibration and it was only in the latter calculation that a correction for this change was applied. Although in this instance the error introduced by using the bridge ratio method is small, it does highlight a source of inaccuracy and the advantage of using absolute resistance values.

A simple instrumentation performance check can be achieved by substituting a second known standard resistance for the prt, and using the ratio at bridge balance to evaluate the primary standard resistance. The result can then be compared with the measurement taken by the national standards laboratory, the National Physical Laboratory (NPL), and any difference provides a figure for the systematic bridge error. If the absolute value of the standard resistance is known, then inter-comparison checks with other bridge systems are possible, a history of the long term stability can be determined and temperature compensating procedures applied.

Confidence in the accuracy of a temperature calibration system is enhanced when the component values and errors are fully understood. The performance of the bridge and associated components is primarily dependent on the quality and full understanding of the bridge, prt and standard resistance, and if the value of the latter is known to a sufficient accuracy, then the prt resistance, and hence temperature, can be obtained and related to the required accuracy

The external 25 Ω reference resistance used with the bridge and which is the subject of this report, is based on a design originating from Wilkins at the U.K. National Physical Laboratory (ref.6).

In normal day to day usage there are three contributory factors that may effect a resistance change and hence introduce temperature errors: stability, self heating and environmental temperature changes.

3.0. Long Term Stability

From the manufacturers specification , the quoted long term stability in resistance for the standard resistors is 2ppm/year, equivalent to a 50 μΩ resistance or 0.0005°C change in temperature. Long term changes are, in the most part, due to molecular changes within the sensing element brought about by mechanical stress, and could be introduced into the material during the forming of the element, or as local stress where the element is supported. Mechanical shocks can also cause material stress and can not only change the value at that instant but could cause changes over a longer period. Resistance change is not a constant, it is usual to find the stability error decreasing with time. The two standard resistors currently in use at IOSDL are returned to NPL at regular intervals where their values are measured at 20° C. Tables 2 and 3 list the calibration data for the two resistors and figure 1 illustrates the long term stability over a 11 year period.

Table 2 Standard Resistor Serial Number: 220371

NPL Calibration Results.

Date	Resistance Value (Ω)	1990 Value * (Ω)	Measurement Temperature °C	ΔR $\Omega*10^{-6}$	≈ΔT m°C
19/12/83	25.000 690	25.000 650	20.00 ± 0.01	-	-
22/5/91	25.000 685	25.000 685	20.00 ± 0.005	+35	0.35
22/4/93	25.000 686	25.000 686	20.00 ± 0.005	+1	0.01

Over 10years, stability ≈ 0.036m °C/ year.

* Changes with the International Reference Standard of Resistance 1991

Table 3 - Standard Resistor Serial Number: 239022

NPL Calibration Results.

Date	Resistance Value (Ω)	1990 Value * (Ω)	Measurement Temperature °C	ΔR $\Omega*10^{-6}$	≈ΔT m°C
19/1/82	24.999 825	24.999 783	20.00	-	-
3/6/85	24.999 935	24.999 895	20.00 ± 0.01	112	1.12
24/11/88	24.999 945	24.999 905	20.00 ± 0.01	10	0.1
22/5/91	24.999 905	24.999 905	20.00 ± 0.005	0	0
22/4/93	24.999 903	24.999 903	20.00 ± 0.005	-2	-0.02

Over 11years, stability ≈ 0.11m°C/ year.

* Changes with the International Reference Standard of Resistance 1991

(Pre 1990 Cal.Value) * 0.999 99839 = (Post 1990 Cal. Value)

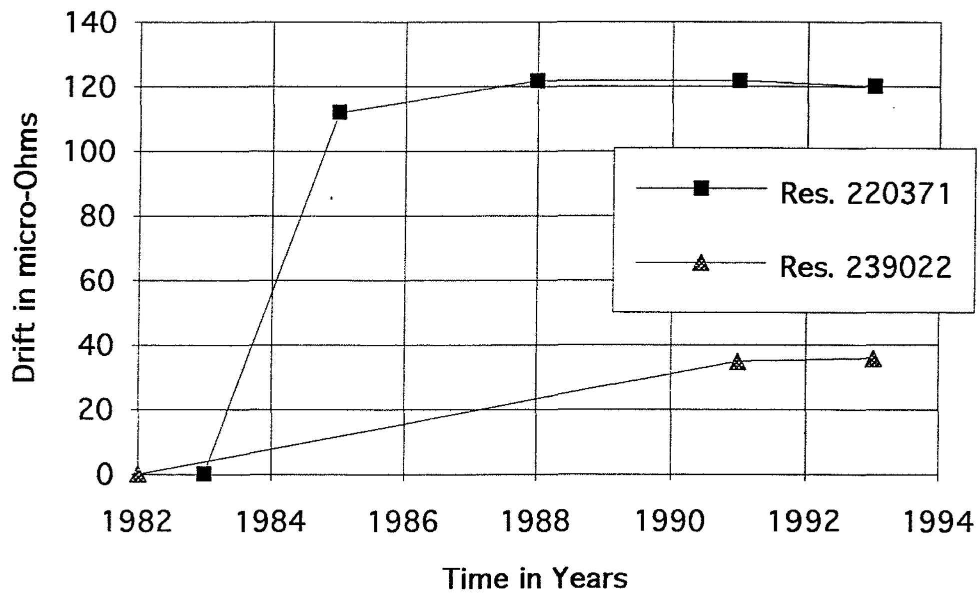

Fig.1 25 Ω Standard Resistor stability drift

4.0. Self Heating Effect

The magnitude of the self heating errors depend primarily on the power dissipated within the component and the value of the temperature coefficient (TC). For bridge thermometry applications, where the prt has a high temperature coefficient, the lowest current drive sufficient to obtain the desired resolution is all that is required, and with the 25 Ω prt a 1mA. drive is found to be the optimum. The standard resistor has a lower TC and the element is physically much larger than the prt and so the self heating effect should be reduced. To assist in the calculation of these errors, manufacturers quote a 'loading coefficient' which relates the change in resistance to the power dissipated within the device. For the type 5685A 25 Ω resistors, the specified loading coefficient (LC) is 6ppm/Watt.

Self Heating Effect (SHE) = 6ppm/W, which results in a resistance change of 150 pΩ/μW.

For 25 Ω Resistor
$$= 6*25$$
$$= 150\ \mu\Omega/\text{Watt}$$
$$= 0.15\ \mu\Omega/\text{mW}$$
$$= 0.15 * 10^{-3}\ \mu\Omega/\mu\text{W} \text{ -------- eqn. 2}$$

For bridge thermometry applications the normal drive current is near 1 mA, giving a power dissipation in the 25 Ω standard resistor of 25μW.

Power dissipation
$$= I^2 * R \text{ Watts}$$
$$= (1 * 10^{-3})^2 * 25 \text{ Watts}$$
$$= 25\ \mu \text{ Watts}$$

The change in resistance due to the self heating effect with 25μ W power dissipation: is therefore 3.75nΩ (using eqn. 2).

To relate this standard resistance change as an error in prt temperature measurement, the temperature coefficient of the prt is first evaluated from the prt calibration data. For example, using the data for prt serial number 2438708 shown in Table 1.

Over the range H_2O - Ga, Temperature Coefficient (TC)= $\Delta R / \Delta t$
$$= (28.1523713 - 25.1789421) / (29.7639 - 0.010)$$
$$= 2.9734292/29.7539$$
$$= 0.099934 \approx 0.1\ \Omega/°C.$$
$$TC^{-1} \approx 10\ °C/\Omega$$

The resultant temperature error induced by the change in the standard resistance due to the Self Heating Effect with a dissipation of 25 μ Watts is :
$$\approx 10^{-5} * (25 * 0.15 * 10^{-3})\ °C.$$
$$\approx 0.0375\ \mu°C.$$
$$\approx 37.5\ n°\ C.$$

The F17 bridge is capable of a maximum drive current of 7.07 mA ($5 * 2^{-2}$), and the Self

Heating error is then :

$$\approx 10^{-5} * ((7.07 * 10^{-3})^2 * 25) * (0.15 * 10^{-3})\ ^\circ C.$$

$$\approx 1.875\ \mu\ ^\circ C$$

With the standard resister the error introduced by the Self Heating Effect is therefore sufficiently small and can be ignored in the calibration of oceanic temperature sensors at the present time. However, the self heating errors due to the prt are of significance and the reader is referred to IOSDL internal document 295 (ref.7) for further information.

5.0. Environmental Temperature Changes.

The temperature coefficient, a, of the standard resistor, is the change in resistance with a temperature rise of 1 °C and is expressed as a fraction of the resistance value at 0°C.

$a = (Rt - R_o) / (R_o\, t)$ where a is the temperature coefficient.

R_t is the resistance at t ° C.

R_o is the resistance at 0 °C

t is the temperature in ° C.

Transposing gives $R_t = R_o(1 + a\, t)$ -------eqn.3

The specification for the resistors, type 5685A, quote a figure for a of 3ppm / °C which for the 25 Ω units gives a change of 75 μΩ / °C. For temperature measurement where the standard resistance, the F17 bridge, and the prt are inter linked, a more useful factor is to convert the resistance temperature coefficient of 75 μΩ/°C. into a temperature measurement error.

prt sensitivity = 0.1 Ω/°C.

= 10^5 μΩ / °C.

= 100 μΩ / m°C.

Std. Res. sensitivity = 75 μΩ / °C.

Thus if there is a 1 °C. change in the temperature of the standard resistance, the resultant 75 μΩ change in the value of the standard resistance will result in an apparent prt temperature error of :

= Std. Res. sensitivity/ prt sensitivity

= 75 / 100

Temperature error = 0.75 m°C.

With a prt sensitivity of 100μΩ/m°C the temperature coefficient of the standard resistor results in a temperature error of 0.75m°C/°C Thus for every degree C. that the standard resistance changes from its certificated value, the error in measured temperature is 0.75 m°C. When compared to the errors from stability and self heating effects, the error introduced by the resistance temperature coefficient is dominant and cannot be ignored when a calibration accuracy of 2m°C is required.

The foregoing results have assumed that the temperature coefficient as quoted in the specification is correct. They also assume that there is a linear relationship as shown in equation 3 between temperature and change in resistance. These assumptions have been tested because of the magnitude of the error possibly incurred.

5.1. Experiment to determine the Temperature Coefficient.

The equipment used to carry out the measurements were connected together as shown in Figure 2. The arrangement is similar to that used for normal temperature measurement, with the exception that the prt, which is normally connected to the Rt terminal of the F17 bridge, be replaced by the standard resistor whose temperature coefficient to be determined.

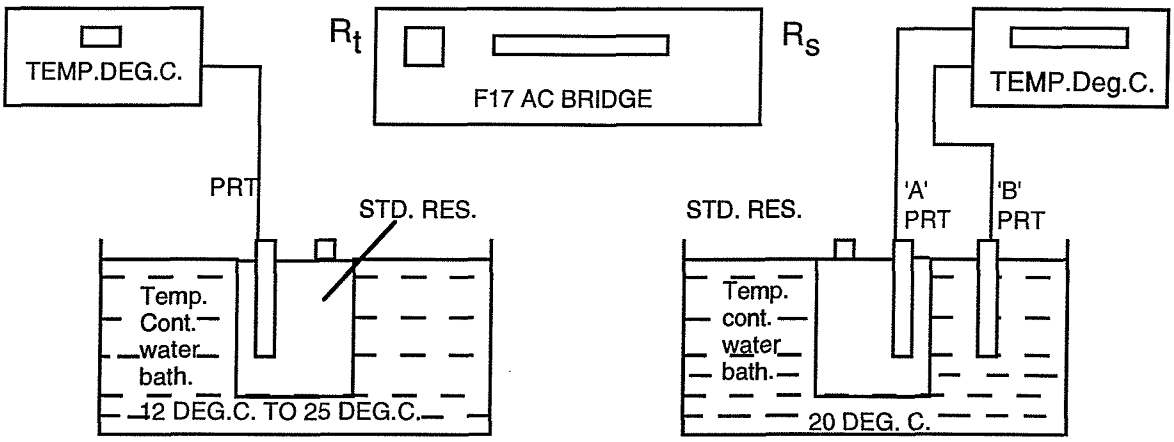

Fig.2.Equipment layout for temperature coefficient experiment

Two resistors were measured, serial numbers 239022 and 220371. In the first experiment resistor 239022 was connected to the Rt terminal of the bridge, and 220371 was connected to the Rs terminal. Both resistors were placed in polythene bags for protection from water ingress before being immersed in separate temperature controlled water baths. Internal and external temperatures of Rs resistor ('371) were monitored using a dual probe ASL F25 bridge. This instrument has a resolution of 0.001°C and calibrated accuracy of better than 0.01°C over the experimental range. The temperature of the water bath in which Rs was immersed was held at 20.000°C ± 5m°C, this being the temperature at which NPL measured the resistance.

The internal temperature of the Rt resistor ('022), immersed in the second temperature controlled tank, was measured using a Neil Brown self balancing temperature transfer standard bridge, model CT-2, calibrated to better than ±0.002°C accuracy with a 0.0001°C resolution.

The temperature of this tank, and hence Rt, was adjusted to give seven stable readings over the range 12.7°C to 25.0°C, and at each step, temperatures and bridge ratio readings were taken and tabulated as in Table 4. Sufficient time was allowed at each temperature for the tank and Rt to stabilise.

On concluding these latter measurements, the standard resistors were interchanged, Rt became '371 and'022 Rs and another set of measurements taken with the temperature of '371 varied over a similar range to that used in the previous set of measurements. The results for this experiment are shown in Table 5.

6.0. Results and Calculations.

Table 4. Standard Resistance 239022 experimental results.

Rt (239022) = 24.999905 Ohms @ 20°C. (NPL Cal. 1991)

Rs (220371) = 25.000685 Ohms @ 20°C. (NPL Cal. 1991)

Room Temp. °C.	Rs. Temp. °C.	Rt. Temp. °C.	Bridge Ratio	Rt. Resistance Ω.
20.0	20.002	25.0256	0.9999815	25.0002225
19.3	19.997	23.2961	0.999978	25.0001350
20.6	20.001	19.9911	0.9999695	24.9999225
20.0	19.996	17.4789	0.9999619	24.9997325
20.8	20.003	15.2139	0.9999534	24.9995225
20.0	20.001	12.7537	0.9999435	24.9992725

Table 5. Standard Resistance 220371 experimental results.

Rs. (239022) = 24.999905 Ohms @ 20°C. (NPL Cal. 1991)

Rt. (220371) = 25.000685 Ohms @ 20°C. (NPL Cal. 1991)

Room Temp. °C.	Rs. Temp. °C.	Rt. Temp. °C.	Bridge Ratio	Rt. Resistance Ω
21.7	20.006	25.0984	1.0000372	25.000835
21.6	20.002	23.4364	1.000036	25.000805
22.2	19.996	22.5503	1.000035	25.000780
19.8	19.998	20.1414	1.0000325	25.000718
19.7	20.000	15.2143	1.0000254	25.000540
20.1	20.001	12.7704	1.0000205	25.000419

Using the observed data, the value of Rt was calculated for each temperature and a polynomial equation derived for each resistor that best described the relationship between the temperature and the value of Rt. Second order equations were derived, eqn.4 and eqn.5, using the least squares method, and the values of the constants and the differences between the calculated and observed values at each temperature are shown in Table 6 and Table 7.

Standard Resistor 239022

$$R_t = C T^2 + BT + A \ \Omega \quad \text{------------} \quad \text{eqn. 4}$$

where R_t = Resistance in Ω

at temperature T°C.

A = 2.4997474 E1

B = 1.7343610E-4

C= -2.5417454E-6

Standard Resistor 220371

$$R_t = C T^2 + BT + A \ \Omega \text{ ------------ eqn.5}$$

where R_t = Resistance in Ω

at temperature T°C.

A = 2.4999537 E1

B = 8.7188066 E-5

C= -1.4153137 E-6

Using equations 4 and 5 to calculate the values of the respective resistors at 20 °C it was found that there was a discrepancy between these experimentally derived values and those measured at NPL. These differences, together with the equivalent errors in temperature measurement, shown in Table 8, can be classified as a systematic error and can be attributed to the component values of the bridge.

Table6: Standard Resistance '022 polynomial fit details.

$y(calc) = Cx^2 + Bx + A$ Where A = 2.4997474E1

B = 1.73436110E-4

C = -2.5417454E-6

Temp. (x) °C	Std. Res. RS'022 Ω	Calc. Res. (y) Ω	Diff. Std-Calc. μΩ
12.753 7	24.999 272 5	24.999 272 3	0.2
15.213 9	24.999 522 5	24.999 524 1	-1.6
17.478 9	24.999 732 5	24.999 728 8	3.7
19.991 1	24.999 922 5	24.999 925 2	-2.7
23.296 1	25.000 135 0	25.000 134 8	0.2
25.025 6	25.000 222 5	25.000 222 3	0.2

Table 7: Standard Resistance '371 Polynomial fit details.

$y(calc) = Cx^2 + Bx + A$ Where A = 2.4999537E1

B = 8.7188066E-6

C= -1.4153137E-6

Temp. (x) °C	Std. Res. RS"371 Ω	Calc. Res. (y) Ω	Diff. Std-Calc. μΩ
12.770 4	25.000 417 5	25.000 419 8	-2.3
15.214 3	25.000 540 0	25.000 536 1	3.9
20.141 4	25.000 718 0	25.000 719 1	-1.1
22.550 3	25.000 780 0	25.000 783 6	-3.6
23.436 4	25.000 805 0	25.000 803 2	1.8
25.094 4	25.000 835 0	25.000833 9	1.1

Table 8: Differences in experimental and NPL derived values for the Standard Resistance

Standard Resistor	Derived value Ω	NPL value Ω	Difference μΩ	Temp. error m°C
239022	24.999926	24.999905	21	0.21
220371	25.000715	25.000685	30	0.30

The value of the prt resistance is determined by substituting in eqn.1 the bridge ratio value and the Standard Resistance referred to the NPL value at 20°C. Therefore the 'A' coefficients in equations 4 and 5 are adjusted by applying the resistance difference values shown in Table 8. Hence the calculated value of resistance at 20°C are identical to the NPL values. Equations 6 and7 are the corrected polynomial equations and from these the working 'look up' Tables 9 and 10 are derived.

Standard Resistor 239022

From eqn.4

$R_t = (C\,T^2 + BT + A - \text{Difference})\ \Omega$

$R_t = (C\,T^2 + BT + A - 2.1E\text{-}6)$ Ω--------- eqn 6

where R_t = Resistance in Ω at temperature T°C.

A = 2.4997474 E1

B = 1.7343610E-4

C= -2.5417454E-6

Standard Resistor 220371

$R_t = (CT^2 + BT + A - \text{Difference})\ \Omega$

$R_t = (CT^2 + BT + A - 3.0E\text{-}6))$ Ω ------------ eqn.7

where R_t = Resistance in Ω at temperature T°C.

A = 2.4999537 E1

B = 8.7188066 E-5

C= -1.4153137 E-6

Table 9: Standard Resistance '022 corrected 'look up' tables.

$Y = Cx^2 + Bx + A - (2.1E\text{-}6)$ Where A = 2.4997474E1

B = 1.7343610E-4

C= -2.5417454E-6

Temp. (x) °C	Std. Res. RS'022 Ω
19.5	24.999 868
19.6	24.999 876
19.7	24.999 883
19.8	24.999 890
19.9	24.999 898
20.0	24.999 905
20.1	24.999 912
20.2	24.999 919
20.3	24.999 926
20.4	24.999 933
20.5	24.999 940

Table 9: Standard Resistance '022 corrected 'look up' tables.

$Y = Cx^2 + Bx + A - (2.1E\text{-}6)$ Where: A = 2.4999537E1

B = 8.7188066E-5

C= -1.4153137E-6

Temp. (x) °C	Std. Res. RS'022 Ω
19.5	25.000 669
19.6	25.000 672
19.7	25.000 675
19.8	25.000 679
19.9	25.000 682
20.0	25.000 685
20.1	25.000 688
20.2	25.000 691
20.3	25.000 694
20.4	25.000 697
20.5	25.000 700

Using statistical methods, it was determined from the data provided in Tables 6 & 7 that the random uncertainty in determining the value of the resistance, using the adjusted equations 6 & 7, was equivalent to ±0.02m°C for resistor '022 and ±0.03m°C for resistor '371. Further uncertainties are introduced in measuring the temperature of the standard resistor, the higher the accuracy of the temperature measurement, the less the error in determining the standard resistor value from the 'look up' table. In practice the resistor is at laboratory temperature which is normally within the range 20±1°C Inspection of the 'look up' table at this temperature indicates that for an ambient temperature change in 0.1°C, the temperature sensitivity of resistor '022 is approximately 7μΩ, equivalent to a temperature measurement of 0.07 m°C, and for resistor '371, the temperature sensitivity is 3μΩ, equivalent to a 0.03m°C.

Temperature against Resistance plots for Standard Resistors 239022 and 220371 are shown in Figure 3 and Figure 4 respectively.

7.0. Conclusions.

This investigation into the errors introduced into bridge thermometry measurements by the reference resistor has examined long term stability, self heating and temperature sensitivity characteristics.

The long term stability errors are variable and should decrease with time, but they can be in the region of 0.04 m°C/year (resistor 220371) which is of sufficient magnitude to justify regular measurement by a national standards laboratory at intervals of 2 years.

Self heating effect induced errors are small, equivalent to less than 2μ°C, and as such can be ignored for oceanographic temperature accuracy requirements.

The temperature coefficient experiments have shown that significant errors can be introduced if this factor is ignored or if manufactures data are not checked. Surprisingly, it was found that there was a 2:1 difference in the temperature coefficient values of nominally identical resistors. If uncorrected, for a 1°C change near the operating temperature of 20°C, this temperature sensitivity could induce errors equivalent of up to 0.0006°C. 'Look up' tables and temperature controlled environments for the standard resistors are two possible solutions that could reduce this error.

8.0. References

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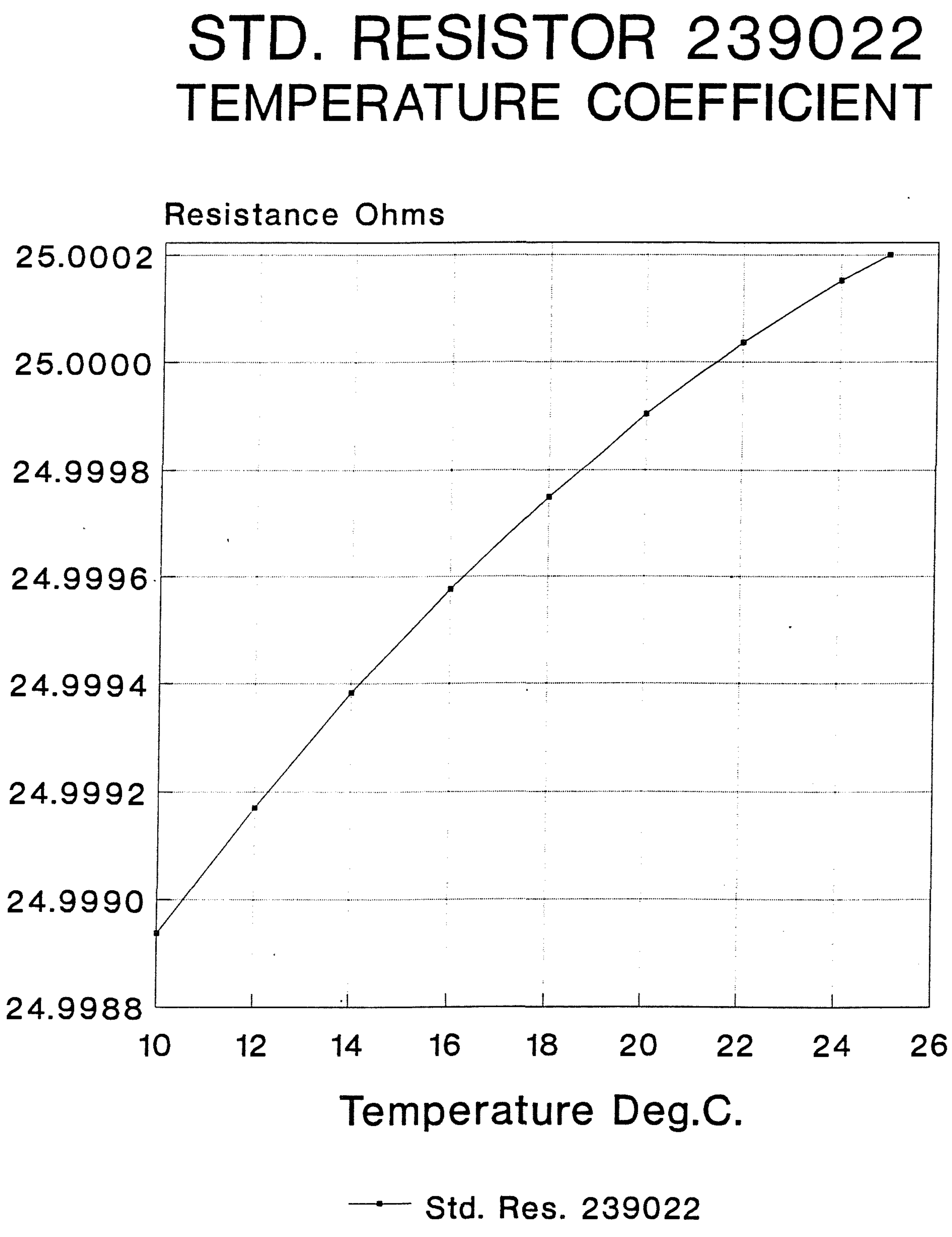

Fig. 3: Standard Resistor 239022 Temperature against Resistance Plot

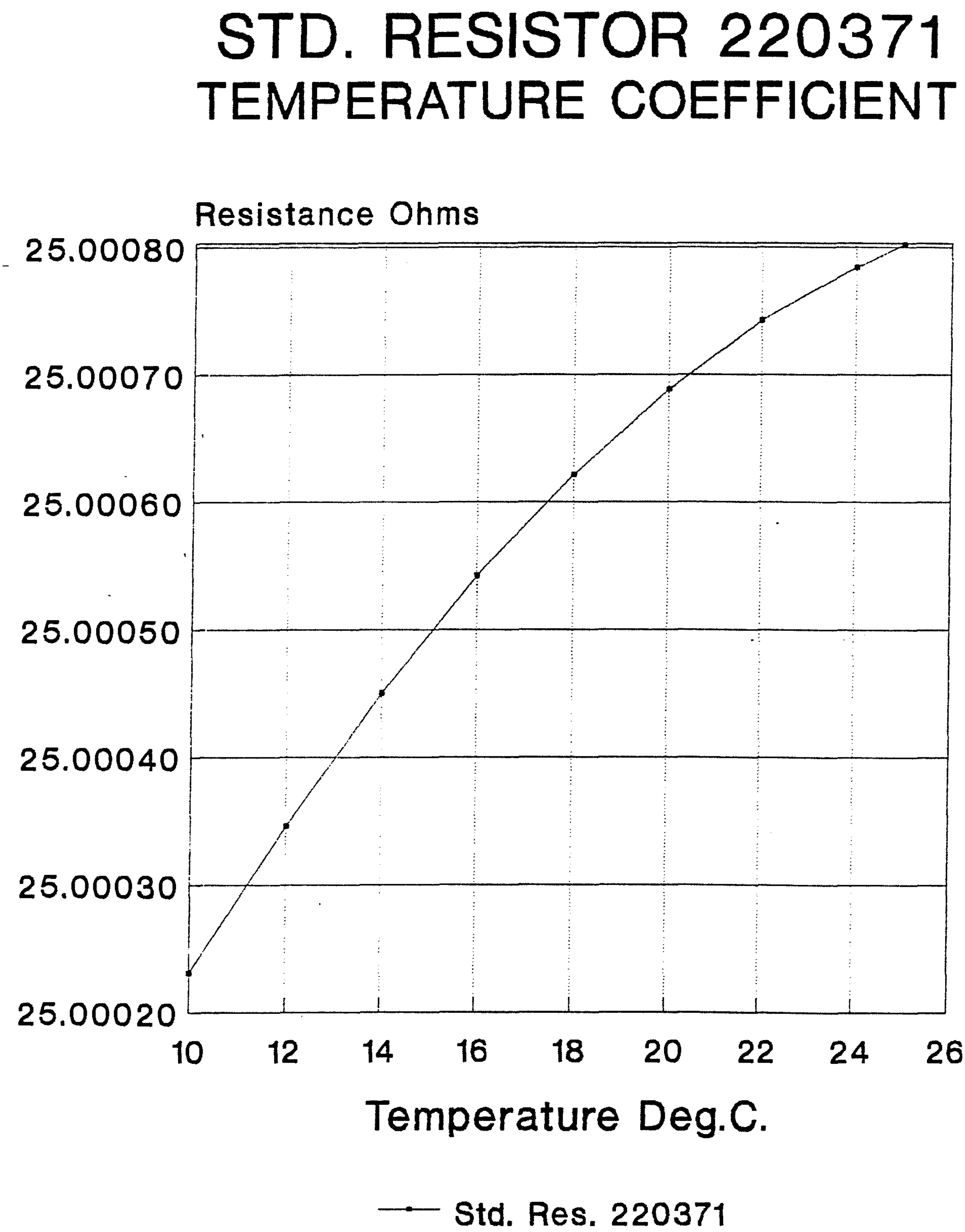

Fig.4: Standard Resistor 220371 Temperature against Resistance Plot