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CALIBRATION OF THE CLTS AND VERIFICATION OF THE STANDARD FOR THE PT100 TEMPERATURE SENSORS FOR THE B0 MODEL COIL

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ABSTRACT

In this paper the LASA calibration facility for the temperature sensors is described.

After an overview of the most widely used temperature sensors in cryogenic applications, the calibration curves of some CLTS and Pt100 installed on the B0 model coil are reported and discussed.

Then, by general considerations and from the specific results, the accuracy of every type of sensor is discussed.

Good reading electronics is needed for accurate temperature measurements, especially for the Cryogenic Linear Temperature Sensors (CLTS).

For CLTS the calibration is mandatory if used at low temperature.

It is recommended to verify the characteristics of the Pt100, in order to check the standard of the sensors, either USA or EU.

The calibration is necessary if good accuracy in the measurements is required and is anyway necessary if Pt100 are used at low temperature (below 60 K).

1. - INTRODUCTION

The Barrel Toroid Magnet (BT) [(1)] is part of the Magnet System of the ATLAS Detector for the large Hadron Collider (LHC). It provides the magnetic field required by the muon spectrometer. It consists of eight flat superconducting coil of 25 m length and 5 m width, radially assembled around the beam axis.

The field will extend over a length of about 26 meters with an inner bore of 9 meters and an outer diameter of about 20 meters. Because these coils are about 5 times larger than any other superconducting coil ever built, the CEA (Saclay), CERN and INFN (Milan) decided to build a working model, called B0, which will be similar to one BT coil, both for the design concept and the construction procedure with the same width and the same cross section (4.5 m x 0.30 m) but with a reduced length (9 m), in order to qualify the design, verify the manufacturing procedure and validate the technical solutions.

In Fig.1 the B0 coil in the test station at CERN is shown.

FIG. 1 – The Bo model coil in the test station at CERN.

Being B0 a test magnet, a certain amount of sensors has been installed, in order to have a complete understanding of the behaviour of every component of each part of the magnet. The full list of the sensors is reported elsewhere[(2)], here we can recall that the temperature sensors foreseen are of four types:

- The Carbon sensors
- The Cryogenic Linear Temperature Sensor (CLTS)
- The Pt100
- The thermocouple in differential configuration.

According to the cost sharing decided by the collaboration, CEA provided the calibrated carbon sensors, INFN provided the thermocouples and the calibrated CLTS and Pt100.

In the developing of the ATLAS project about one hundred of CLTS and Pt100 have been calibrated at LASA.

Previously other CLTS sensors have been calibrated and used al LASA to measure the thermal conductivity of the riveting system foreseen for the thermal screen of the B0 and Barrel Toroid for ATLAS.

Here, after a general review of the most used cryogenic temperature sensors, their accuracy, the sensitivity of the related electronics and the need of calibration is discussed, by using a typical curve for the CLTS and Pt100.

2. – GENERAL CONSIDERATIONS

Let's first recall some characteristics and a general overview of the temperature sensors.

We neglect the thermocouples, because this type of sensors is widely described (see for example[(3)]). We will recall only the differential configuration arrangements of a thermocouple and the expected values.

2.1. – The Carbon Temperature Sensor

Carbon temperature sensors, like the CLTS and the Pt100 are classified as Resistance Temperature Device (RTD), being the temperature determined by measuring the resistance of the sensing material. The difference respect to the other RTD thermometer is that carbon can be considered as a semiconductor, being $dR/dT < 0$. The high variation of the resistance with the temperature, their low price and the small dimensions make these sensors widely used for accurate low-temperature measurements (see section 3 for details about the accuracy of a RTD sensor).

In addition the RTDs provide absolute temperature measurements, since no reference junctions are involved, as for thermocouples.

The cost of a single carbon sensor is of the order of 1-2 €, conversely the calibration, due to the using of the cryogen and the manpower, rises the cost to about 150 € each.

In Fig. 2 a typical calibration curve for a carbon sensor is shown[3].

From these calibration points, with an appropriate interpolation relation, all the intermediate points can be derived. For the example of Fig 1 the interpolation relation is :

$$T = \frac{T_{0.552} + T_{1.049}}{2}$$

with

$$T_{1.049} = \frac{(\ln R)^{1.049}}{(B_0 + B_1 \ln(R) + B_2(\ln(R))^2 + B_3(\ln(R))^3 + B_4(\ln(R))^4)^{\frac{1}{1.049}}}$$

and

$$T_{0.552} = \frac{(\ln R)^{0.552}}{(A_0 + A_1 \ln(R) + A_2(\ln(R))^2 + A_3(\ln(R))^3 + A_4(\ln(R))^4)^{\frac{1}{0.552}}}$$

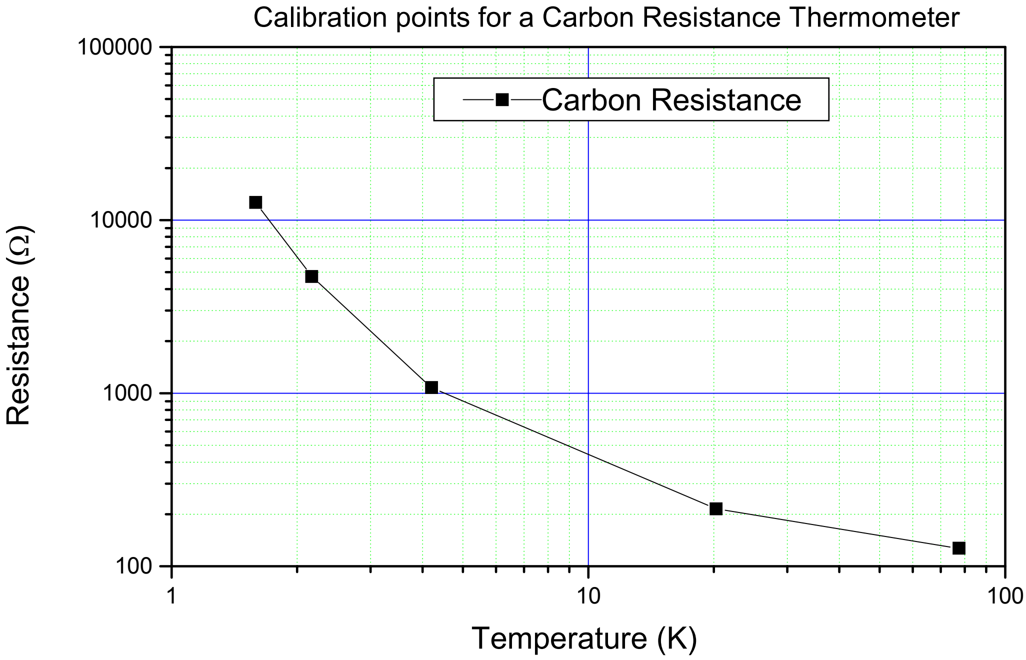


FIG. 2 – A typical calibration curve for a Carbon temperature sensor.

The coefficients are reported in Table 1.

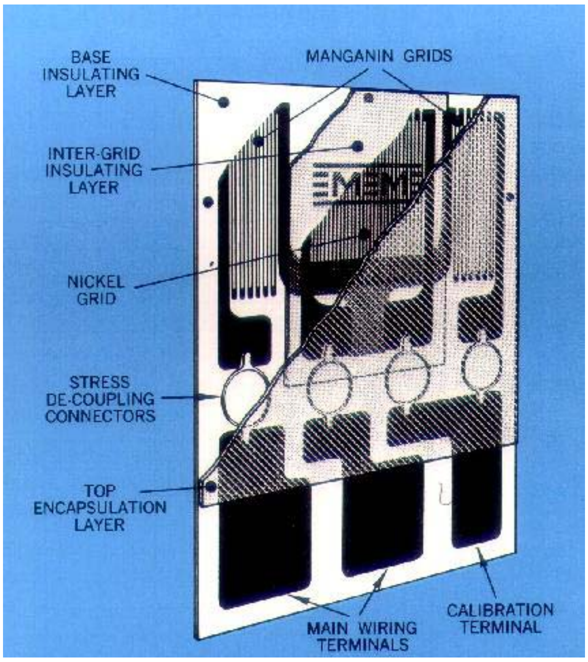
TABLE 1 – Interpolation coefficient for the upper relations

A_0	-1.11361616E+00
A_1	-1.24296317E-01
A_2	1.28962773E-01
A_3	-1.15804905E-02
A_4	4.03581472E-04
B_0	6.53886764E+00
B_1	-3.33626398E+00
B_2	5.27031119E-01
B_3	-2.91239620E-02
B_4	1.12665289E-03

2.2. - CLTS

This kind of RTD sensor can be used on the whole range of temperature foreseen in our application (4-300 K).

The sensor, shown in Fig. 3 and 4, is composed of two thin foil sensing grids laminated into a glass-fiber-reinforced epoxy-phenolic matrix, and electrically wired in series. The two alloys are special grades of nickel and manganin that are processed for equal and opposite nonlinearities in resistance, versus temperature characteristics, resulting in a linear response of



the sensor.

FIG. 3 – The CLTS temperature sensor

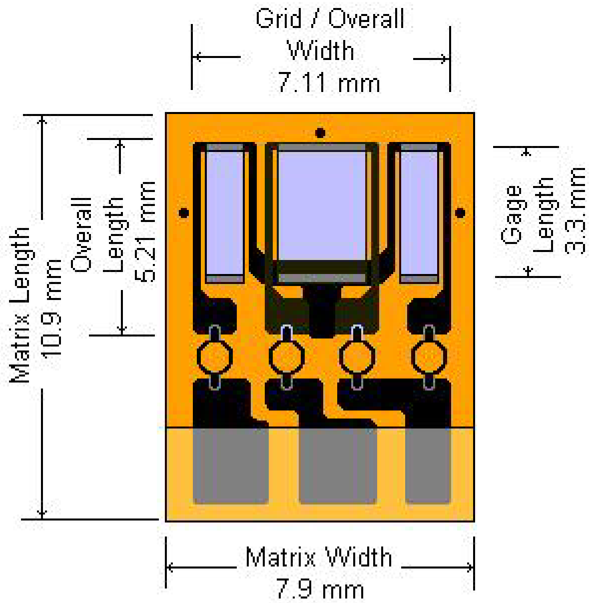


FIG. 4 – Dimensions of the CLTS.

The low thermal mass and thickness (0.1 mm) of the sensor guarantee a quick response to variation of the temperature.

CLTS together with integral printed circuit terminals is indicated as CLTS-2B.

The nominal resistance of the CLTS-2B is 290 ± 0.5 % Ω at 297.05 K (23.9 °C) and the resistance decrease linearly with the temperature, reaching the nominal value of 220 Ω at 4.15 K (-269 °C), resulting in a slope of 0.239 Ω/deg. Nonlinearity error can be introduced by the thermal expansion of the mounting surface and by strains induced during the gluing procedure.

The cost of this type of sensor is about120 €.

The CLTS sensor generally requires a calibration, as we will see in the following, in this case the cryogen and manpower costs should be taken into account. With appropriate reading instrumentation resolution of 0.01° can be achieved.

2.3. – Pt100

The Pt100 is a typical RTD sensor, consisting of a fine wire of Platinum, either wrapped around a mandrel and covered with protective coating, or with a flat shape like the CLTS. The latter has been used in the B0 model coil, because of the flat surfaces where the sensors have been placed. The Pt sensing matrix is embedded in a protective Kapton foil.

The mean slope of the resistance versus the temperature is usually referred as α and it describes the average resistance variation per unit of temperature from the ice point to the boiling point of water. The slope of the curve for one sensor depends on the purity of the Pt.

There are different standard slope used, as shown in Table 2.

TABLE 2 - Different Standard Slope for the Pt100 Temperature Sensors

Pt TC	0.003902 (U.S. Industrial Standard)
Pt TC	0.003920 (old U.S. Standard)
DIN 43760	0.00385

In 1983 the International Electromechanical Commission (IEC) adopted the Deutsche Institute for Normung (DIN) standard of Pt; they are 100 Ω at 0 °C with an α of 0.00385 Ω/ Ω/°C (based on the fact that the resistance at 100 °C is 138.50 Ω, and the resistance at 0 °C is 100 Ω, so the variation of the resistance per °C is 38.5/100 = 0.00385 Ω/ Ω/°C). So the standard variation of the resistance versus the temperature $R(T) = R_0(1+\alpha T)$. is

Let's remind that the α coefficient is only the average value between 0 °C and 100 °C, while locally the slope may be not constant.

Two classes of accuracy has been defined for the Pt temperature sensors:

- Class A devices, with accuracy within ± (0.15 ± 0.002 |T|)
- Class B devices, with accuracy within ± (0.3 ± 0.005 |T|)

both with T measured in °C.

Pt has a good linear dependence of the resistance versus the temperature, but more accurate interpolation is the following:

- $R_T = R_0(1 + AT + BT^2)$ for 0 < T < 850 °C
- $R_T = R_0(1 + AT + BT^2 + C(T\text{-}100)T^3)$ for -200 < T < 0 °C

with $A = 3.9083 \times 10^{-3}$ °C^{-1}

$B = - 5.775 \times 10^{-7}$ °C^{-2}

$C = - 4.183 \times 10^{-13}$ °C^{-4}

$R_0 = 100\ \Omega$

For the higher precision, needed for standard platinum resistance thermometer[4], conforming to the International Temperature Scale (ITS - 90)[5], polynomial interpolation of order up to 15 is necessary.

Another widely used curved, used to fit the resistance vs. temperature dependence of the RTD is the so-called Callendar - Van Dusen equation:

$$R_T = R_0 + R_0\alpha\left[T - \delta\left(\frac{T}{100}-1\right)\left(\frac{T}{100}-1\right) - \beta\left(\frac{T}{100}-1\right)\left(\frac{T}{100}\right)^3\right]$$

with R_0 = Resistance at 0 °C

α = temperature coefficient at T = 0 °C (typically 0.00392 Ω/ Ω°C)

δ = 1.49 (typical value for 0.00392 Pt)

$\beta = 0$ for $T > 0$ or $\beta = 0.11$ (typical value) for $T < 0$.

The exact values for α, β, and δ are determined by measuring the resistance at four different temperature and by solving the resultant equations.

This equation has been replaced in 1968 by a 20th order polynomium, to get a more accurate curve fit.

2.4. – Thermocouples in differential configuration

The thermocouple allows to determine the temperature respect to a reference junction[(4)].

In the B0 coil is important control the temperature difference between two adjacent panels of the thermal screen (the radiation shield of the cold mass at about 5 K respect to the vacuum vessel) in order to avoid mechanical stresses of the screen panels.

To this aim three points has been chosen where monitor the temperature gradient: four screen panels two by two and the thermalization of the tie rod (1), i.e. the junction between the tie rod and the thermal screen.

The differential configuration allow to determine with high precision the temperature difference, because the output voltage is directly related to this quantity and because the systematic errors of measuring two absolute temperatures are automatically avoided.

In Fig. 5 the scheme of the differential configuration of the thermocouples is shown.

The points 1 and 2 are the points between which the temperature difference is measured by reading the voltage between A and B.

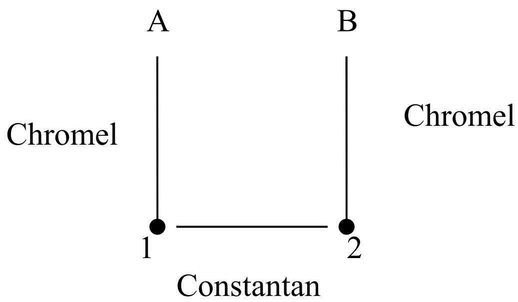


FIG. 5 – Differential Thermocouples configuration.
A,B terminal for voltage measurements; 1,2 temperature gradient measuring points

With the configuration of Fig. 5 if the temperature in 1 is higher than in 2 then V_B-B_A > 0.

For this type of sensor no calibration has been done, we report here only a plot of the used thermocouples (the "E" Chromel-Constantan type) where the output signal expected vs. the temperature gradient is shown for different temperatures (Fig. 6).

The plot has been done by using the standard properties of the thermoelectric materials.

Each curve refers to a temperature and it can be determined by the fact that at that temperature the gradient is obviously zero ad so zero is the voltage expected. For example the curve relative at T = 30 K is the first one from the top, and it passes through the zero at 30 K (x-axis).

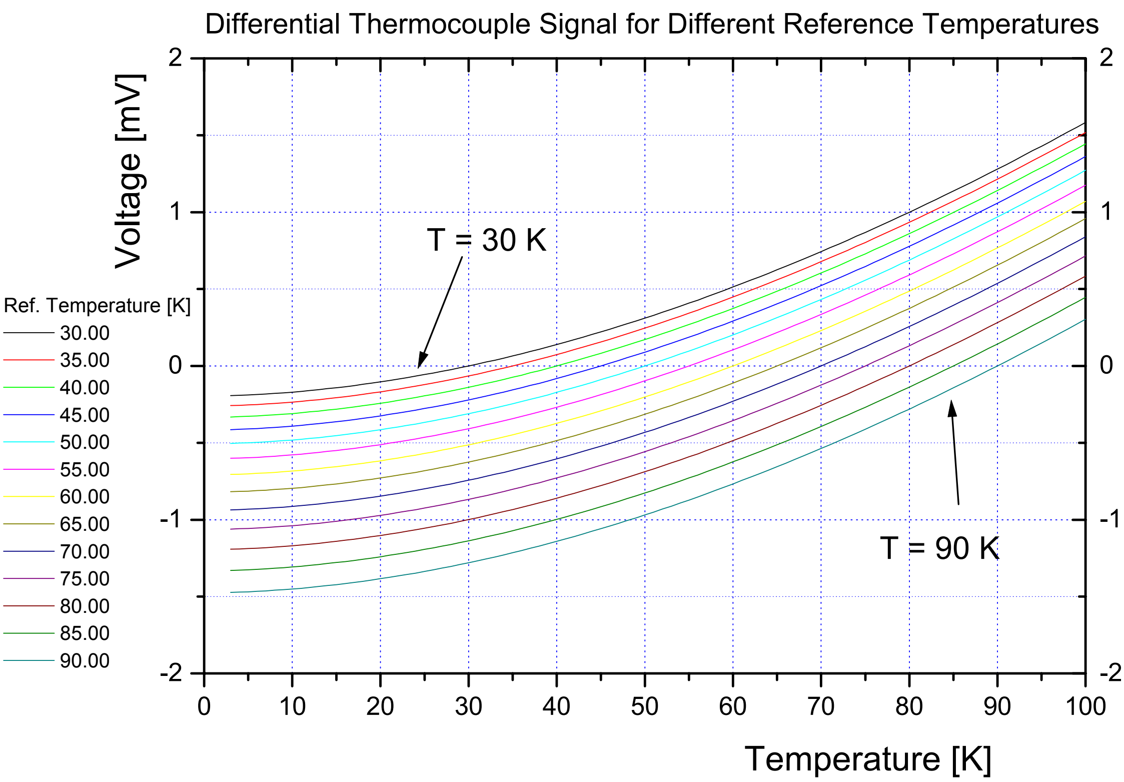


FIG. 6 – Voltage signal between point 1 and 2 of Fig. 5 for an "E" type thermocouple in differential configuration. See text for details.

3. – ACCURACY AND NEED OF CALIBRATION

3.1. – Accuracy

Let's consider a CLTS sensor. According to the standard, as told before, the resistance dependence respect to the temperature can be represented by the linear relation

$$R(T) = \alpha T + R_0 \tag{1}$$

with $\alpha = 0.239\,\Omega/\text{deg}$ and $R_0 = 219.008\,\Omega$.

The relative variation of the temperature respect to the relative variation of the resistance is

$$\frac{dT}{T} = \left(1 - \frac{R_0}{\alpha T + R_0}\right)^{-1} \frac{dR}{R} = \left(1 - \frac{R_0}{R}\right)^{-1} \frac{dR}{R} \tag{2}$$

so, by putting the numeric value, for T = 4.2 K we get dT/T = 219.02 dR/R.

$$\frac{dT}{T} = 219.02 \frac{dR}{R} \tag{3}$$

Supposing a relative variation of the resistance of 0.1 % the corresponding temperature variation is about 22 %, that is, at T = 4.2 K, about 0.9 K.

This indicates that good reading instrumentation is needed, in order to achieve accurate temperature measurements.

The dependence of the relative temperature error versus the relative resistance error is not so dramatic for the Pt100 and for the carbon.

3.2. – Calibration

In order to have a good accuracy in the measurements of the temperature it was decided to use the facility at the laboratory to make a verification of the characteristics and an accurate calibration of the of the temperature sensors that should be provided by LASA.

As a matter of fact, the embedding of the Pt100 in the protective kapton foil and the gluing on the surface whose temperature must be measured, slightly varies the characteristics.

So e calibration is necessary, if good accuracy is required.

4. – THE CALIBRATION FACILITY

The experimental setup used to calibrate the temperature sensors, consists, mainly of two parts, the cryostat and the data acquisition system

4.1. – Cryostat

The main component of the apparatus is the Magnex C2000/200 cryostat.

It is vacuum insulated, liquid nitrogen shielded and super insulated to reduce cryogenic losses. The cryostat is manufactured entirely in non-magnetic steel.

The cryostat main characteristics are shown in Table 3.

TABLE 3 – Interpolation coefficient for the upper relations

LN2 capacity (l)	LHe capacity (l)	LN2 evap. rate (ml/h)	LHe evap. rate (ml/h)	Neck Access (mm)
20	15	250	250	200

In Fig. 7 the closed cryostat, ready for the data acquisition is shown.

The vacuum is provided by a turbo-molecular pumping system. In steady state, when the cryostat is cold, the pressure is lower than 2*10-6 mbar. Cryogenics lines are used to supply LN and LHe.

In order to avoid any damaging of the sensors during the integration in the B0 coil most of the sensors to be calibrated are mounted on a pure Aluminium (25 x 25 x 2 mm3) with an M-Bond resin AE-15 (provided by M-M). The gluing on the Al plate eases the placing and replacing of the sensors in the cryostat. Once fixed the sensors on the surface, the same glue is used to coat and protect the sensors from mechanical and environmental damaging

FIG. 7 –The calibration cryostat

The sensors have then been placed into the B0 coil by screwing the plate on the measuring surface. In Fig. 8 a CLTS on the measuring Al plate is shown.

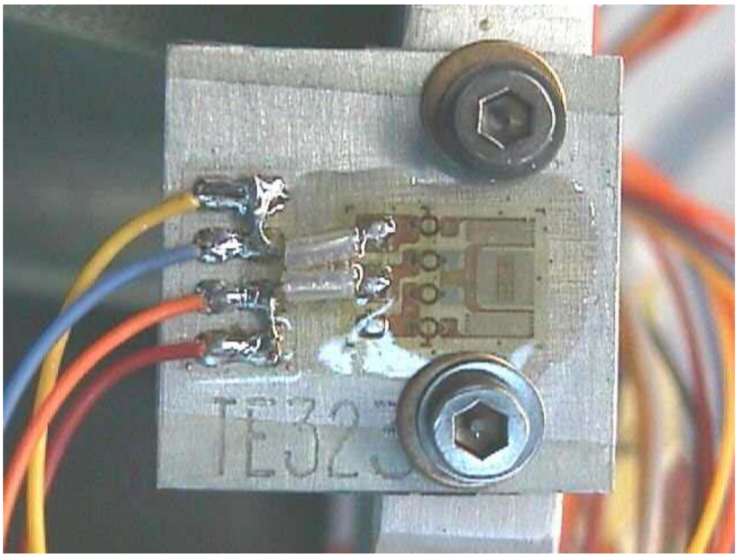


FIG. 8 – A CLTS mounted on the AL plate to avoid damaging during the definitive installation

A good contact pressure is obtained using stainless steel screws and CuBe conical washers. A comparison among contacts with vacuum grease, with CRY-CON grease and without any grease has been done. The results show that CRY-CON reduces the sensor self-heating in vacuum of about 0.4 K

In order to avoid radial temperature dishomogeinity the sensors are fixed on the external part of an Al plate. A fiberglass resin support holds the plate placed at the bottom of the cryostat. Up to 20 sensors can be set on the plate in the same time.

Not all the sensors to be installed in the B0 coils allow the use of the Al plate; as a matter of fact mechanical constraints require a simple gluing of the sensors directly onto the measuring surface.

This direct gluing is necessary on the most mechanically solicited parts, like the tie rods and the tie rod roots. As an example let's consider the most loaded tie rod; it withstand a force of about 170-180 tons, any hole in it or mechanical machining can reduce its mechanical characteristics and performances. Another place where is not allow any screwing is, as obvious, the cooling pipe. For this group of sensor the fixing on the calibration plate is obtained a small nylon plate with CRY-CON grease used to enhance the thermal contact (see Fig. 9).

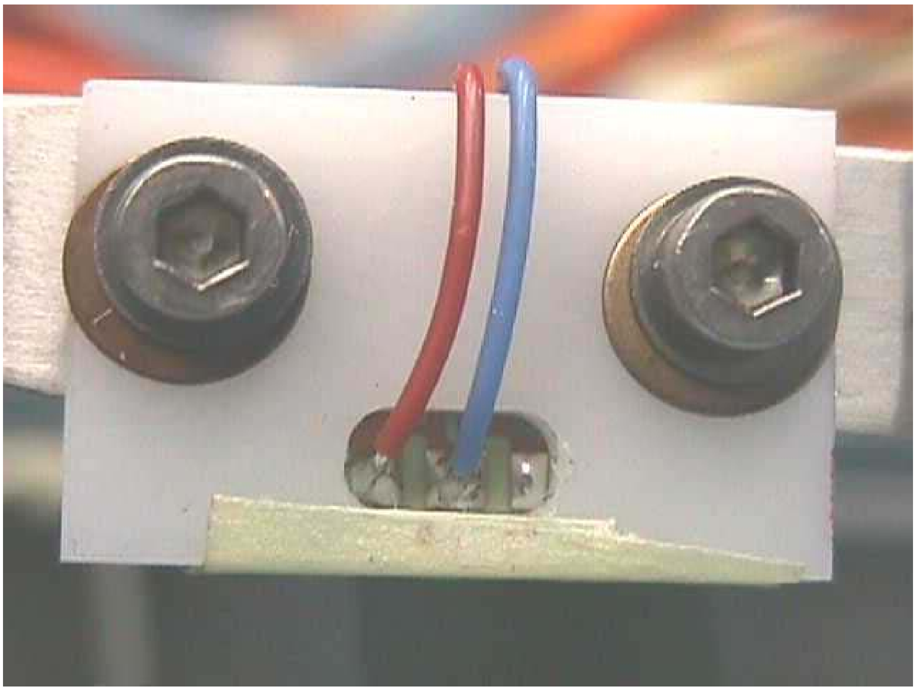


FIG. 9 – The dummy plate used to fix the temperature sensors that cannot be glued onto an Al plate.

In Fig. 10 the sample-holder with some sensors is shown.

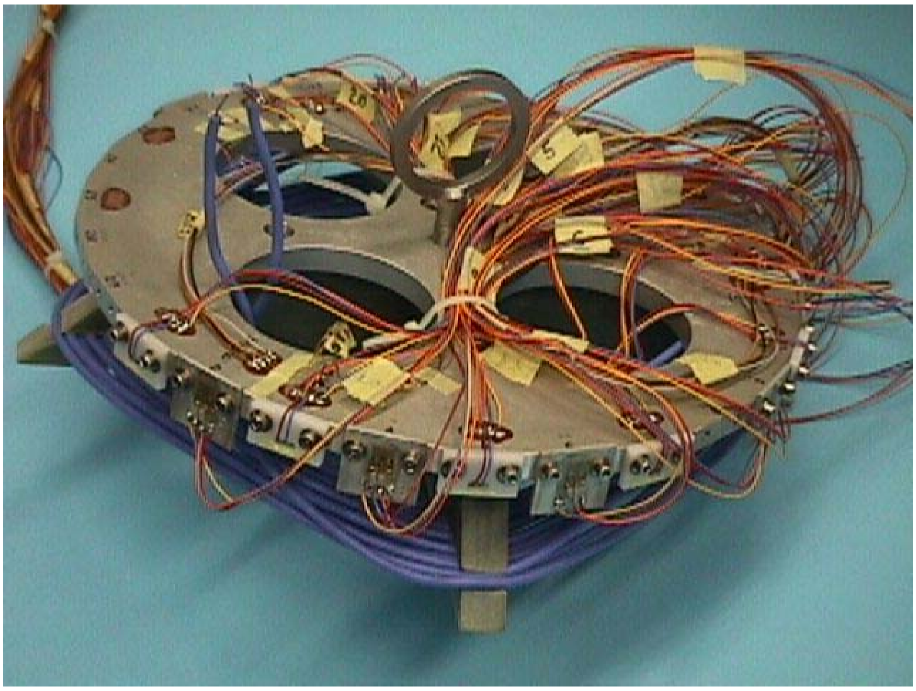


FIG. 10 - The sample-holder with some sensors installed, both with Al plate and with the nylon fixing plate.

4.2. – Measurement technique and data acquisition

The calibration of the sensors is done with a four-wire volt-amperometric method. The resistance values signal is red by a HP 34970A multiplexer (6 ½ digit resolution). The resistance – temperature relationship is determined by reading the temperature on the reference temperature sensors, one Pt 100 DIN 43760, from room to LN2 temperature, and two Lake Shore calibrated Carbon Glass Resistor (CGR) for lower temperature. 1 mA Current from the multiplexer powers the sensors to be calibrated; this value of current does not affect the sensors with self-heating. As a matter of fact the resistance measurements carried out by powering the sensors with 100 µA external power supply gave the same results.

The reference Pt100 has its own circuitry to convert the resistance into ° Celsius, a 100 µA high stability generator powers every CGR, and the voltage across the sensor is acquired.

A LabView 5.1 software drives the system; the measurement is real time displayed on a graphic screen and the data are stored in Excel format files.

Once placed the sensors on the sample holder and placed into the cryostat, the sensors thermalize at room temperature and the corresponding data are acquired. Then LN2 is sent into the cryostat in order to have the sample holder fully immersed in it.

For measurement at LHe temperature, the external thermal shield is filled with LN2, then LHe is sent into the cryostat until the full immersion of the sensors.

In this way three "steady state" calibration point are acquired (Room, LN2 LHe temperature). In addition temperature intermediate among the three steady state point are determined in a dynamic mode. This is done by removing the cryostat closing flange allowing the cryogen to naturally evaporate. The data are acquired during the evaporation.

Because of the long warming up time, respect to the measurement time, these measurements can be considered at steady state as well. The error on the measurements is given by the instrumentation error (about 0.6%) and the repeatability is in the same range.

5. – RESULTS

Not all the calibration curves are reported here, but the main characteristics of some of them are shown and discussed.

5.1. – CLTS

Totally 36 CLTS have been calibrated, 12 of which were mounted on the Al plate, the remaining 24 were not glued and fixed with the nylon dummy plate.

In Fig. 11 the calibration curve for the CLTS named TE323 is shown. This sensor is mounted on the Al plate (see Fig . 8)

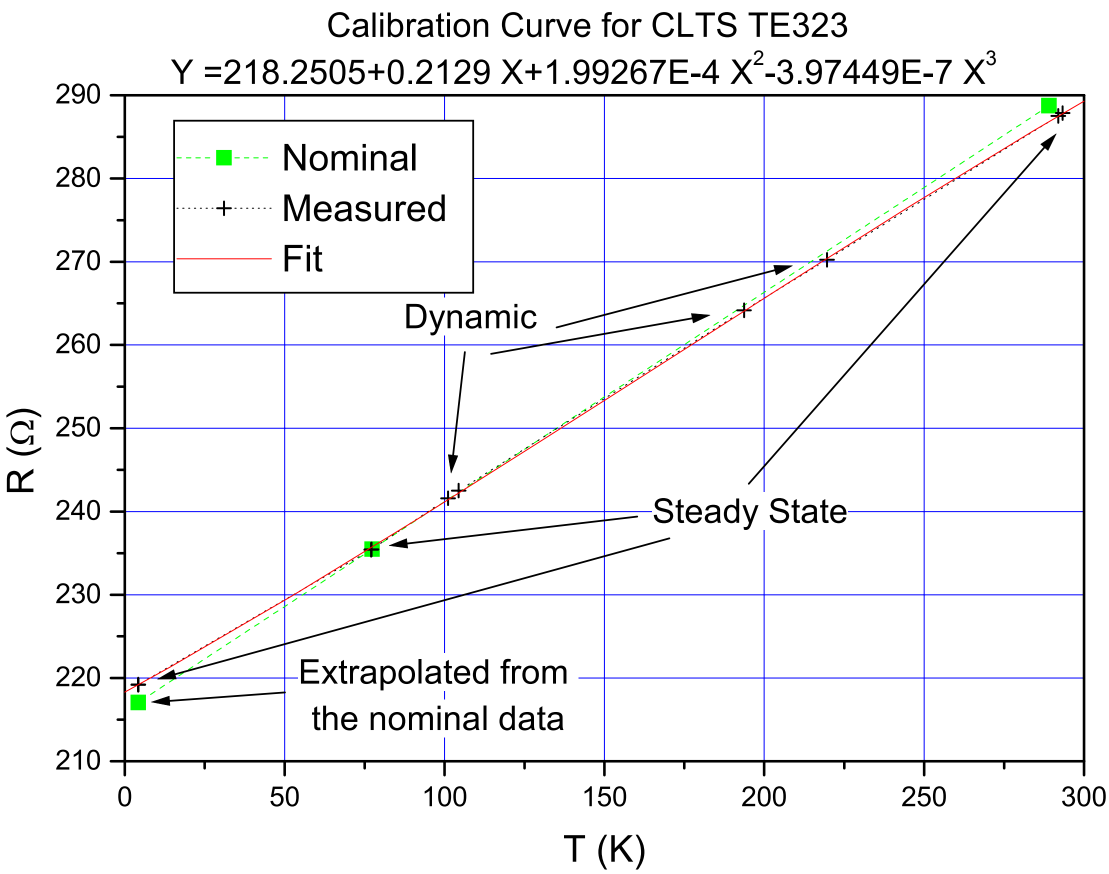


FIG. 11- The calibration curve for the Al plate mounted CLTS TE323.
Square symbols and dashed line - Factory data
Cross symbols and dotted line - calibrated values
Continuous line - polynomial fit of the measured data.

In Fig. 11 three data group or curve are reported, the nominal curve, i.e. the nominal data (square symbols, dashed line), the measured values as from the LASA calibration (cross symbols, dotted line), and the fitting of the measurements (continuous line).

The data given by the providing factory were only at LN2 and at room temperature. We report on the same curve the linearly extrapolated value at 4.2 K.

In Fig. 12 the same curve for the sensor TE524, not mounted onto the Al plate, is shown.

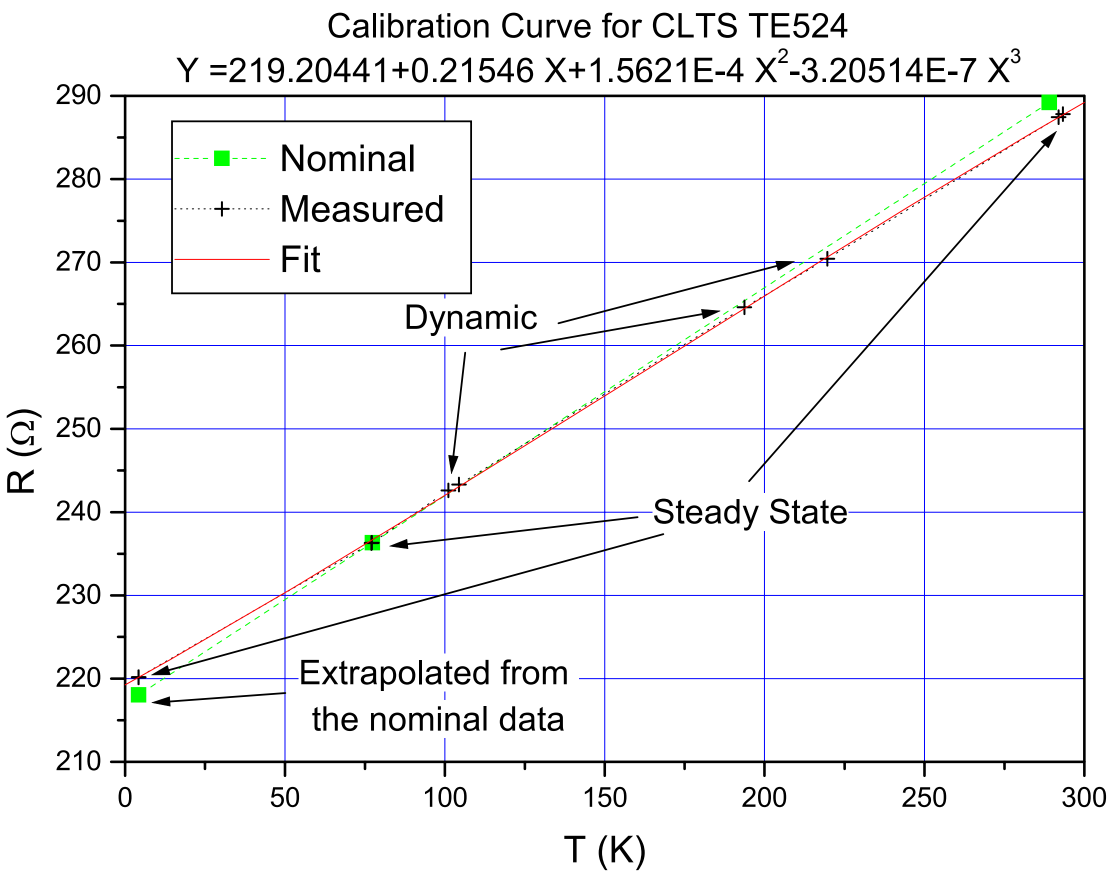


FIG. 12 - The calibration curve for the Al plate mounted CLTS TE524.The symbols and line types are the same as in Fig 11.

If we neglect the quadratic and cubic terms, the reported sensors have the one having the minimum and the maximum coefficient of the resistance vs. temperature relationship respectively (i.e. α_{323} = 0.21290 Ω/deg. α_{524} = 0.21546 Ω/deg. and R_{0323} = 218.2505 Ω and R_{0524} = 219.2044 Ω) .

5.2. – Pt100

The nominal characteristic of the Pt100, as given by the supplier should be α = 0.00392 Ω/ Ω/°C, but the embedding in the Kapton protective foil can modify the characteristics, so a verification of the characteristics, has been carried out only at LN2 temperature.

50 Pt 100 has been calibrated, of which 26 were mounted on the Al plate and the remaining 24 has been calibrated with the dummy nylon plate.

As for the CLTS the measured data are fitted with a third degree polynomium. In Fig.13 and 12 the data of the Pt100 sensors TE041 and TE744 are shown. The chosen Pt100 are that with the maximum and minimum value of α and of R_0, but it must be reminded that in this case the higher order terms are not negligible.

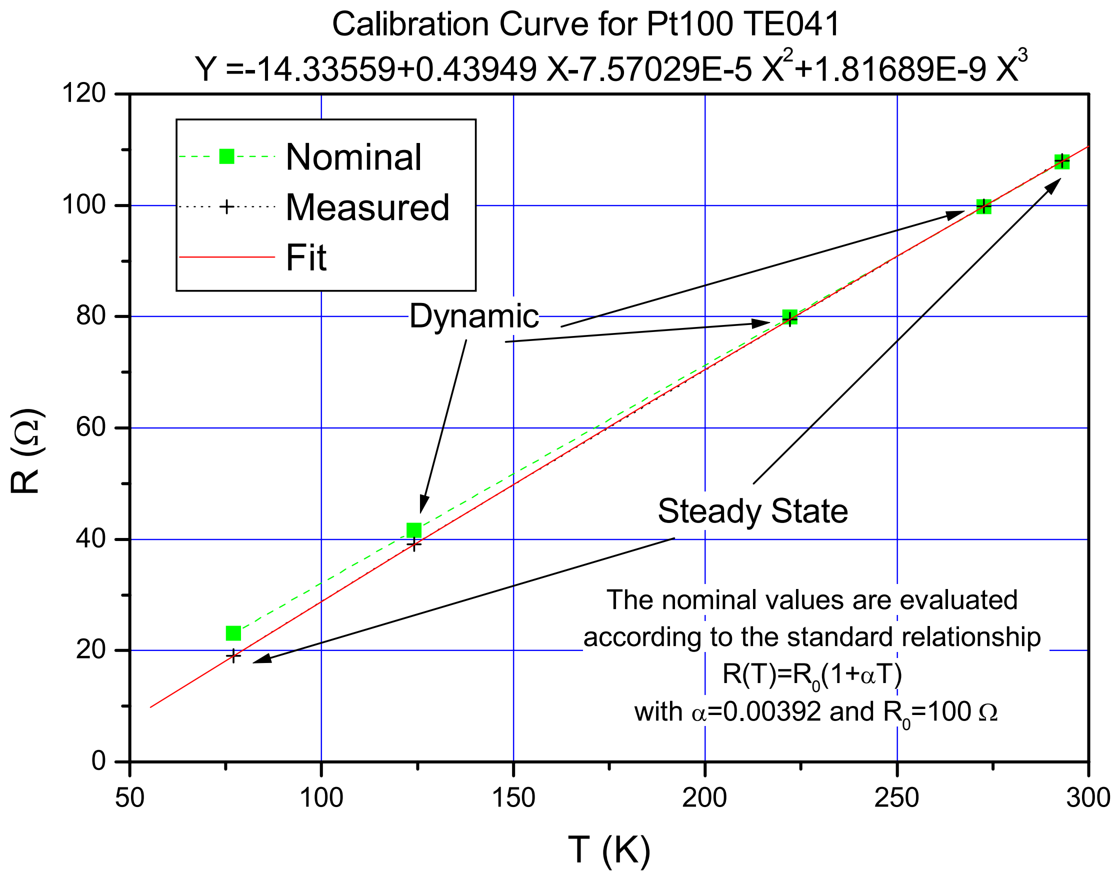


FIG. 13 - The calibration curve for the TE041 Pt100.
Square symbols and dashed line - Factory data
Cross symbols and dotted line - calibrated values
Continuous line - polynomial fit of the measured data

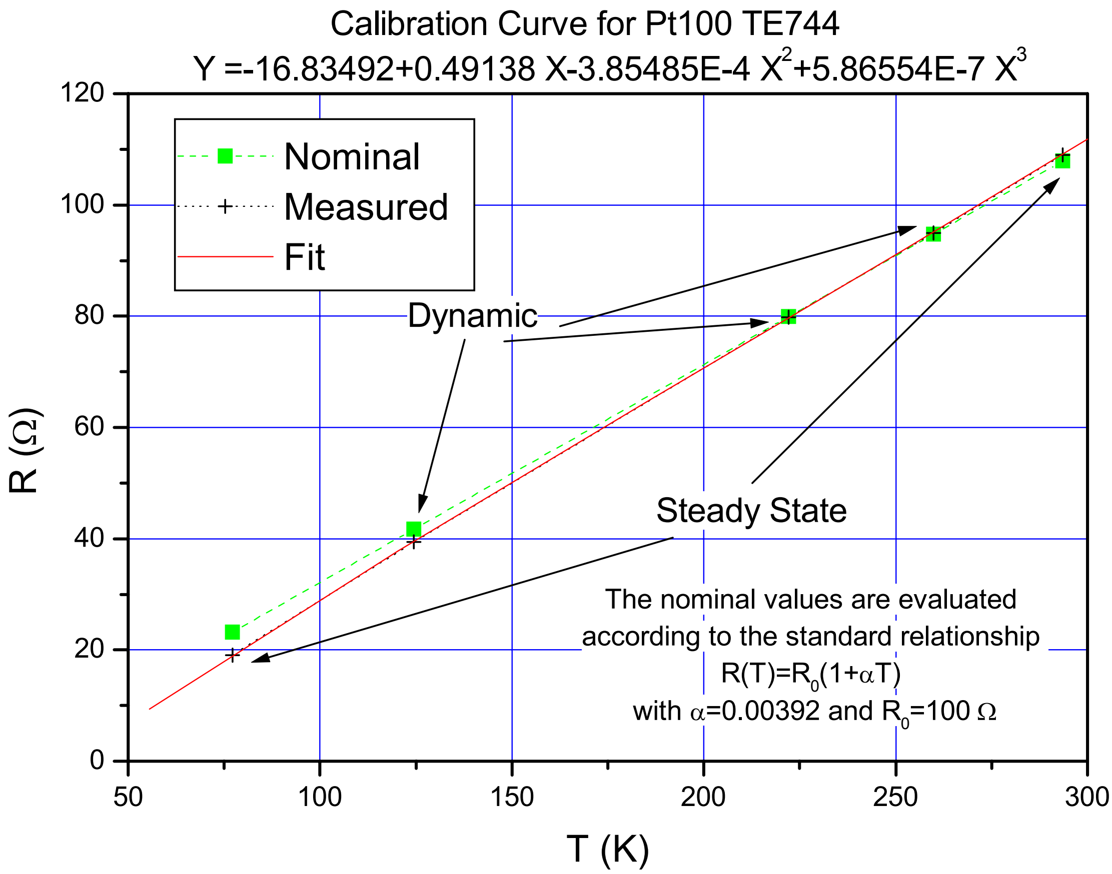


FIG. 14 - The calibration curve for the TE744 Pt100. The symbols and line types are the same as in Fig 13.

5. – ANALYSIS

By looking at the calibration curve of the CLTS it is clear that a calibration is always needed, if these sensors must be used at low and around room temperature.

As a matter of fact the 4.2 K extrapolated resistance is about 0.95 % lower than the real value. It means that, according to (3) a variation of some kelvin must be expected. An accurate calculation for the CLTS TE323 gives the following :

$$\frac{dT}{T} = 243.19\frac{dR}{R} = 2.3$$

Being T = 4.2 K a ΔT = 9.6 K follows, so the reading without calibration indicates a temperature of about 13 K instead of 4.2 K, as illustrated in Fig. 15.

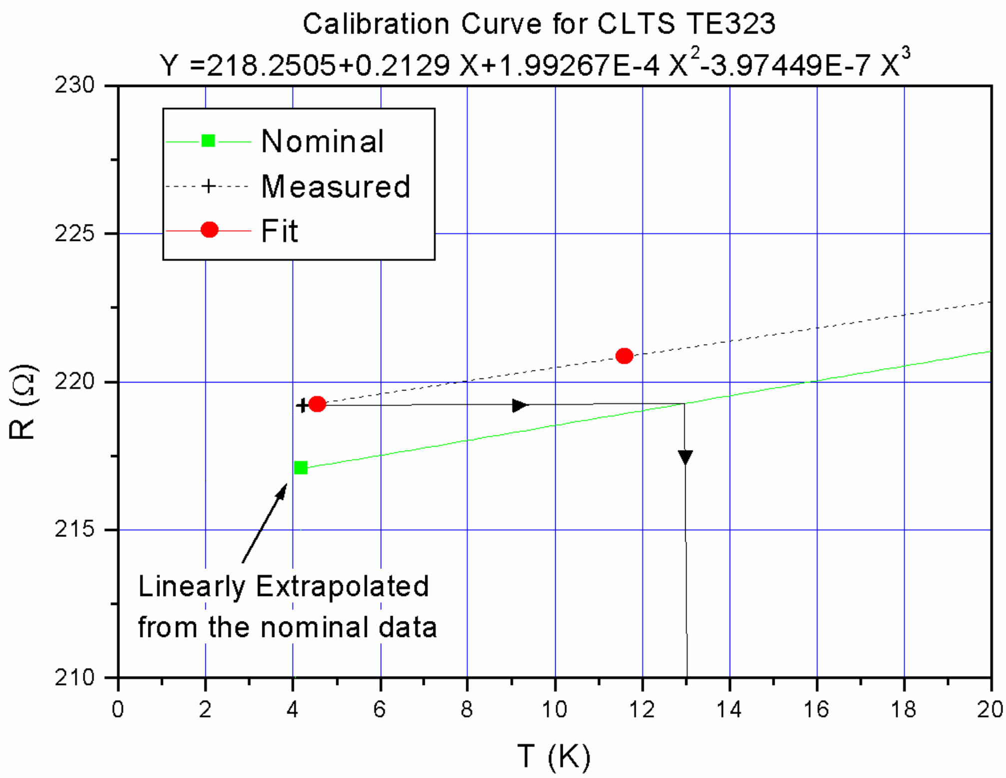


FIG. 15 - The error due to a non calibrated CLTS sensor.

The same problem arises when the indetermination of the resistance is due to an error of measurement. In Fig. 16 and 17 the relative and absolute temperature error for the CLTS 323 are plotted as a function of the temperature due to an error of 0.1 % error in the resistance measurement.

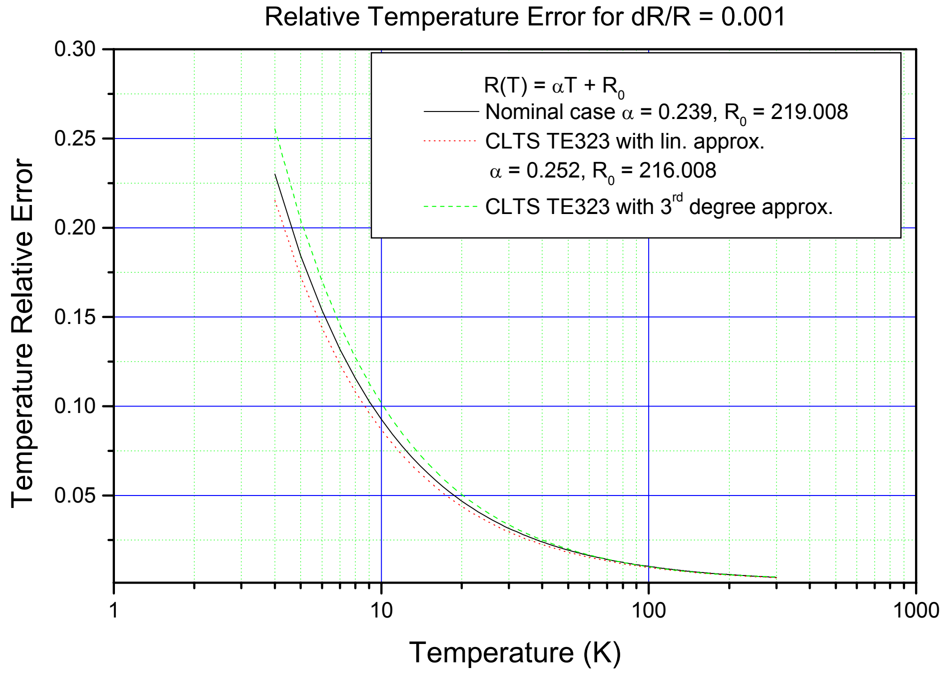


FIG. 16 – The relative temperature error induced by a resistance error of 0.1 % in a CLTS for the nominal values of the characteristics of the sensor and for the linear and the cubic interpolation of the data for the TE323.

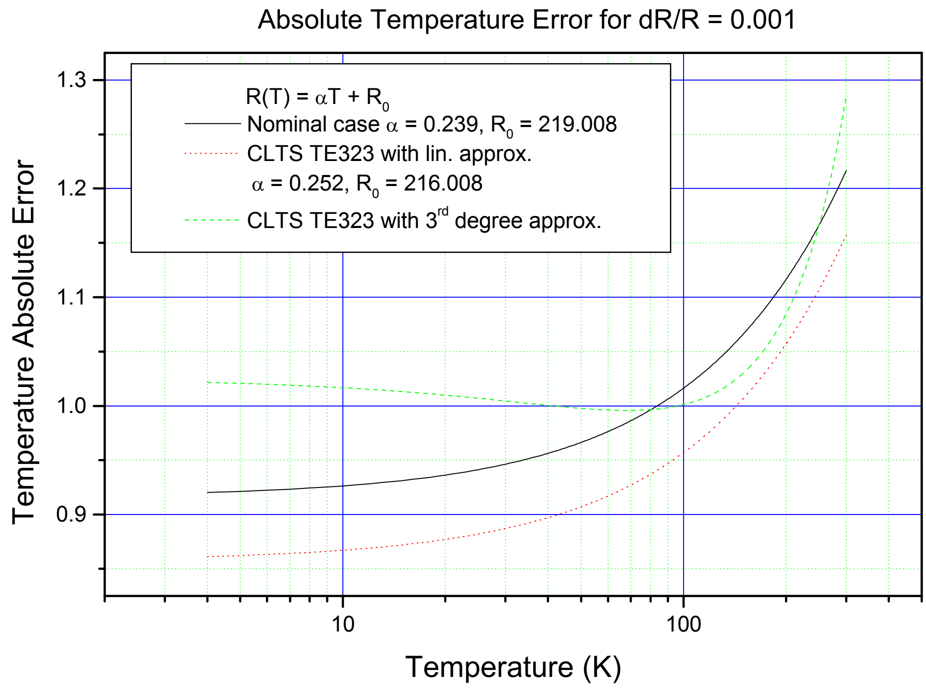


FIG. 17 – The absolute temperature induced by a resistance error of 0.1 % in a CLTS for the nominal values of the characteristics of the sensor and for the linear and the cubic interpolation of the data for the TE323.

This fact shows the need of an accurate calibration and of a good resistance measuring system, as told in section 3.

6. – CONCLUSIONS

The calibration facility at the LASA laboratory has shown a good performance and it is a precious tool for cryogenic temperature measurements, especially if CLTS are going to be used.

As discussed in section 3 and 5 we think that a calibration of the CLTS is always needed, because of the errors that an indetermination in the resistance induce in the temperature.

The Pt100, as standard product should not need a calibration, but a verification of the standard (U.S. or European) is recommended, even if the error induced are less significative than for the CLTS, in addition the Pt100 are used at relatively high temperature (higher than 60 K) and generally in cryogenic applications in this range of temperature a high precision is not needed, as at lower temperature.

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