Defence Science Journal, Vol. 57, No. 3, May 2007, pp. 195-208

REVIEW PAPER

Cryogenic Temperature Sensors

S. Kar and R.G. Sharma
Inter University Accelerator Centre, New Delhi-110 067

ABSTRACT

This paper describes the different cryogenic temperature sensors used at cryogenic temperatures down to 1 K. The characteristics of these temperature sensors have been discussed in detail with their operating range, sensitivity, and accuracy. Other properties like interchangeability, effect of thermal cycling, effect of ionizing radiation (neutron or gamma ray), effect of magnetic field has also been described. It is extremely important to choose the right temperature sensor for right kind of application in a specific operating environment. This paper gives an overview of some of the most widely used cryogenic temperature sensors.

Keywords: Cryogenic temperature sensors, gas and vapour thermometer, resistive temperature sensor, semiconducting temperature sensor, thermocouple

1. INTRODUCTION

Cryogenics refers to the field of production of low temperatures and the studies at low temperatures. Why do we need very low temperatures for studies? The behaviour of most materials at very low temperatures is quite different compared to that at ordinary temperatures. The lower this temperature more subtle is the nature of this behaviour. At extreme low temperatures, it could be spectacular. Superconductivity and superfluidity (in liquid ^3He and ^4He) are perhaps the two most fascinating phenomena in condensed matter physics where one observes quantum behaviour of matter on a macroscopic scale. In fact, whenever the temperature obtainable was reduced by a significant step, some discovery or the other of very fundamental importance took place. Some of these led to high technology development and benefited the common man directly.

At ordinary temperatures, most of these spectacular properties or the so-called quantum properties are masked by the lattice oscillations. As one goes down to lower and lower temperatures, these oscillations or rather the phonon vibrations die down and one can study these properties and look into the finer details of the matter. How does one make studies at low temperatures? The best method is to have a suitable refrigerant bath, which is best provided by a liquefied gas covering the temperature range of interest. For example, liquid nitrogen provides a bath temperature of 77 K to 65 K; liquid hydrogen provides a bath temperature of 20 K to 14 K. The lowest bath temperature is provided by liquid ^4He which boils (at atmospheric pressure) at 4.2 K and one can go down to 0.8 K by pumping over the bath. It is thus a standard practice to go to 1 K using liquid ^4He and raise the temperature up to 300 K (room temperature) using a temperature controller. There are several techniques employed to go to still low temperatures in the range of mK, μK, nK and the world record is 250 pK, held by the Helsinki University of Technology,

Revised 19 November 2006

Finland. Interestingly, Research at low temperatures in India, down to 1 K, interestingly started at National Physical Laboratory (NPL) as early as 1952. Since than, it spreaded far and wide in the country and today there are more than 15 centres carrying on high-level research and developing sophisticated technologies (such as superconducting Tokamak, Cyclotron and LINAC[1], all using liquid helium). Indian Space Research Organisation is using large quantities of liquid hydrogen and liquid oxygen as liquid propellants for their PSLV and GSLV launch rockets. Yet another organisation in India having embarked on using cryogens and cryocoolers is Defence Research & Development Organisation (DRDO). The number of devices like IR detectors need low temperatures for operation. Their requirement is however limited to liquid nitrogen temperatures. Miniature cryocoolers have been developed by Solidstate Physics Laboratory (SSPL), Delhi.

Apart from the production of low temperature, equally important is to have suitable sensors to monitor these temperatures fairly accurately. The temperature read by the sensor has to have its traceability to the international standard on a Kelvin scale. In principle, any physical property that shows a linear or nearly-linear variation with temperature can be used as a sensor in that particular temperature range. These properties could be resistivity of metals, alloys, and semiconducting materials, magnetic susceptibility, thermoelectric power, NMR, electrical noise, vapour pressure of liquid gases, dielectric constant and many other properties. The sensor to be used must be robust against all types of shocks (mechanical or thermal) and reproducible.

Temperature is usually measured in terms of physical properties such as pressure of a gas, equilibrium vapour pressure of a liquid, electrical resistance, magnetic susceptibility, and junction voltage of a diode. Many sources are available with more specific information[2-4].

2. TEMPERATURE SENSOR SELECTION

The importance of choosing a proper temperature sensor for the specific situation is great. The sensor has to be chosen based upon desired resolution, precision, and reproducibility. Further, the sensor should withstand the effect of thermal cycling. The selection of a sensor for a specific application also requires prioritizing the most important factors necessary for the application and compromising to the less important factors. Any one or the several factors such as operating temperature range, type of excitation, sensitivity, interchangeability, package size, thermal and electrical response times, power dissipation, and environmental compatibility (magnetic, ionizing radiation or radio frequency).

Temperature sensors can be classified into the following major categories:

(a) Fluid thermometry (gas and vapour pressure thermometers)

(b) Metallic resistance thermometry (platinum RTD and *Rh-Fe* RTD)

(c) Semiconducting resistance thermometry (carbon glass, germanium, and cernox)

(d) Semiconductor diodes (silicone diodes)

(e) Thermocouples

2.1 Fluid Thermometry

2.1.1 Gas Thermometers

Equation of state for a gas is a specific function of pressure (P), volume (V) and temperature(T). If one of the variables is held constant and the second variable is measured, the third one can be calculated from the equation of state. Therefore, if volume of gas is kept constant, temperature can be determined as a function of pressure. The simple constant volume gas thermometers is the one used by Simon (1952). It consists of a bulb connected by a fine capillary to a Bourdon-type pressure gauge maintained at room temperature. The P-T behaviour is made as linear as possible by minimising the extraneous volumes in the gauge and the connecting capillary tube. This simple gas thermometer is very accurate at low temperatures. It needs some correction at higher temperatures. Corrections for the extraneous volumes decrease with decreasing bulb temperature in as much as the proportion of gas in the bulb increases.

If, however, the sensing bulb is made small compared to the external volume of the system at ambient temperature, the characteristic is far from linear, the sensitivity increasing as the bulb temperature decreases. A Bourdon-type gas thermometer is used for monitoring the cool-down of the cryogenic systems.

2.1.2 Vapour Pressure Thermometers

The pressure exerted by saturated vapours in equilibrium with its liquid is a very definite function of temeperature and as such, can be used to measure the temperature of a liquid. One of the biggest advantages of vapour pressure thermometer is its sensitivity in its useable temperature range. The fluids commonly used for vapour pressure thermometers (VPT) at low temeperatures are oxygen, nitrogen, hydrogen, and helium. The vapour pressure curves for all these gases are shown[5] in the Figs (1) to (3). These thermometers are accurate and can be used in the range of the critical point and the triple point of the fluid. Hence, several regions are inaccessible to VPT. For example, the range from 40 K to 50 K, is above the range of neon and below that of oxygen and nitrogen (shown in Figs (3) and (4). There are some typical characteristics of VPT like for a given fluid the sensitivity, dP/dT increases rapidly with the decrease in temperature and lower the boiling point of fluid,the greater is this sensitivity. In addition, the response time of these thermometers is good and these are not effected by any ionizing radiation or magnetic field. Within its limits, however, these thermometers are very accurate and sometimes these are used as secondary standard thermometers.

2.2 Metallic Resistance Thermometry

The principle of metallic resistance temperature sensor are based on the tempearture-dependency of the resistivity of metals. In general, the metallic thermometers have positive temepearture coefficient (PTC). According to the Mattheissen's rule, the total resitivity of a pure metal is given by

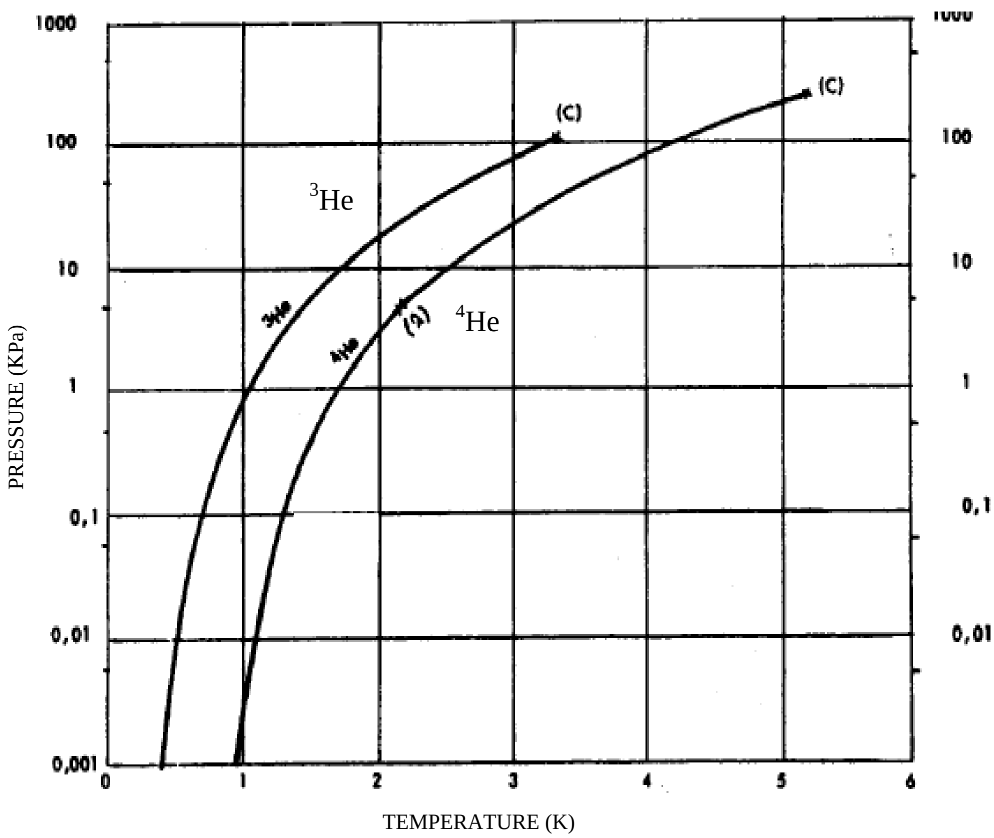


Figure 1. Vapour pressure curves for helium.

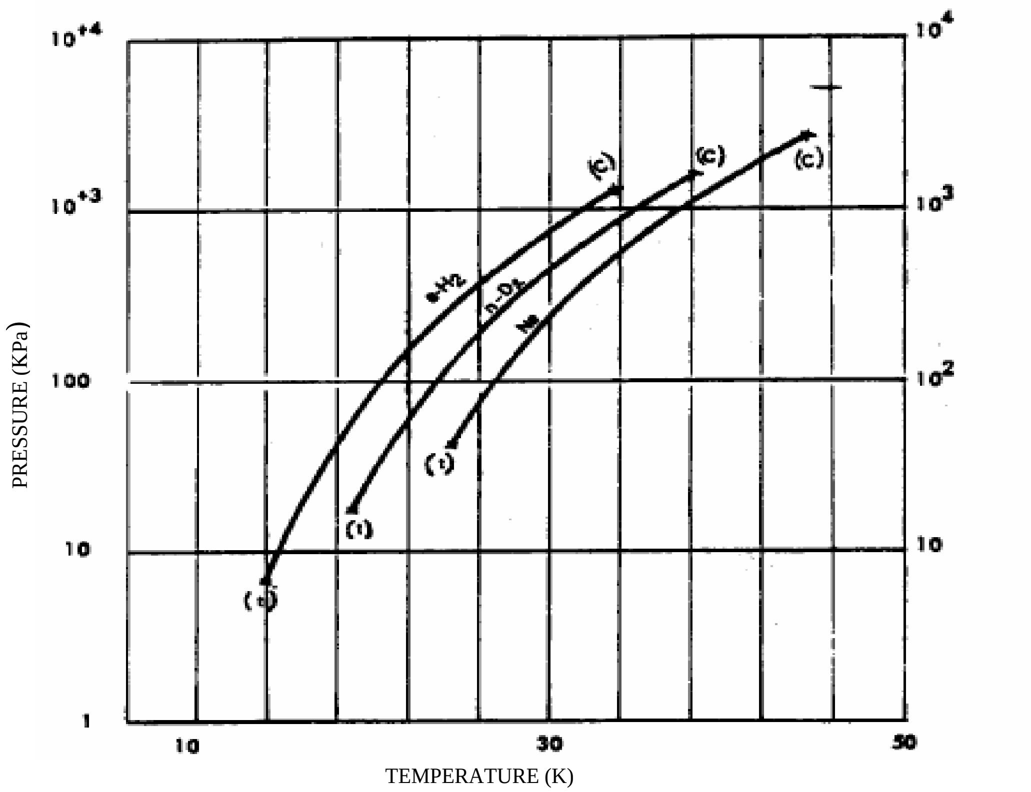


Figure 2. Vapour pressure curves for hydrogen and neon.

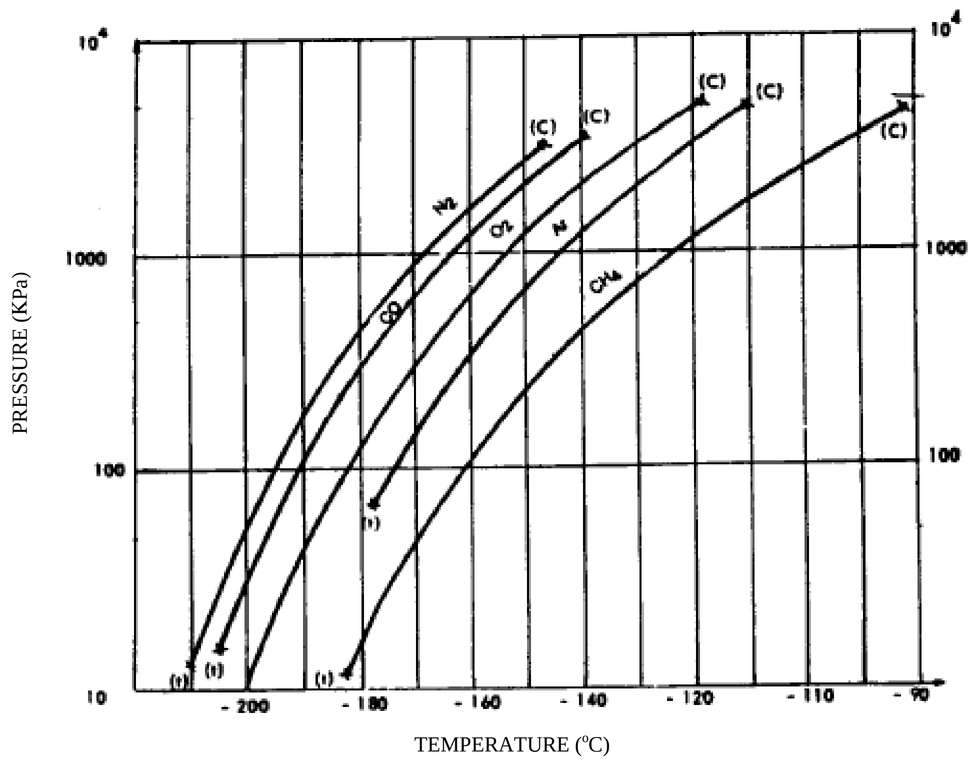


Figure 3. Vapour pressure curves for nitrogen, oxygen, carbon monoxide, and methane.

$$\rho = \rho_0 + \rho_i$$

where ρ is the total resistivity, ρ_0 is the residual resistivity, which is temperature-independent and caused by the scattering of electrons by impurities and imperfections. ρ_i is the intrinsic resistivity caused by the scattering of electrons by lattice vibrations (phonons). ρ_i is temperature-dependent. Below about 20 K, the resistivity of a pure metal is just the residual resistivity and temperature-indepemdent. It cannot therefore be used as a thermometer below this temperature.

2.2.1 Platinum-resistant Temperature Sensors

Platinum-resistant temperature sensors are most accurate and reproducible sensors available over

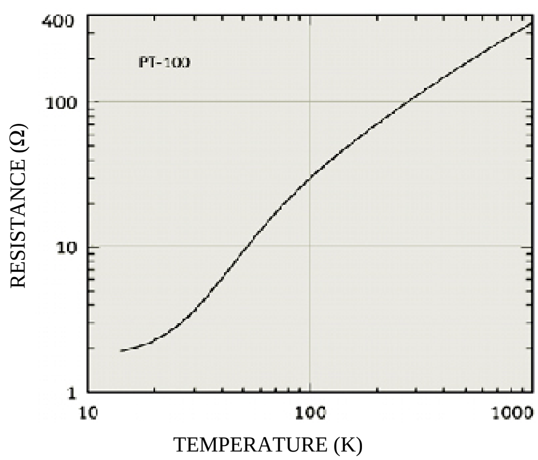


Figure 4. Typical resistance temperature characteristic curve of PT-100.

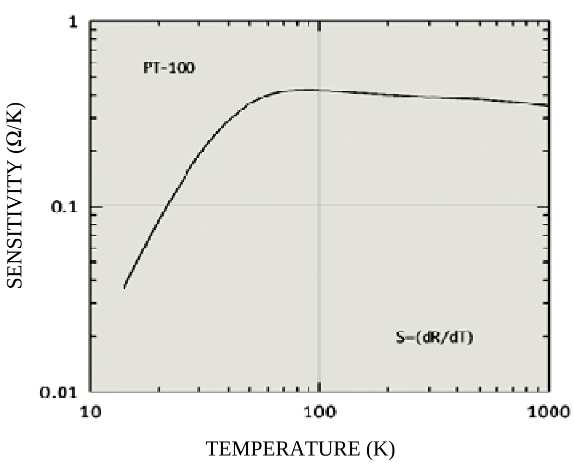


Figure 5. Typical sensitivity curve of PT-100.

a wide range of temeperature which is almost from 20 K to 800 K depending on models from different commercial manufacturers. It has some big advanages. For example, the resistivity is almost linear with the temperature and platinum resistance thermometers follow the standard industrial curve (IEC-751) as shown in the Fig. 4 for PT-100 of Lakeshore Cryotronics. Platinum is easily available in the purest form and its purity can be reproduced batch by batch during manufacturing. As mentioned earlier, the sensitivity of platinum sensor drops drasticaly below 20 K as shown in Fig. 5.

This limits their use only down to 20 K. Platinum sensors can however be used in magnetic environment. These sensors have relatively low magnetic field dependence above 50 K. Magnetoresistive temeperature errors of platinum sesnors above 65 K are shown[6,7] in the Fig. 6. The errors continue to increase below 65 K. These sensors can withstand the ionizing radiation environment as well. Figure 7 shows the shift in temperature in ionizing radiation due to 2.5×10^{12} neutron/cm^2 fluence from a nuclear pool reactor. The neutron flux was 3.75×10^7 neutron/cm^2/s with irradiation performed at 298 K (work done by Lakeshore Cryotronics). Thermal response time of platinum sensors is typically ~2-3 s at 77 K and 10–20 s at 273 K. Platinum sensors are extensively used for measurment studies and controlling different valves of LN2 lines at Inter University Acceleration Centre (IUAC), New Delhi.

2.2.2 Rhodium-Iron Temepearture Sensors

Rhodium-iron (*Rh-Fe*) temperature sensors are widely used over a wide range of temperature (1.4 K–350 K). The greatest advantage of *Rh-Fe* sensor is that it has nearly linear resistance-temperature behaviour from 500 K to 50 K, and then from 50 K to 1 K. Figure 8 shows the dependency of resitivity on temperature for two different *Rh-Fe* sensors of Lakeshore Cryotronics. The sensitivty of the *Rh-Fe* sensor remains high over a usable ranges as shown in Fig. 9, *Rh-Fe* sensors are very stable over repeated thermal cycling and under extended exposure of ionizing radiation. Thin film *Rh-Fe* sensors is also available whose thermal time constant is of the order of ms whereas the

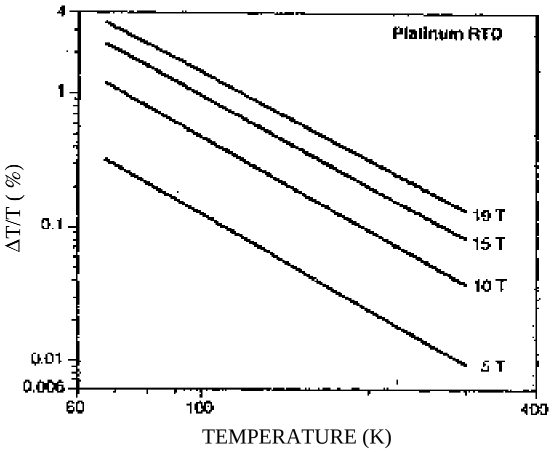


Figure 6. Error in temperature of a PT-100 in magnetic field.

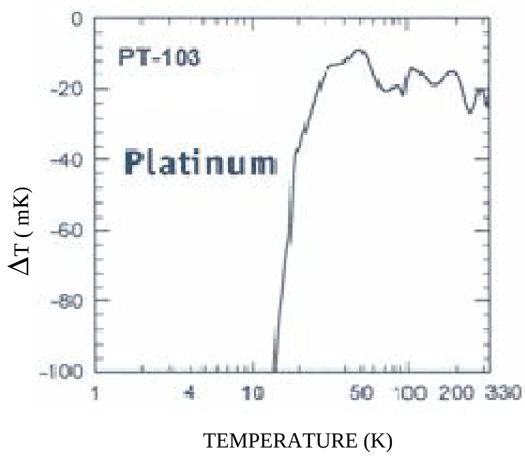


Figure 7. Temperature shift as a function of temperature in ionizing radiation.

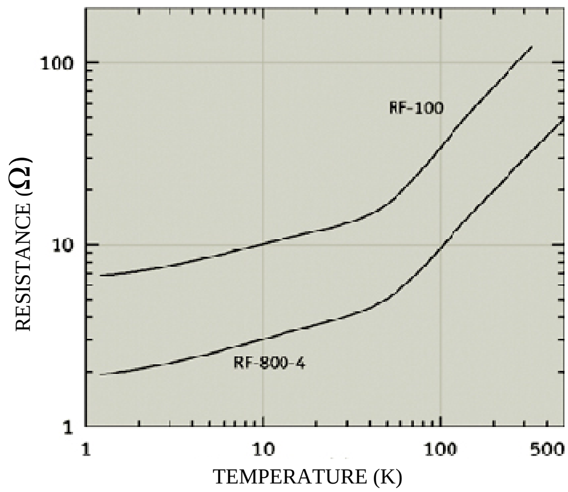


Figure 8. Typical resistance temperature characteristic curve of *Rh-Fe* sensors.

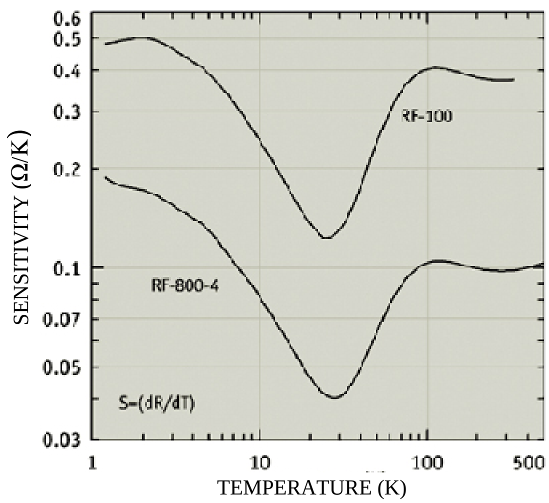


Figure 9. Typical sensitivity curve of *Rh-Fe* sensors.

thermal time constant of wire-wound resistors (like PT-100) is of the order of seconds. Its main disadvantage is the difficulty in maintaining the homogeneity in the batch-to-batch production. Its magnetoresistance is, however, larger than that of platinum, and is thus not a suitable sensor in magnetic environment.

2.3 Semiconducting Resistance Thermometry

Some of the semiconductors have excellent thermomeric properties at low temeperatures. In general, the electrical conductivity of a semiconductor is much less than that of metallic conductor but higher than that of an insulator. Semiconducting resistors typically have negative temperature coefficient, therefore the sensitivity (*dR*/*dT*) of the semiconducing thermometers in the low temeperature range is much higher than that of metallic thermometers. For example, the *dR*/*dT* for a typical semiconductor is -50 x 10^{-3} ΩK^{-1} at 273 K, whereas for platinum at the same temperature it is 4 x 10^{-3} ΩK^{-1}. Below 4.2 K, these sensors have an accuracy of order of 1 mK. The most common semiconducing temperature sensors are germanium, carbon, carbon-glass, and Cernox™ sensors.

2.3.1 Germanium Temperature Sensors

The germanium sensor is usually a small single crystal. The resistance increases very rapidly with the decrease of temeperature. Its typical temperature-dependence of the resistance is shown in Fig. 10.

The sensitivity also increases rapidly with the decreasing tempearture as shown in Fig. 11. Thus, one gets a very high degree of accuracy at low temperatures.

Germanium sensors have extremely good stability (about ± 0.5 mK at 4.2 K) and probably the best choice for high accuracy measurement in the temperature range 0.05–30 K when magnetic field is not present. The exact range depends upon the doping of germanium. For this reason, germanium resistance sensor remains the standard sensor for accurate measurement below 30 K. The thermal mass of these sensors are very small, resulting in a time constant of ~ 200 ms at 4.2 K. The measuring current (excitation current) has to be chosen properly as Joule heating may create a shift in temeperature because of its low thermal mass. Most of the models[8] use 1 A for T < 2 K, 10 A for 2 K < T <15 K, 15 A for 15 K< T <40 K and 1mA for 40 K< T <100 K. These sensors can also be used in ionizing radiation environment but not in a magnetic environment because of their large magnetoresistivity.

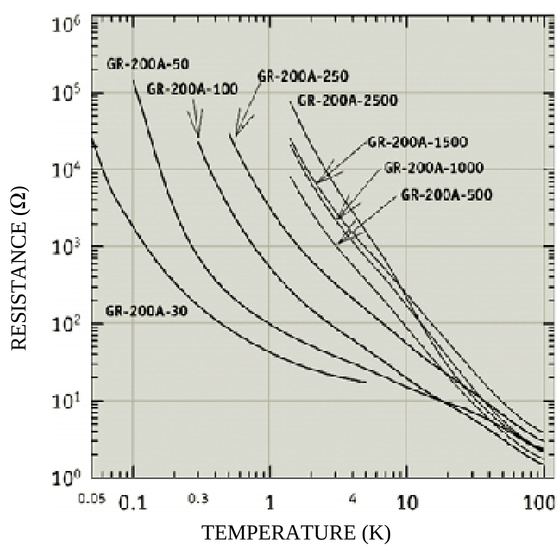


Figure 10. Resistance temperature characteristic of typical *Rh-Fe* sensors.

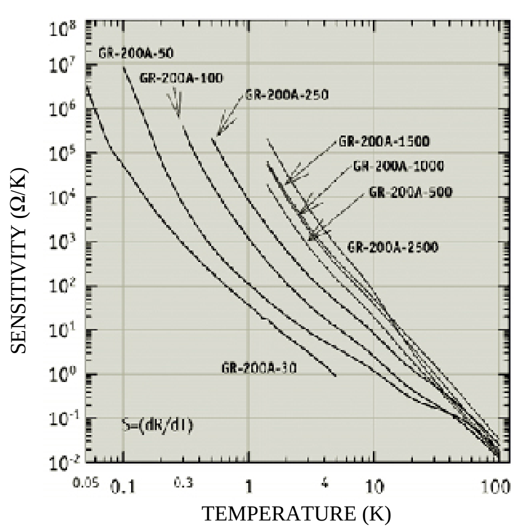


Figure 11. Sensitivity of typical *Rh-Fe* sensors.

2.3.2 Carbon Resistance Temperature Sensors

Carbon resistors[9] are widely used at very low temperatures because of their high sensitivity at lower temperatures. Commercial carbon resistors manutactured by Allen-Bradley were introduced as temperature sensors by Clement and Quninell (1952). Since that time carbon resistance thermometers (CRT) have been used for low temperature application widely from 100 K to 1 K. Although these are less reproducible than the metallic resistance thermometers, yet these are very popular because of their smal size and being exceedingly inexpensive. The resistance of a CRT increases roughly exponentially with the decreasing temperature (Fig. 12) and the sensitivity too increases smoothly at low temperatures (Fig. 13). The resistance of a typial sensor is 1 KΩ at 1 K. The nominal resistance value R (300 K) of a sensor is chosen in such a way that its value at the lowest temperature is managable, because of its exponential increase at very low temperature. Figure 12 clearly shows that at any given temperature, the smaller the value of R (300 K), the smaller is the sensitivity (dR/dT) at lower temperatures.

Reproducibility of the CRT is rather poor and can go up to 2 per cent of change in resistance at 4.2 K after thermal cycling. For very accurate measurements these sensors need calibration after every every thermal cycling. An increase in the resistance at liquid helium temperature is always observed after the first few thermal cycling (2 % for 1000 Allen-Bradley resistors). The phenomenon is associated with carbon granules rearrangement due to the thermal shock. The thermal response is very fast (~ 10 ms at 4.2 K) because of its low mass.These are relatively insensitive to nuclear radiation and have smaller magnetoresistance[10-11].

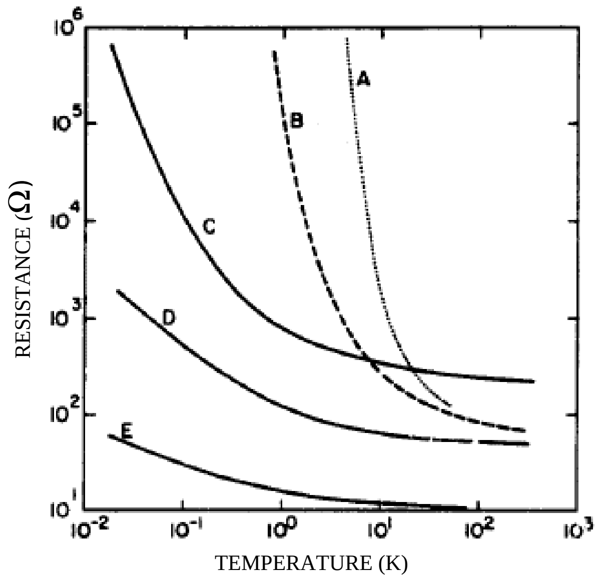


Figure 12. Resistance temperature characteristics for several commercial resistors: (A) thermistor; (B) 68 Ω Allen-Bradley; (C) 220 Ω Speer (grade1002); (D) 51 Ω Speer (grade 1002); (E) 10 Ω Speer (grade1002)[5,9,13,22].

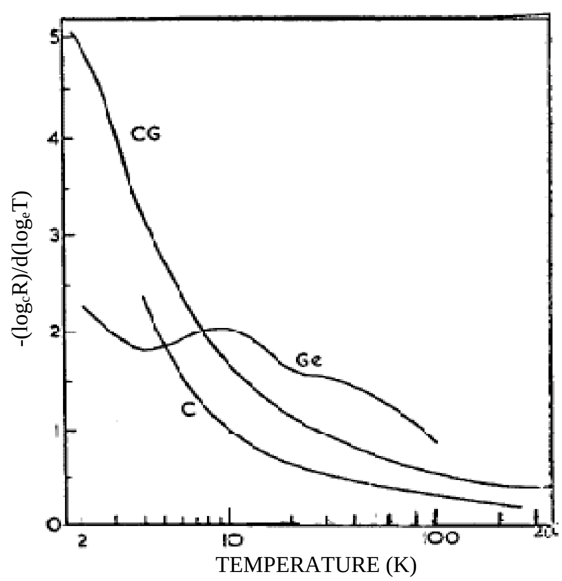


Figure 13. Relative sensitivity versus temperature for carbon (*C*), carbon-glass (CG), and germanium (*Ge*) sensors[5,9,13,22].

2.3.3 Carbon-glass Temperature Sensors

Carbon-glass thermometers were developed to combine the low sensitivity of carbon-resistance sensors to magnetic field with an improved stability by impregnating porous glass with high purity carbon[12,13]. The resistance-temperature characteristic

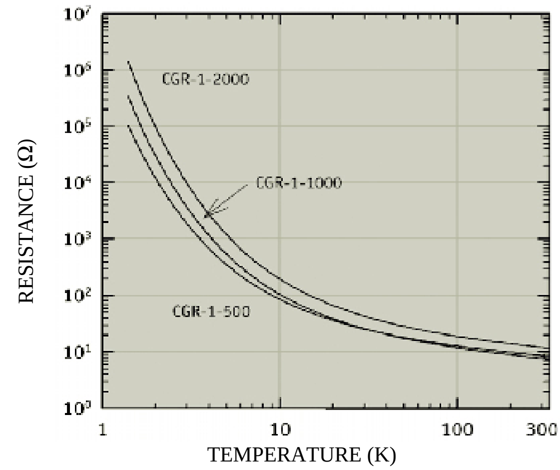


Figure 14. Resistance temperature characteristics of different carbon-glass sensor of Lakeshore Cryotronics.

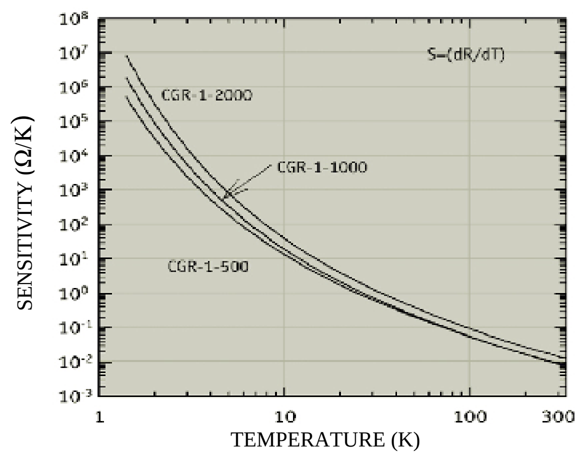


Figure 15. Sensitivity curves of typical carbon-glass sensors of Lakeshore Cryotronics.

is monotonic over the wide range of temperature (1 K–325 K) as shown in Fig. 14 but their reduced sensitivity (~ 0.01 Ω/K) above 100 K limits their usage at higher temperature. This sensor is highly reproducible below 100 K and its sensitivity is extremely high below 10 K (Fig. 15). These sensors can be used in magnetic field up to 20 T (Fig. 16) provided suitable corrections are made for the field-induced temperature errors[14]. It is moderatelty resistant to ionizing radiation.

2.3.4 Cernox™

Cernox[15] is probaly the best among all non-metallic resistive tempearture sensors. Cernox sensors are ceramic oxynitride thin films sputtered onto a sapphire substrate. This is only one of this category that can be used from 300 mK to well above room temperature. Its sensitivity is lower than that of carbon-glass sensors at low temperatures, and higher at high temperatures. The resistance-temperature relationship is shown in the Fig. 17.

Cernox sensors have much smaller magnetic field-induecd errors than the carbon glass sensors, but vary in a complicated way with temperature[16]. For example, the magnetoresistance becomes large below about 4.2 K as shown in Fig. 19. These sensors are highly resistant to ionizing radiation. Fig. 20 shows the shift in temperature due to 2×10^{12} neutron/cm^2 fluence from a nuclear reactor for a typical cernox sensor of Lakeshore Cryotronics. The neutron flux was 7.5×10^7 neutron/cm^2/s with irradiation performed at 4.2 K (work done by Lakeshore) and the associated Gamma-ray dose was 23 Gy. Cernox sensors have proven to be very stable over repeated thermal cycling and these are repeatable to about ± 3 mK at 4.2 K. Sometimes even the stability improves after thermal cycling[17]. A typical temperature shift after 100 thermal shocks from 305 K to 77 K is shown in Fig. 21.

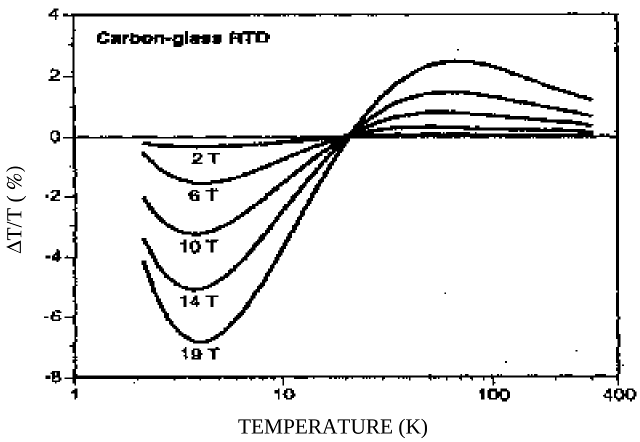


Figure 16. Error in temperature of a typical carbon-glass in magnetic field.

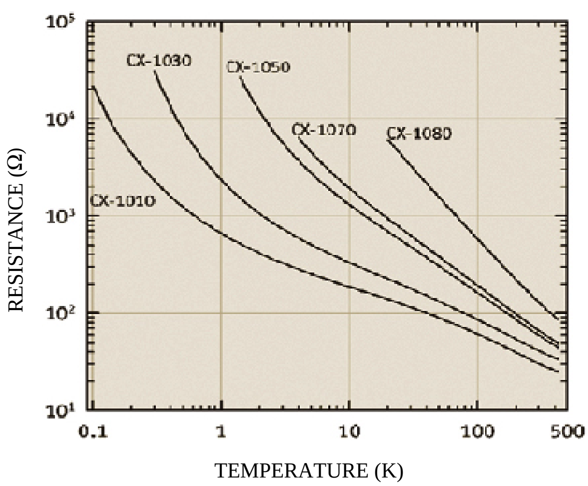


Figure 17. Resistance temperature characteristics of different Cernox sensors of Lakeshore Cryotronics.

These thin-film sensors are easily mounted in packages designed for excellent heat transfer and their thermal response is much faster, e.g. at 4.2 K the response time is ~2 ms.

The main disadvantage of Cernox sensors is that it does not have any standard temperature response curve like that of silicone diodes. Hence, before using any Cernox sensor, it has to be calibrated properly and the response curve will be specific for that particular sensor only. Therefore there is no interchangeability between differrent sensors.

2.4 Semiconductor Diodes

2.4.1 Silicon Diodes

The forward voltage of a semiconductor junction[18-19] at a constant current is a well-defined function of temperature and has been widely used for last 50 years to measure temperature in the range 1-400 K. In a forward biased *p-n* junction,

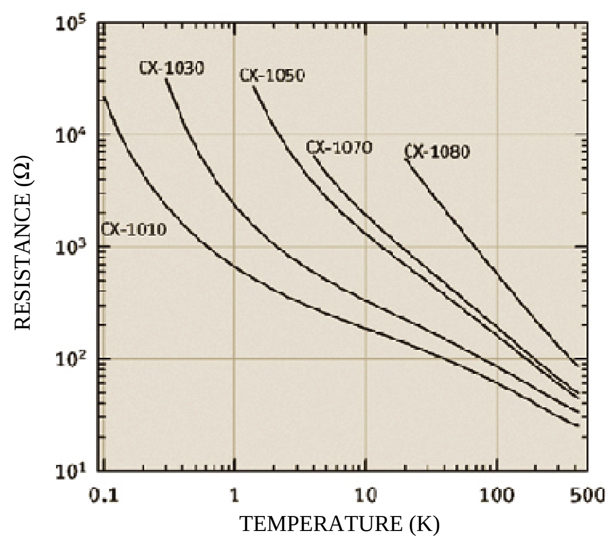


Figure 18. Sensitivity curve of different Cernox sensors of Lakeshore Cryotronics.

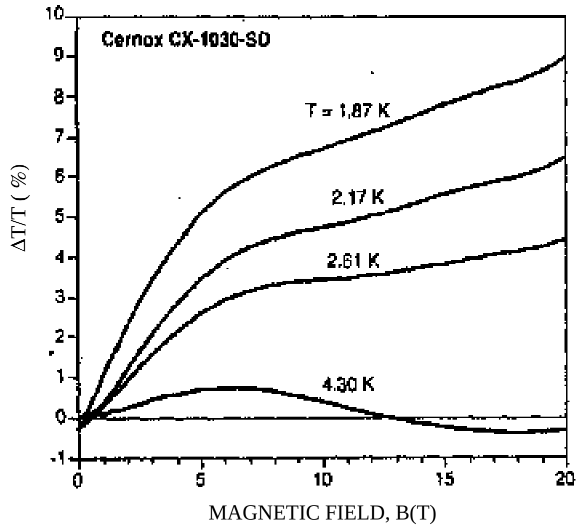


Figure 19. Magnetic field dependency curve of a typical Cernox sensor.

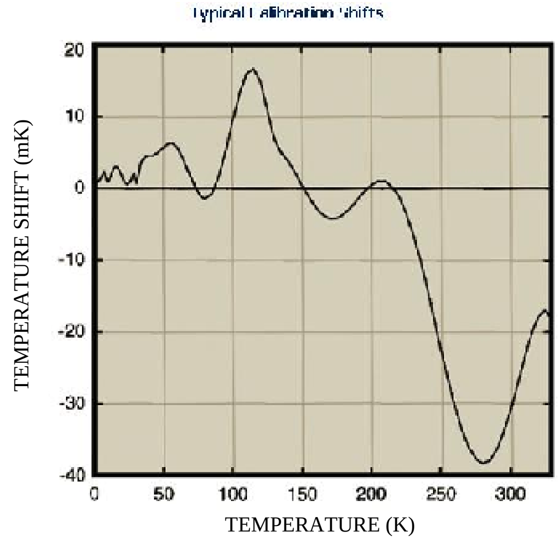


Figure 21. Effect of thermal cycling of a Cernox sensor.

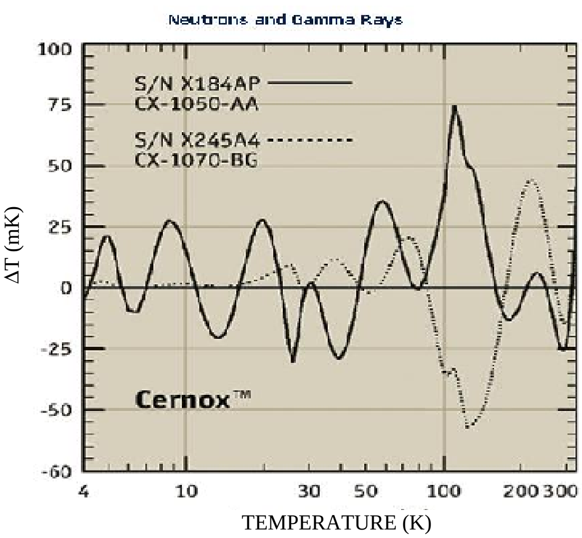


Figure 20. Temperature shift of Cernox sensors in radiation environment.

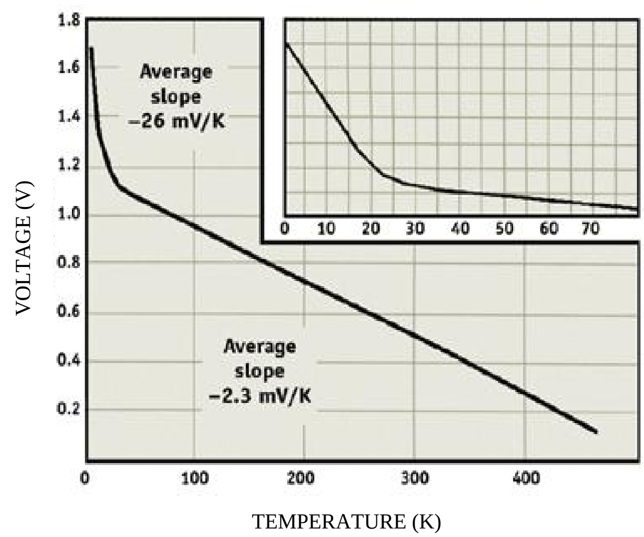


Figure 22. Typical forward voltage-temperature curve of a silicone diode excited at 10 μA DC.

the forward current (I) is related to the junction voltage (V) as

$$I = I_i \exp (qV/nkT)$$

Where q is the electronic charge, n is a constant, k is Boltzman's constant, and T is the absolute temperature. I_i is the intrinsic carrier concentration.

Commercially, two types of *p-n* junctions, namely gallium-arsenide and silicone are used as cryogenic temperature sensors. The silicone diode is a most widely used sensor since it is very stable and reproducible. Gallium-arsenide on the other hand is less stable but is preferred in a magnetic environment because of its low magnetic field-dependence at low temperature.

An important feature of diodes is the interchangeability. A single diode series from a given manufacturer will have some degree of interchangeability defined in terms of tolerance bands about a standard voltage-temperature curve for that series. Interchangeability can be as good as ± 0.1 K at 2 K and ± 0.5 K at 300 K. Figure 22 shows a standard voltage-temperature characteristics curve with 10 μA excitation current for a silicone diode (DT-470 series) of Lakeshore Cryotronics. It is obvious that the curve has two distinct regions with two different slopes, namely an exponential extrinsic low temperature region (T < 20 K) and a linear intrinsic high-temperature region (T > 20 K). This change in slope occurs for silicone junctions at 1.1 V. Because of this, the sensitivity of diode sensor increases below T = 20 K, as shown in Fig. 23.

Silicone diodes can be used in an ionizing radiation environment[20]. A typical temperature shift as a function of temperature due to 10,000 Gy gamma radiation dose from Co-60 source is shown in Fig. 24. Dose rate was 40 Gy/min at 4.2 K during irradiation. Magnetic field strongly affects silicone diodes specially below 50 K. The sensor also shows a magnetic field orientation-dependence. To minimise the magnetic field-induced temperature errors, the sensor should be oriented so that the package base is perpendicular to magnetic field flux lines. The affect of the thermal cycling was also studied for different silicone diodes of Lakeshore Cryotronics. Figure 25 shows the shift in temperature over thermal cycling[21]. The figure also indicates that the long term stability of the silicone diodes at 4.2 K, 77.35 K and at 305 K is nearly ± 0.2 mK per thermal cycle.

Scientists at IUAC have been extensively using silicone diodes (DT-470 series of Lakeshore) in several liquid helium cryostats of superconducting LINAC in the temperature range of 4.2 K to 350 K. A small filter circuit is required to minimise the RF-noise in measurement if these are used in radio frequency environment.

8. THERMOCOUPLE THERMOMETRY

Thermocouples[22] are most useful where low mass or differential temperature measurements are required. They must be calibrated *in situ* because the entire length of the wire contributes to the output voltage if it traverses a temperature gradient. Variation in wire composition, homogeneity, or even strain can affect the temperature readings. Many types of thermocouples are available for low-temperature application. Most common type of thermocouples are copper versus constantan (Type T), nickel/10 %

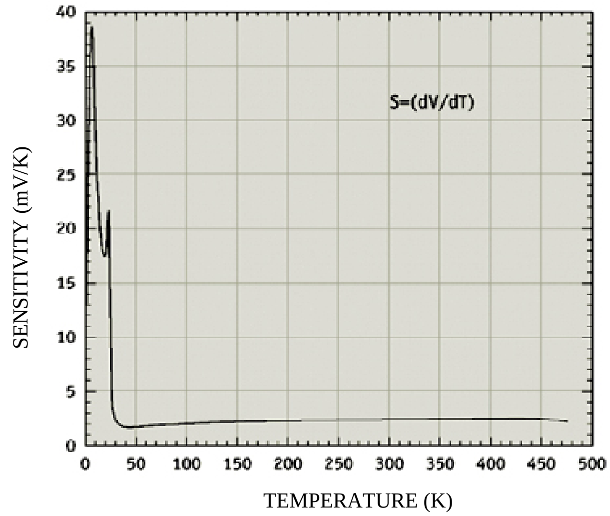


Figure 23. Typical sensitivity curve of a silicone diode excited at 10 μA DC.

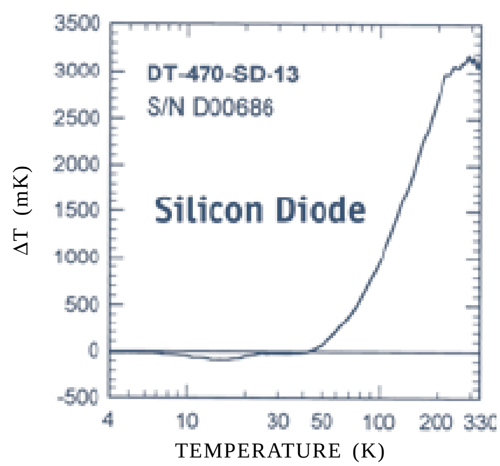


Figure 24. Shift in temperature for silicone diode in gamma radiation environment.

chromium versus constantan (Type E), nickel/10 % chromium versus nickel/5 % aluminium and silicone (Type K), chromel versus Au/0.07 % Fe, chromel versus Au-0.03 % Fe and chromel versus Au-0.15 %t Fe.

Type E thermocouples are widely used in temperature range from 3-1000 K. It has the highest sensitivity among other Types (T and K) used in low temperature applications. Chromel-Au/Fe (0.07 %) thermocouple consists of gold and 0.07 % Fe as the negative thermoelement and a Ni-Cr alloy (chromel) as the positive thermoelement. This thermocouple is more widely used in cryogenic temperature range because of its relatively high thermoelectric sensitivity

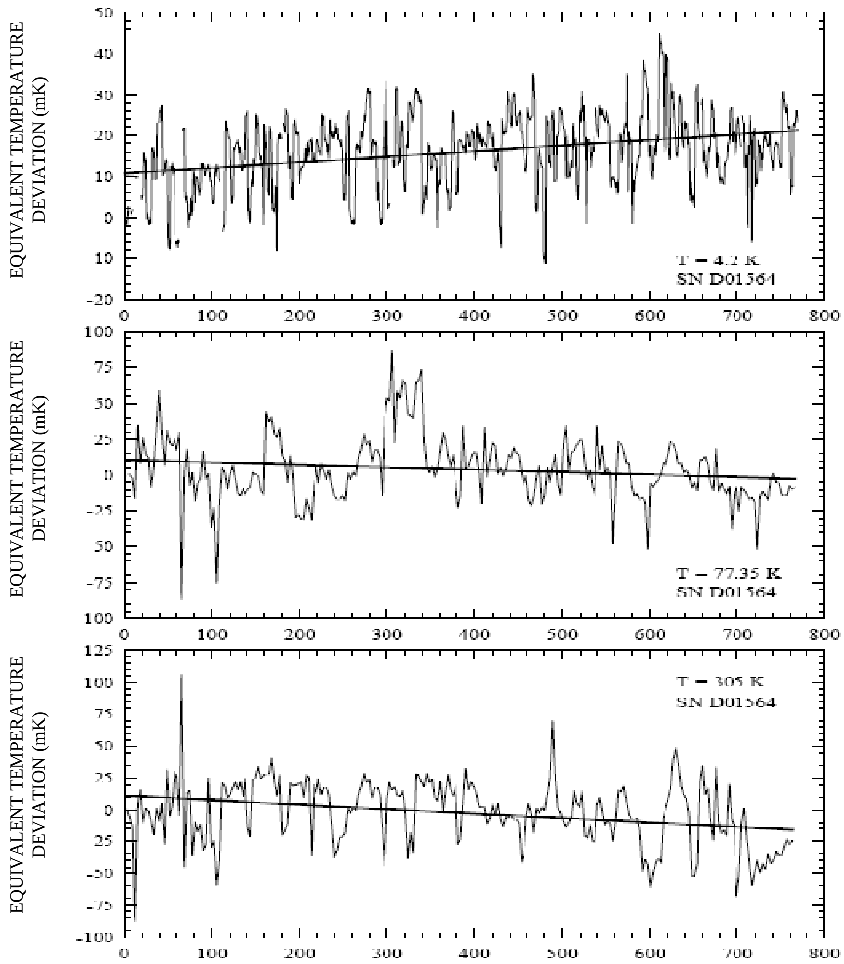


Figure 25. Shift in temperature versus thermal cycling at 4.2 K, 77 K and 305 K.

(>15 V/K above 10 K). We had been using *Au*/*Fe* (0.03 %) vs. chromel thermocouples between the temperature range of 1 K and 300 K for a variety of transport properties measurements successfully. However every time the thermocouple was calibrated against a fixed point, either 77 K or 4.2 K.

9. CONCLUSIONS

It was thus found that the cryogenic thermometry has now developed to the extent that one has very accurate and reproducible sensors for the entire range of temperature, starting from room temperature down to 1 K. The user can make a choice depending upon his requirement of accuracy, the temperature range of interest, and the cost of the sensor. Platinum sensors are generally preferred for use down to 77 K. Beside, the sensor is commercially available and is very inexpensive. Below 77 K, one has many choices. For magnetic field environment cernox is the best sensor available but needs individual calibration. Silicon diodes and carbon-glass sensors are widely used sensors in the temperature range of 1 K to 300 K. These have the advantage that there is complete interchangeability between the sensors produced batch-to-batch by a particular manufacturer. Germanium sensors are used for fine control of temperature of the order of mK below 30 K where there is no magnetic field. *Au-Fe* versus chromel thermocouples are very versatile sensors covering a range of 1 K to 300 K where differential temperature measurements are involved. In this paper the discussion are confined to a temperature range of 1K to room temperature (~300 K). There are sensors of a large variety which can measure temperatures in the range of mK, μK, and nK.

ACKNOWLEDGEMENTS

The authors are grateful to all the manufacturers and the suppliers of the sensors referred to in the paper for using and reproducing at times their data and other information published by them in literature and brochures. We thank Dr. Amit Roy and Mr T.S. Datta for useful discussions. We would also like to thank all the personnel of cryogenic group, IUAC. Mr R.G. Sharma would like to thank the Council of Scientific and Industrial Research (CSIR) for the financial support for his Emeritus Scientist Scheme.

REFERENCES

1. Prakash, P.N. Superconducting linear accelerator system for NSC. *In* Proceeding of 9th Conference on HIAT at NSC, New Delhi, Pramana, November 2002, **59**(5). pp. 849-58.
2. Rubin, L.G.; Brandt, B.L. & Sample, H.H. Cryogenic thermometry: A review of recent progress II. *Cryogenics*, 1982, **22**, 491-03.
3. Rubin, L.G. Cryogenic thermometry: A review of progress since 1982. *Cryogenics*, 1997, **37**, 341-56.
4. Courts, S.S.; Holmes, D.S.; Swinehart, P.R. & Dodrill, B.C. Cryogenic thermometry: An overview. *Appl. Cryo. Tech.*, 1991, **10**, 55-69.
5. Quinn, T.J. Report of ITS-90 techniques for approximating the international temperature scale of 1990. Bureau International Des Poids Et Mesures, 1997. pp. 73-74.
6. Rubin, L.G.; Brandt, B.L. & Sample, H.H. Some practical solutions to measurement problems encountered at low temperatures and high magnetic fields. *Adv. Cryo. Eng.*, 1986, **319**, 1221-230.
7. Brandt, B.L.; Rubin, L.G. & Sample,H.H. Low temperature thermometry in high magnetic field. VI industrial grade pt resistors above 66 K: *Rh-Fe* and *Au-Mn* resistors. *Rev. Sci. Instrum.*, 1988, **59**, 642-45.
8. Flynn, T.M. Cryogenic Engineering. Ed. 2. Marcel Dekker, New York, 2005. pp. 608-610.
9. Quinn, T.J. Report of ITS-90-Techniques for approximating the international temperature scale of 1990. Bureau International Des Poids Et Mesures, 1997. pp. 108-11.
10. Schlosser W.F. & Munnings, R.H. A method of reducing the effective magnetoresistance of carbon resistor thermometers. *Cryogenics*, 1972, **12**, 225-26.
11. Sample, H.H.; Neuringer, L.J & Rubin, L.G. Low temperature thermometry in high magnet fields III. Carbon resistors (0.5 K-4.2 K), thermocouples. *Rev. Sci. Instrum.*, 1974, **45**, 64-73.
12. Lawless, W.N. Thermometric properties of carbon-impregnated porous glass at low temperatures. *Rev. Sci. Instrum.*, **43**(12), 1743-747.
13. Quinn, T.J. Report of ITS-90-Techniques for approximating the international temperature scale of 1990. Bureau International Des Poids Et Mesures, 1997. pp. 116-17.
14. Sample, H.H.; Brandt, B.L. & Rubin, L.G. Low temperature thermometry in high magnet fields V. Carbon-glass resistors. *Rev. Sci. Instrum.*, 1982, **53**, 1129-136.
15. Swinehart, P.R.; Courts, S.S. & Holmes, D.S. Metal oxy-nitride resistance films and methods of making the same. US Patent No. 5367285, 1994.
16. Brandt, B.L.; Liu, D.W. & Rubin, L.G. Low temperature thermometry in high magnetic field VII. Cernox sensors to 32 T. *Rev. Sci. Instrum.*, 1999, **70**, 104-10.
17. Ch. Balle, *et al*. Influence of thermal cycling on cryogenic thermometers. *Adv. Cryo. Eng.*, 2000, **45**, 1817-823.
18. Rao, M.G. Semiconductor junctions as cryogenic temperature sensors. *Temp. Amer. Inst. Phy.*, **5**, 1205-211.
19. Dodrill, B.C.; Krause, J.K.; Swinehart, P.R. & Wang, V. Performance characteristics of silicone

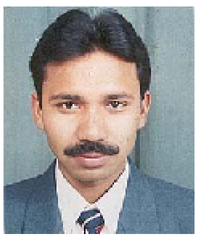
diode cryogenic temperature sensor. *Appl. Cry. Tech.*, 1991, **10**, 85-107.

20. Courts, S.S. & Yeager, C.J. Gamma radiation induced calibration shifts in four cryogenic thermometer models. *Adv. Cryo. Eng.*, 2004, **49**, 404-11.

21. Courts, S.S. & Swinehart, P.R. Long term stability of a cryogenic diode thermometer. *Adv. Cryo. Eng.*, 2002, **47B**, 1636-643

22. Quinn, T.J. Report of ITS-90-Techniques for approximating the international temperature scale of 1990. Bureau International Des Poids Et Mesures, 1997. pp. 148-59.

Contributor



Mr S. Kar obtained his MSc (Physics) from the University of Kalyani, Kalyani, West Bengal in 1996. Presently, he is working as Scientist D at the Inter University Accelerator Centre, New Delhi. He was a Visiting Scientist in the Legnaro National Laboratory (LNL-INFN), Italy, in 2001 and worked in ALPI-LINAC project of Legnaro National Laboratory His areas of research involve: Development of RF-superconductvity linear accelerator, thermosyphon cooling, heat transfer, temperature sensors, warm bore cryofree magnet, etc.