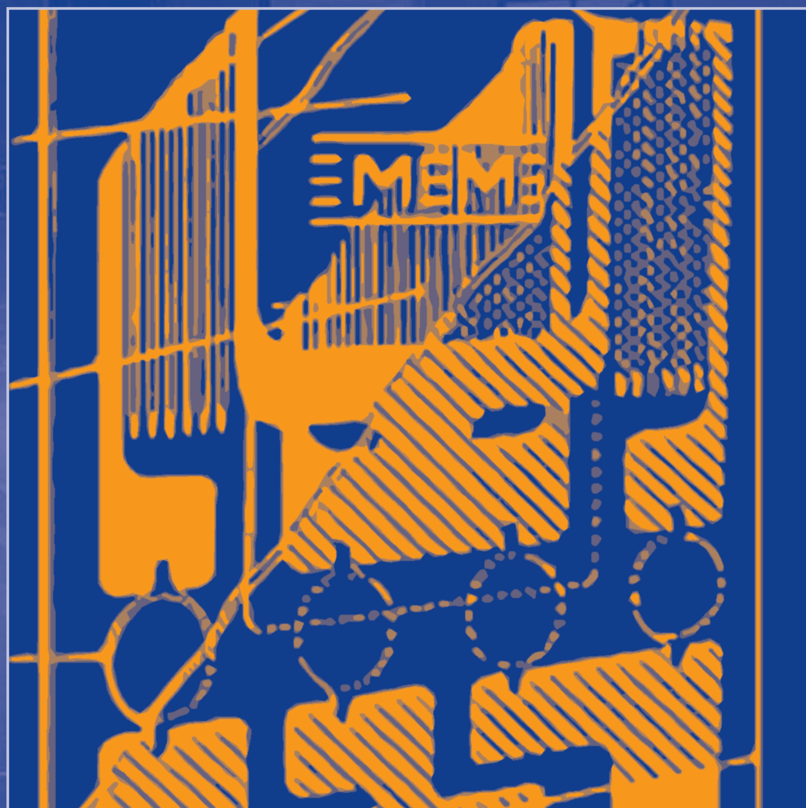
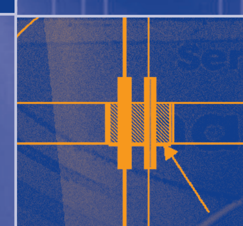
Thermometry



- CCS and Cernox Sensors for 1.4 K – 400 K and Low Sensitivity to Magnetic Fields
- Nuclear Orientation Thermometry for ULT Applications (<50 mK)
- Capacitance Sensors for Low Sensitivity to Magnetic Fields
- Rhodium-Iron Sensor for 1.4 K to 900 K
- Thermocouples for High Temperatures
- Silicon Diodes and CLTS for Accurate Calibration Over a Wider Range



Oxford Instruments provides a comprehensive range of temperature sensors enabling precision measurement and control from 300 K down to 3 mK. We are pleased to introduce several new sensors: the economical Carbon Ceramic chip enables measurements from 1.4 to 300 K in the presence of high magnetic fields, with superior stability; the $_{60}$Co source, together with our nuclear orientation electronics enables measurement in the 3 – 50 mK range, crucial for dilution refrigerators, complementing our R_uO_2 sensor, optimal for temperatures from 50 mK to 4.2 K.

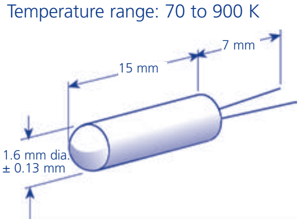
Standard sensors such as Cernox, Rhodium-Iron, CLTS, capacitance sensors and thermocouples provide a variety of temperature ranges and sensitivities, optimal for your experimental conditions. All of the above are compatible with our ITC series of temperature controllers without requiring customization or special ordering. We provide calibration options appropriate to your experimental needs and budget.

OXFORD INSTRUMENTS

Guide to Sensor Selection

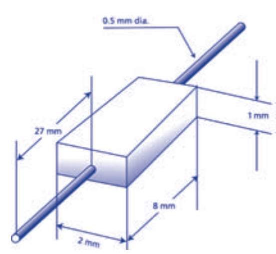
Platinum 100 Ω

Temperature range: 70 to 900 K



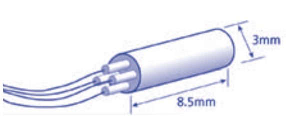
CCS

Temperature range: 1.4 to 373 K



Cernox

Temperature range: 1.4 to 420 K



What cryogen are you using?

Liquid Nitrogen

→ Platinum 100

→ Also satisfactory:

- Copper/Constantan Thermocouple,
- Chromel/Au-0.03% Fe Thermocouple
- Silicon Diode

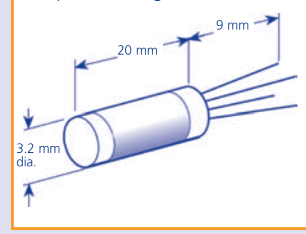
Liquid Helium (^{4}He)

→ Is the thermometer in a magnetic field >1 Tesla?

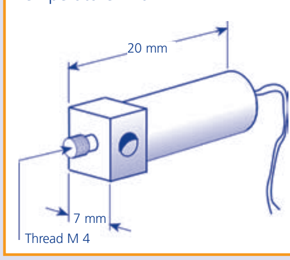
- **Yes** → Temperature range
  - **1.4 K - 400 K** → Cernox or Carbon Ceramic Sensor (CCS)
  - **10 K <T <500 K** → Thermocouples may be suitable in a magnetic field:
    - Chromel/Au-0.03% Fe Thermocouple (>3 K)
    - Chromel/Au-0.07% Fe Thermocouple (>1.5 K)
- **No** → Rhodium-iron
  - Also satisfactory:
    - CLTS Copper/ Constantan Thermocouple,
    - Chromel/ Au-0.03% Fe Thermocouple (>3 K)
    - Chromel/ Au-0.07% Fe Thermocouple (>1.5 K)
    - Silicon Diode

- ^3He
  - T <1 K
    - Is the thermometer in a magnetic field >1 Tesla?
      - Yes → Capacitance Sensor combined with Ruthenium Oxide
      - No → Ruthenium Oxide
- $^3He/^4He$ (dillution refrigerator)
  - >50 mK → Ruthenium Oxide
  - <50 mK → Nuclear orientation, using Ruthenium Oxide for control

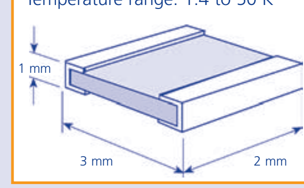
Rhodium-Iron
Temperature range: 1.4 to 800 K



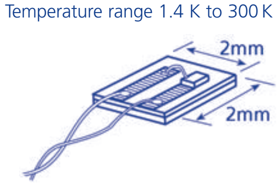
Ruthenium Oxide
Temperature: Max 4.2 K



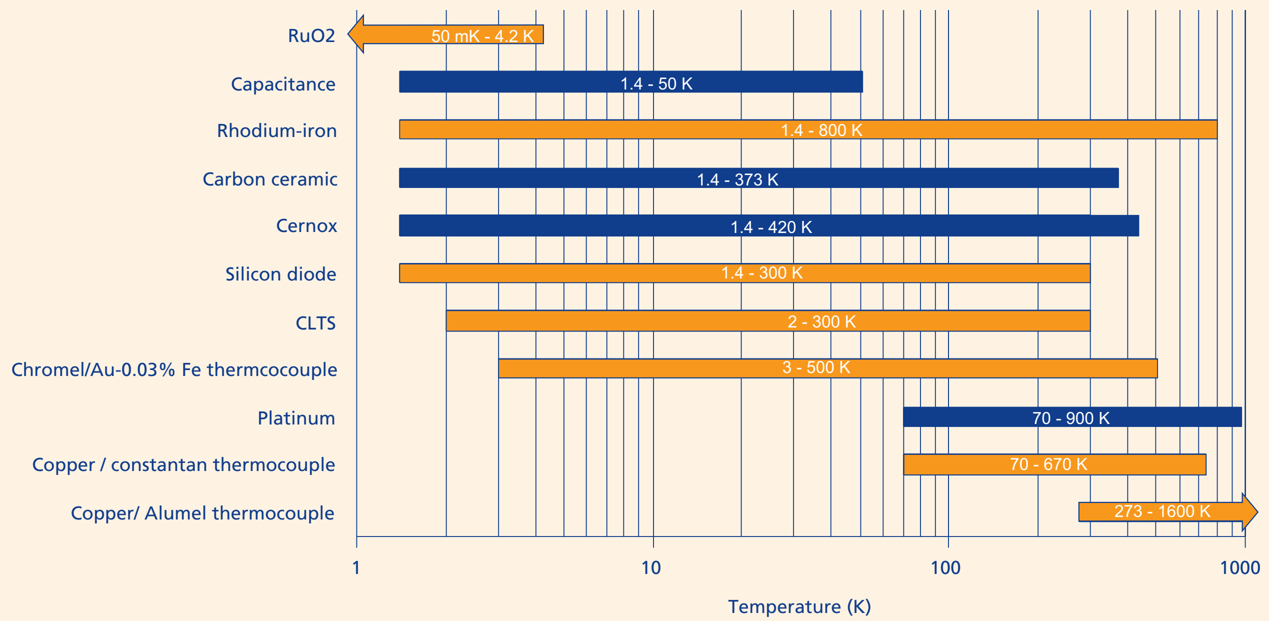
Capacitance Sensor
Temperature range: 1.4 to 50 K

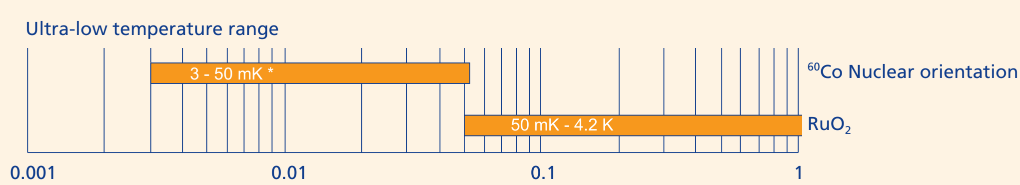


Miniature Silicon Diode
Temperature range 1.4 K to 300 K



Recommended Sensor Temperature Ranges





Notes

* Nuclear orientation thermometry is sensitive to external magnetic fields, and the source can be damaged by high fields. See sensor page for details.

Suitable for use in magnetic fields

Not Suitable for use in magnetic fields

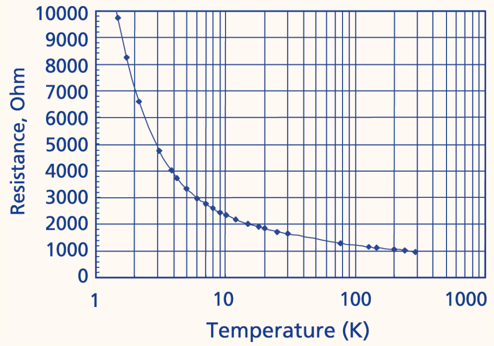
Carbon Ceramic Sensor - Temperature Range: 1.4 to 300 K

Oxford Instruments introduces a new sensor, suitable for use in high fields. Performance is similar or superior to the Cernox sensor in most respects. The carbon ceramic sensor (CCS) is a 2-leads device for 4-wire measurement, possessing high sensitivity, excellent stability and robustness. Its long-term stability is better than 15 mK at 4.2 K after 15 years. It is recommended for accurate temperature measurement in industrial and in high neutron irradiation environments. An excitation current of 100 μA is used over a temperature range of 77.4 K to 300 K and 10 μA is typical over 1.4 K to 77.4 K.

Two groups of calibrated sensors with different sensitivities at 4.2 K are available. Versions are available with 3-point calibration for temperature range 3 K-110 K and with 24–point calibration (1.4 K, 2.5 K and 4.2 K to 300 K) for applications requiring higher degree of accuracy.

The upper calibration temperature could be extended up to 373 K. Calibrated sensor is supplied with data, polynomial curve fit and table of the fit.

The calibration curve of CCS-A1 sensor



Properties at 4.2 K:

- magnetic field error ~1 % at B ≤6 T;
- heat capacity 1.3×10^{-4} J/gK;
- time response ~1 ms;
- weight 0.075 g

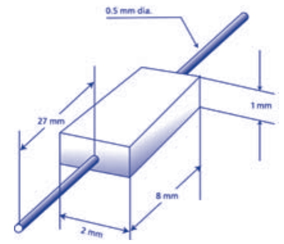
1. Sensor Accuracy for 24 point calibration

Temperature	1.4 K	4.2 K	77 K	273 K
Accuracy	10 mK	10 mK	40 mK	0.1K

2. Sensor Accuracy for 3 point calibration

Temperature	3K	10K	30K	110K
Accuracy	25 mK	70 mK	0.5K	2K

CCS
Temperature range: 1.4 to 373 K

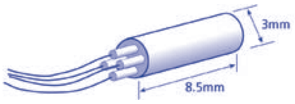


Catalogue Numbers by Sensitivity and Temperature Range				
Sensitivity at 4.2K (Ω/K)	24-point calibration A - (1.4 – 300 K)	24-point calibration B - (2.5 – 300 K)	24-point calibration C - (4.2 – 300 K)	3-point calibration D - (3 - 110 K)
(1) 800 - 1200	T2-101	T2-111	T2-121	T2-131
(2) 500 - 800	T2-102	T2-112	T2-122	T2-132

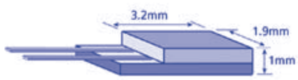
Cernox™ Resistance Sensor - Temperature Range 1.4 K to 420 K

Cernox

Temperature range: 1.4 to 420 K



Canister



Hermetic

The Cernox 1050 resistance sensor is the standard sensor for use in magnetic fields up to and in excess of 20 Tesla as it has a very small magnetic field dependence.

The Cernox is available in two packages: the canister package and the hermetic package.

The canister package is somewhat more robust and is convenient for insertion in a hole. It has four colour-coded leads, 15 cm long.

The hermetic package is advisable in situations where reduced size or a fast thermal response time is necessary. The hermetic package is slightly magnetic. This may have an effect on some very sensitive magnetic measurements, but since the total mass of ferromagnetic material is only a small fraction of the total sensor mass (itself only 40 mg), the effect will be negligible in most cases.

Any Oxford Instruments 500 series temperature controller (ITC 501, 502, or 503) can be used.

Calibration

A calibration, if purchased, includes:

- Certificate of calibration. This states that the calibration conforms to the International Temperature Scale (1990), and is traceable to NIST
- Measured calibration data
- A fit to the data based on Chebychev polynomials, with deviations
- An interpolation table
- With full calibration, sensor operates to 420° K
- All supplied on CD

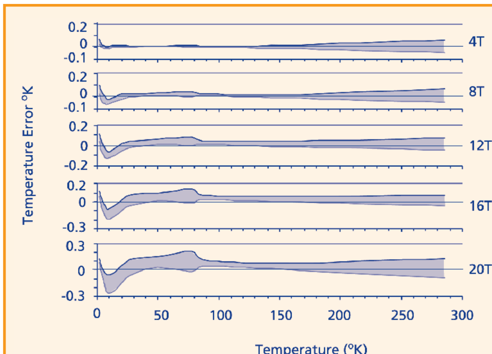
The magnetic field dependence has been described in detail in fields up to 32 T between 2 and 286 K (see graphs and reference below).

Specifications

	Canister package	Hermetic package
Thermal response	0.4 sec at 4.2 K	15 msec at 4.2 K
Temperature limit	325 K	325 K
Long-term stability	±25 mK in the range 1 K to 100 K 0.05% of temperature in the range 100 K to 325 K	

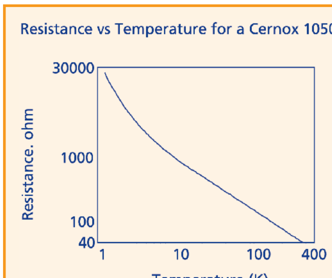
Temperature error due to magnetic field, K

The error in measured temperature due to magnetic field is likely to lie between the upper and lower lines in each graph. (Canisters mounted with long axis parallel to magnetic field)



Reference

Low temperature thermometry in high magnetic fields VII. Cernox sensors to 32 T, B.L. Brandt *et al,* Rev. Sci. Instrum., vol 70, No 1, 1999, pp 104-110.



Ordering information

	Uncalibrated	Calibrated (1.4 – 300 K)	Calibrated (1.4 – 420 K)	Mounting clamp
Canister	T1-107	T1-108	-	-
Hermetic	T1-109	T1-110	T1-112	A6-106 (with 2.1 mm hole for fixing screw)

27 Ω Rhodium-Iron - Temperature Range 1.4 K to 800 K

The Rhodium-Iron 27 Ω sensor is a 4-wire device possessing excellent stability. An excitation current of 1 mA is typical. The resulting change in temperature due to self-heating is less than 1 mK over the range 1.4 to 300 K, provided the sensor is properly installed.

Two standard versions of the sensor are available: three-point calibration and full calibration. The full calibration is made between 1.4 and 300 K. When a three-point calibration is used, two of the reference points can be used to adjust the span and zero of a standard curve stored in the temperature controller. A generic calibration curve is available over the full range 1.4 – 800 K. At present calibration data for individual sensors is not available above 300 K.

A full calibration, if purchased, includes:

- Certificate of calibration. This states that the calibration conforms to the International Temperature Scale (1990), and is traceable to NIST
- Measured calibration data
- A fit to the data based on Chebychev polynomials, with deviations
- An interpolation table
- All supplied on CD

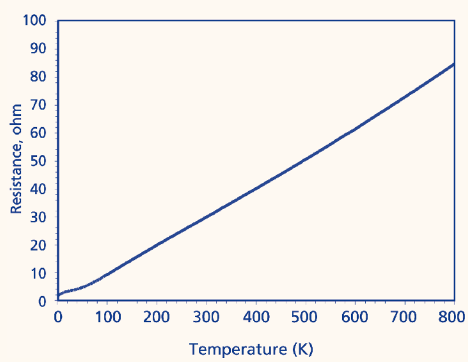
The table below shows the percentage relative error when rhodium-iron resistance sensors are used in magnetic fields. The use of these sensors at temperatures less than 80 K is not recommended in the presence of magnetic fields.

Rhodium-Iron resistance laboratory standards are also available. Please contact your Oxford Instruments representative for further information.

Magnetic field dependence of rhodium-iron sensors

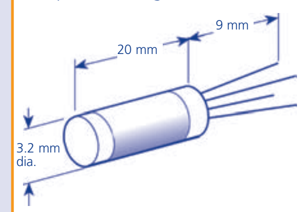
|ΔT|/T (%) in magnetic field B				
T	B			
	2.5 T	8 T	14 T	19T
4.2 K	11	40 (6 T)	–	–
40 K	1.5	12	30	40
87 K	0.2	1.5	4	6
300 K	0.01	0.1	0.4	–

Resistance vs temperature for a rhodium-iron sensor



Rhodium-Iron

Temperature range: 1.4 to 800 K



Ordering Information

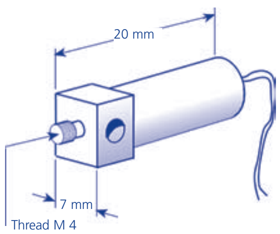
	Sensor	Mounting block	Temperature controller/monitor
Three-point calibrated sensor	T1-102	A6-101	ITC 501, 502, 503, or 601 (standard curve already stored)
Fully calibrated sensor	T1-103	A6-101	ITC 501, 502, or 503

Ruthenium Oxide Temperature Sensors

- Temperature Range 50 mK - 4.2 K

Ruthenium oxide

Temperature: Max 4.2 K



The thick film RuO_2 chip sensor has been mounted in a gold-plated copper holder. The holder is designed to give a good thermal contact between the sensor and the object of interest while also minimising the mechanical strain on the sensor. Such a strain can cause the calibration to change after thermal cycling. The sensor is wired using four 0.2 mm diameter (36 SWG) polyester enamel coated copper wires, a pair each for the excitation current and measured voltage.

The thermometers have a nominal resistance of 2210 Ω at room temperature, and about 25000 Ω at 50 mK. The sensor has a thread which may be screwed into an ISO metric M4 tapped hole. It also has a clearance hole so that it can be fixed with an M3 bolt.

Ruthenium oxide sensors have relatively small magneto-resistance. For information, see "Magnetoresistance of RuO2-based resistance thermometers below 0.3 K", by Watanabe *et al*, Cryogenics, vol 41, p 143 (2001).

Ordering Information	
30-point (Roth1) calibrated sensor	T1-201
Generic (Roth2) Calibration	T1-202

Calibration

Ruthenium oxide sensors are available with two forms of calibration:

Type "Roth1": A full individual calibration. At temperatures below 650 mK the Provisional Low Temperature Scale PLTS-2000 was applied using a ^{3}He melting curve thermometer. At temperatures above 650 mK the ITS-90 was applied using calibrated germanium resistance thermometers traceable to the US-NIST with the atmospheric boiling point of ^{4}He being used as a fixed point. Checks were made using a CMN paramagnetic susceptibility thermometer and a superconducting fixed-point device.

The accuracy of the Type 1 calibration is

50 mK	<	T ≤150 mK	± 5 mK
150 mK	<	T ≤1.5 K	± 10 mK
1.5 K	<	T ≤4.2 K	± 30 mK

Type "Roth2": A 'generic' calibration. These sensors come from the same production batch as the Type 1 sensors and are mounted on the same type of support. They are thermally cycled to create reproducible resistance versus temperature characteristics. They are supplied with calibration based on the average of a representative sample of Type 1 sensors.

The accuracy of the Type 2 calibration is

50 mK	<	T ≤150 mK	± 19 mK
150 mK	<	T ≤1.5 K	± 70 mK
1.5 K	<	T ≤4.2 K	± 200 mK

The International Temperature Scale (ITS-90) and the Provisional Low Temperature Scale (PLTS-2000) have been used.

Both calibrations are accompanied by a document giving advice on sensor mounting and temperature measurement.

Temperature range

The range of calibration (both types) is 50 mK - 4.2 K.

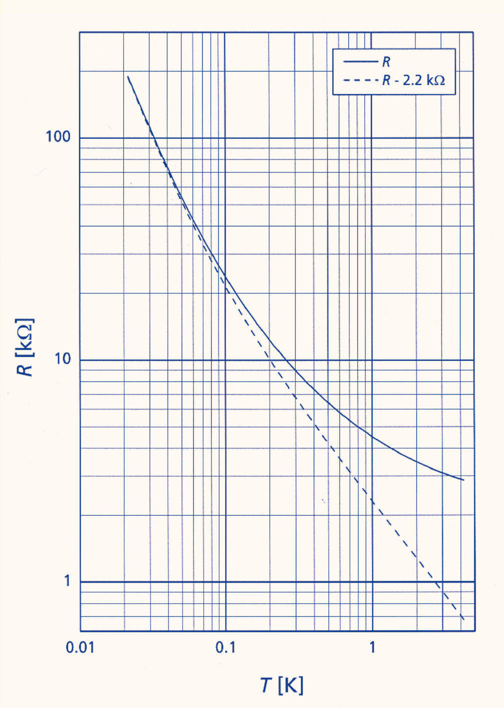
Below 50 mK the sensor does not give accurate results. It can, however, be be used for temperature control purposes in the range 20 – 50 mK in conjunction with another thermometry system (eg nuclear orientation).

Measurement equipment

Above 240 mK, an Oxford Instruments ITC 501, 502, 503 can be used (see Electronics).

Below 240 mK, an AC bridge or IGH with Femtopower card must be used (see Electronics section).

The thermal time constant of the sensor (determined by its heat capacity and thermal resistance to the holder) increases as the temperature drops, and may be several minutes at the lowest temperatures.



Self heating and radio frequency heating

It is important to ensure that the heat dissipated in the sensor is not sufficient to raise its temperature above that of the experimental apparatus. This heat can come from a variety of sources, but in resistance thermometry the most common source of problems is a high excitation current. In general, heat dissipation of the order of one picowatt (10^{-12} W) is acceptable in the milli-kelvin range.

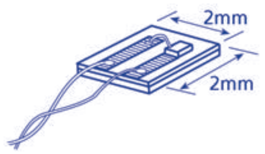
Currents can also be induced by radio frequency (R.F.) interference. These problems can be reduced by screening the cables and using low pass electrical filters on all wires going into the cryostat.

The Oxford Instruments Femtopower system supplied with dilution refrigerators performs a pseudo DC measurement which has been optimised to measure RuO_2 sensors and allows filtering of the measurement lines down to very low frequencies. The Femtopower system can also be fitted to an ITC503.

Typical resistance against temperature curve for a 2210 Ω ruthenium oxide sensor.

Miniature Silicon Diode - Temperature Range 1.4 K to 300 K

Miniature Silicon Diode
Temperature range 1.4 K to 300 K



This fast responding sensor is useful where space is a restriction and a wide temperature range is required.

The sensor may be mounted on a flat surface by applying GE varnish to the back surface and very carefully pressing it down onto its mating surface. Great care must be taken not to damage the 25 µm gold wire bonded to the diode.

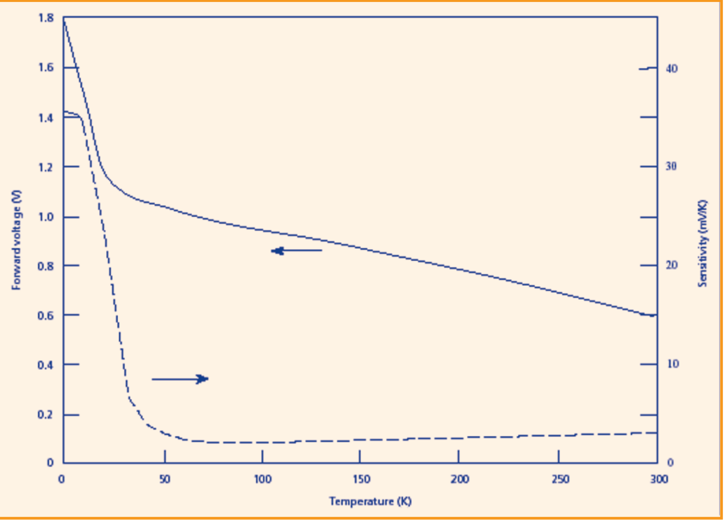
A typical sensor conforms to the standard voltage versus temperature relationship to within ± 0.1 K at 4.2 K and ± 0.5 K at 77 K. Individual calibrations are not supplied.

Magnetic Field Dependence Of Silicon Diode Sensors

	lΔTl/T (%) in magnetic field B	
T	(B = 1 T)	
	Junction parallel to field	Junction parallel to field
4.2 K	43	5
77 K	0.2	0.3

Silicon diodes exhibit strong orientational dependence when used in magnetic fields.

Silicon diode voltage (solid line) and sensitivity (dashed line) as a function of temperature (typical curves)



Catalogue Number	Temperature Controller/Monitor
T1-104	ITC 501, 502, 503, or 601 (standard curve already stored)

CLTS Temperature Sensor - Temperature Range 2 to 300 K

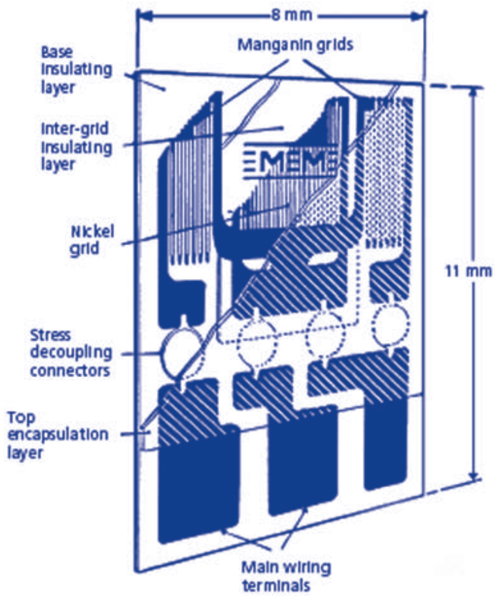
The Cryogenic Linear Temperature Sensor (CLTS) is a flat flexible sensor, incorporating manganin and nickel foil sensing grids, designed to have equal and opposite non-linearities. It is the only available sensor with a nearly linear dependence of resistance with temperature.

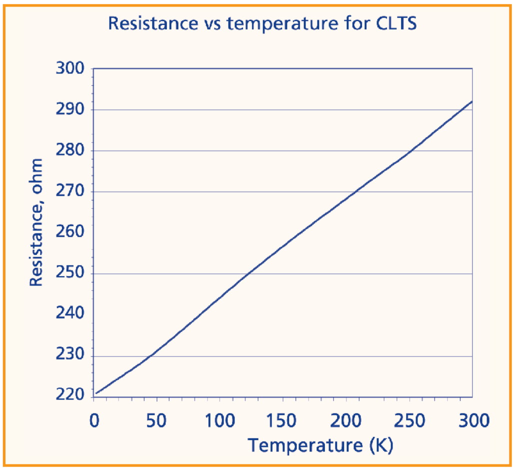
Because of its low mass and thin construction (only 0.1 mm thick, mass 0.02 g), the CLTS responds to temperature changes accurately and quickly. Special design features protect the sensor from damage due to thermal shock, even during plunges from room temperature directly into liquid nitrogen or liquid helium.

The CLTS is not recommended for use in strong magnetic fields.

It can be mounted using M-Bond 600 epoxy-phenolic adhesive (Vishay Measurements Group), or another suitable low viscosity adhesive, ensuring that the glue layer is as thin as possible. The sensor should be clamped in position while the adhesive cures. It can be mounted on flat or curved surfaces. The bonding surface is chemically and mechanically treated for proper bonding.

The CLTS is slightly sensitive to strain caused by differential contraction. As with any sensor, it is recommended that the resistance at the boiling point of helium is checked after installation.





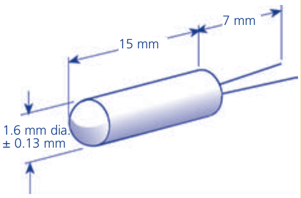
Catalogue number	Temperature Controller/Monitor
T1-105	ITC 501, 502, 503 (standard curve already stored)

Platinum 100 Ω Resistance Thermometer

- Temperature Range 70 K to 900 K

Platinum 100 Ω

Temperature range: 70 to 900 K



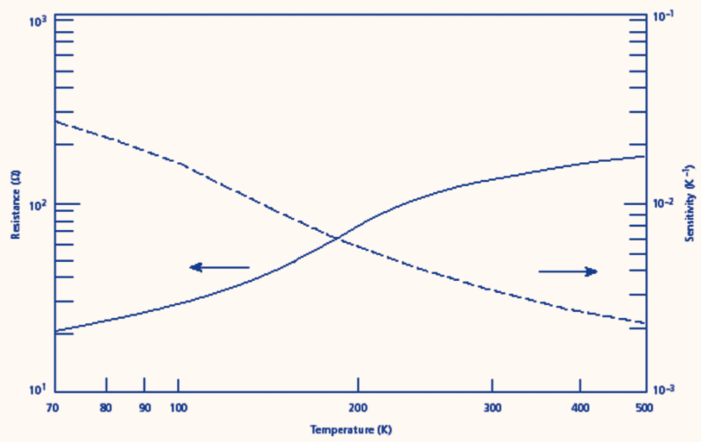
Each sensor conforms to BS 1904/1984 Class A, Band 4 and is supplied with a temperature resistance ratio chart. It is not available with individual calibration.

Platinum resistance sensors may be used in magnetic fields. The table on the right shows the percentage relative temperature error in magnetic fields to 19 Tesla.

Values for long axis of sensor parallel to field

|ΔT|/T (%) in magnetic field B				
T	B			
	2.5 T	8 T	14 T	19T
87 K	0.04	0.4	1	2
300 K	0.01	0.02	0.07	0.13

Resistance (solid line) and sensitivity (dashed line) as a function of temperature for the platinum 100 Ω sensor (typical curves)



Ordering information

Sensor	Mounting block	Temperature controller/monitor
T1-101	A6-102	ITC 501, 502, 503, or 601 (standard curve already stored)

Thermocouples

Fast response time and a small physical measuring junction size make thermocouples a useful choice of sensor where accuracy is not an important consideration.

Every thermocouple needs a reference junction or junctions at a known temperature. For cryogenic applications it is best to put the reference junction in liquid nitrogen in a small dewar or Polyethylene bucket (see Cryogen Handling).

Room Temperature compensation (with the reference junction at room temperature) is suitable for high temperature applications but not recommended for cryogenic work. There are two reasons for this:

a) Thermocouple sensitivity tends to fall at low temperatures so a small room temperature error will cause a larger low temperature error.

b) The actual thermocouple wires must be taken all the way from the cryostat to the controller, since no compensating cable is available for common cryogenic thermocouples.

Type	Temperature range	Temperature controller or monitor
Copper / Constantan	70 - 670 K	ITC 501, 502, or 503
Chromel / Alumel	273 - 1600 K	ITC 501, 502, or 503
Chromel / Au-0.03%Fe	3 - 500 K	ITC 501, 502, or 503
Chromel / Au-0.07%Fe	1.5 - 500 K	ITC 501, 502, 503, or 601

Order information for single wire is shown in top right table. Other thermocouple materials and diameters are available on request.

Order information for twisted pairs of wires is shown in the middle table on the right.

Thermocouple wires

Wires	Dia. (mm)	Insulation	Catalogue Number
Copper	0.2	Polyester	T4-101
Constantan	0.2	Polyester	T4-102
Chromel	0.3	Trimel	T4-103
Chromel	0.2	Polyester	T4-104
Alumel	0.2	Uninsulated	T4-105
Gold - 0.03% Iron	0.3	Polyester	T4-106
Gold - 0.07% Iron	0.2	Polyester	T4-107

Thermocouple twisted pairs

Twisted Pairs	Insulation	Catalogue Number
Copper/Constantan (Type T)	PTE Insulated	T4-108
Chromel/Alumel (Type K)	PTE Insulated	T4-109

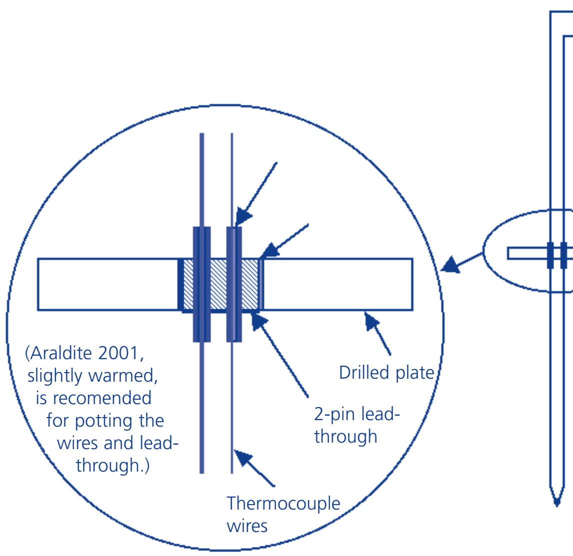
Thermocouple wiring and accessories

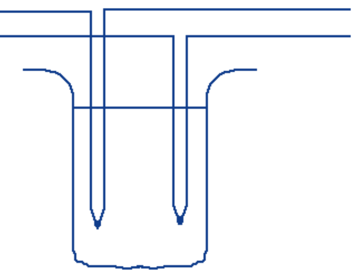
A thermocouple can be wired in a number of different ways. An example is shown on the next page.

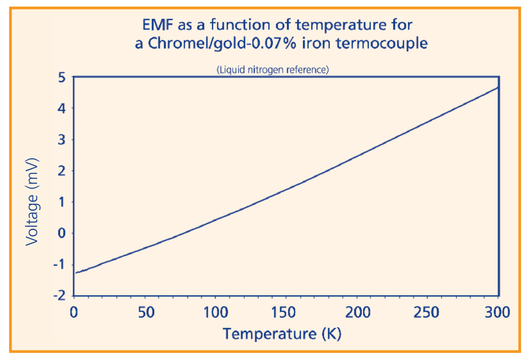
Accessories (see Cryogenic Accessories for details)

	Catalogue Number
Thermocouple mounting clamps	A6-104
Hermetic feedthrough assembly for an existing O.I. hermetic wiring port:	
Feedthrough plate using either	
Blanking plate drilled to accept one leadthrough + 2-pin leadthrough (hollow)	A1-122 + A1-120
OR	
3 x 2-pin seal (hollow)	A1-129
Shroud	A1-105
Flexible cable clamp	A1-104

Thermocouples continued

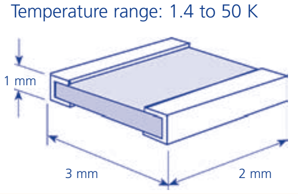






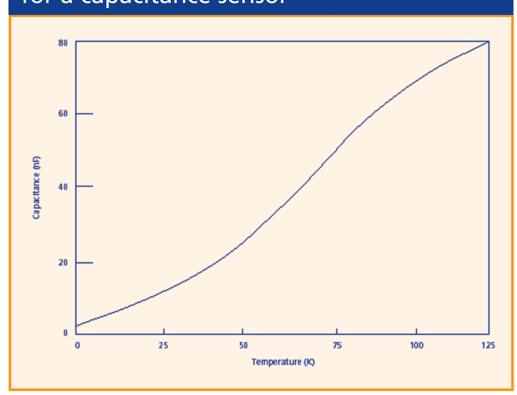
Capacitance Sensor - Temperature Range 1.4 K to 50 K

Capacitance sensor
Temperature range: 1.4 to 50 K



Unlike other cryogenic temperature sensors, capacitance sensors are virtually unaffected by magnetic fields. They are ideal sensors for temperature control in fields up to 20 T and above. However, since they exhibit drift due to aging and thermal cycling, they are not suitable for absolute temperature measurement. The ITC502 and 503 temperature controllers can be fitted with a capacitance range card for temperature measurement with this sensor. When used in conjunction with a temperature controller, it is recommended that a sensor with good long term stability (e.g. rhodium-iron) be used to establish the desired temperature in zero magnetic field. Control is switched to the capacitance sensor to maintain temperature stability while the magnetic field is applied.

Capacitance as a function of temperature for a capacitance sensor



Catalogue Number	Temperature Controller/Monitor
T1-301	ITC 501, 502, 503 with capacitance range card

Nuclear Orientation Thermometry

- Temperature Range 3 mK to 50 mK

The principle of the Nuclear Orientation Thermometer (NO Thermometer) is based on the measurement of the nuclear magnetic polarization of radioactive nuclei (single crystal of Co with ^{60}Co impurities) by detecting a spatial anisotropy of the emitted γ-rays.

The temperature range: 1 mK to 100 mK. Use is commonly limited to a maximum ~ 50 mK because of the long integration periods necessary at higher temperatures). This is the primary technique used by Oxford Instruments at millikelvin temperatures. Nuclear orientation thermometry may be used to calibrate much faster thermometers, like Pt-NMR, PdFe susceptibility, carbon or RuO_2 resistor thermometers.

Accuracy: 0.1% - 0.5% (between 3 mK to 50 mK)

The main advantages of the NO thermometer are:

- It is a primary thermometer and measures absolute temperature
- It is simple to mount on the object and does not require wiring

Practical issues to be considered:

- It is slightly radioactive and requires special precautions (typically ≤5 µCurie)
- It requires certain time to measure temperature (typically few hundreds of seconds)
- **It is sensitive to the external magnetic field and crystal can be damaged in high magnetic field**

Due to the radioactivity of the source (approximately 5 µCu), Oxford Instruments requires evidence of regulatory compliance when ordering, such as a site license for handling radioactive materials.

Detection technique

Oxford Instruments supplies a nuclear multi-channel analyser (MCA) with following specifications:

- MCA including high voltage amplifier, Wilkinson-ADC and microcomputer integrated in a NaI(Tl) detector socket
- 4 hours battery powered with internal rechargeable NiMH batteries
- Low weight: 450 g without battery 550 g with batteries
- Dimensions: diameter 62 mm x 125 mm high
- The MCA is directly attached to the NaI detector socket. The advantage is that no HV and signal cable are needed
- Serial data transfer to a notebook or a computer via RS-232 cable (up to 38,4 k baud, cable included)
- Stand-alone measurement possible without PC/notebook
- Power supply to operate the nanoSPEC and/or charge the internal batteries
- Standard Windows MCA software winTMCA in English
- Complete documentation manuals in English

We provide a choice of NaI (Tl) scintillation detectors with integral line structure and magnetic shielding:

- Type: 51 B 51/2, 2" x 2" thick, energy resolution: ≤7,5 % at 662 keV(Cs137)
- Type: 76 B 76/2, 3" x 3" thick, energy resolution: ≤8 % at 662 keV(Cs137)

Product	Catalogue Number
^{60}Co Source	T3-101
Multichannel Analyser	T3-102
NaI Scintillation Detector, type 51B	T3-103
NaI Scintillation Detector, type 76B	T3-104

Suggested references:

Nuclear Orientation Thermometry, H. Marshak, Journal of Research of the National Bureau of Standards, 88, 175-217, 1983

R. J. Soulen, H. Marshak, Cryogenics, 20, 408, 1980

Nuclear Orientation Thermometry (H. Marshak) in Low Temperature Nuclear Orientation, N. J. Stone, H. Postma (eds), North Holland, 1986

Matter and Methods at Low Temperatures 2nd edition by F. Pobell page 296. Nuclear Orientation Thermometry

How to Choose A Sensor

Sensitivity, stability and accuracy data is given for guidance only, and is not guaranteed.

1. Stability

Since most sensors are rarely if ever recalibrated after being installed, stability is the most important factor affecting the measurement accuracy. The table shows the long-term stability of some sensors.

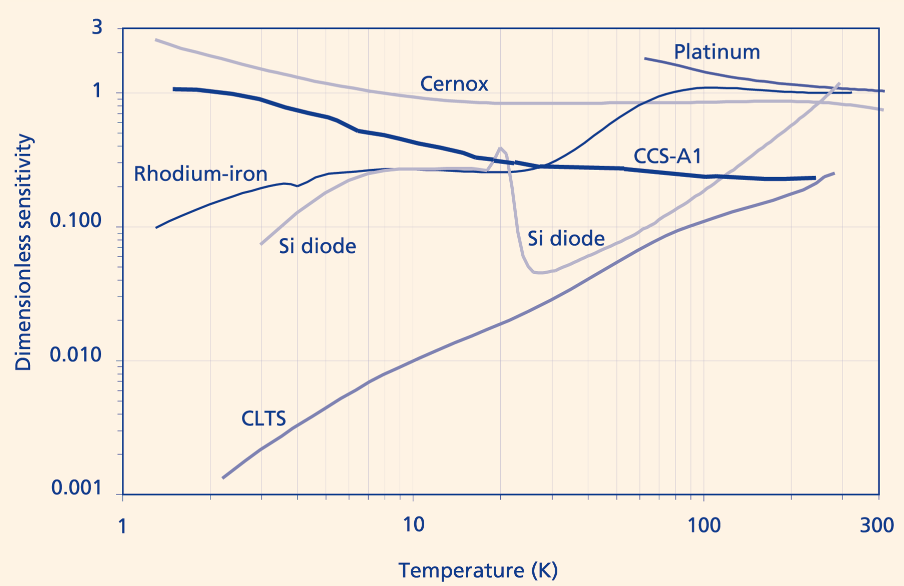
Sensor stability

Sensor type	Stability (mK/year)		
	at 4.2 K	at 77 K	at 300 K
Rhodium-iron	10	10	10
Platinum	-	100	100
Silicon diode	30	30	30
CLTS	500	500	500
Capacitance	>1000	>1000	>1000
Cernox	25	25	150
Carbon ceramic sensor	15 mK in 15 years	data not available	

2. Sensitivity

If a sensor exhibits high sensitivity then less precision is required in the measuring system to achieve a given level of accuracy. High sensitivity sensors usually have a narrow useful temperature range. The figure shows the dimensionless sensitivity of some of the resistance sensors. The figure illustrates the exceptionally high sensitivity of the Cernox at low temperatures.

Dimensionless sensitivity (absolute value) of some sensors



Dimensionless sensitivity $\frac{dR}{dT}\frac{T}{R}$ or $\frac{dV}{dT}\frac{T}{V}$, where T = absolute temperature, R is resistance and V is voltage.

3. Magnetic field

All sensors, except capacitance sensors, exhibit a dependence of their resistance or voltage on magnetic field. Some show a strong or unpredictable effect making them unsuitable for use in a magnetic field. Others show a weaker, quite predictable dependence. Capacitance sensors exhibit virtually no magnetic field effect and may be used for temperature control. They are not suitable for absolute temperature measurement.

4. Size

Listed in order of increasing size the sensors are: thermocouples, silicon diode, Cernox (hermetic package), platinum, rhodium-iron, Cernox (canister), mounted ruthenium oxide.

Application Notes

Sensor installation

Measurements undertaken with accurately calibrated thermometers are of little use unless attention is given to sensor mounting. When mounting sensors, consideration must be given to thermal contact, temperature range, strain effects and unwanted heat loads.

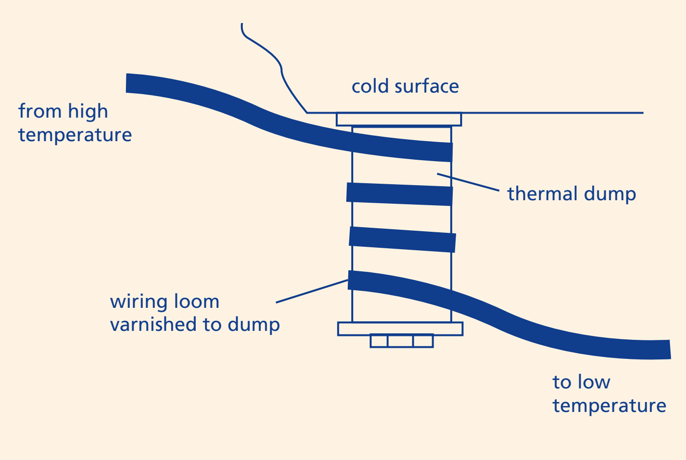
Cylindrical sensors are best mounted in a hole in the object to be measured, with a radial clearance of at most 0.1 mm. For temperature environments not exceeding 300 K, a thermally conductive grease (Type 'N' grease, A4-902) is recommended. For applications above 300 K, a high temperature sensor cement (C4-105) should be used. See Laboratory Essentials for specified consumables.

Thermocouples are usually brought into contact with the object to be measured using a clamp. Enhanced thermal contact is achieved by wrapping the junction in either indium (to 300 K), lead (to 500 K), or aluminium or copper tape.

Silicon diodes are very delicate and must be handled with care. The top face of the sensor must not be touched as this could result in damage to the diode chip or the 25 μm gold wire. The sensor may be mounted on a surface using GE low-temperature varnish (C5-101).

Sensors should never be mounted on a surface exposed to thermal radiation from room temperature. If necessary a covered mounting bracket should be fabricated. It is extremely important to ensure that the wiring for the sensor does not introduce unwanted heat loads. This is accomplished by thermally anchoring the leads on to the object to be measured. Additionally, wires should be anchored to intermediate stages in the cryostat to reduce conducted heat loads from room temperature. The simplest way is to wrap them around a copper post which is held at a known temperature. GE varnish is used to make sure that they are in good thermal contact with the post. Although its thermal conductivity is poor, it gives a large area of contact. See Figure below.

Thermal anchoring of leads



The same techniques can be applied to systems working at millikelvin temperatures. A heat load of 0.1 μW is enough to produce noticeable warming at these temperatures.

In a dilution refrigerator the wiring is typically fixed at the following temperatures:

- 4.2 K, cooled by the liquid helium bath, where the majority of the heat is absorbed
- 1.2 K, on the 1 K pot
- 0.6 K, on the still
- 50 mK, on the cold plate
- on the mixing chamber, to cool the wires to the same temperature as the experiment

If the wires are in gas or liquid – for example, if the experiment is carried out in liquid helium or helium gas in a variable temperature insert, the gas flows over the wires before it leaves the cryostat. This cools them effectively, and it is only necessary to make sure that sufficient length of wire is in contact with the cold gas. Allow the wires to spiral around some convenient mechanical support, such as a pumping line or support leg.

If it is important that the capacitance between the wires and ground is very low (for example, less than 100 pF), alternative methods of heat sinking have to be considered. One method is to clamp the wires firmly, and another is to encapsulate them in epoxy resin.

reference

Sensor mounting at milli-kelvin temperatures

When measuring milli-kelvin temperatures it is essential that the sensor is in intimate thermal contact with the part of the apparatus whose temperature is to be measured. It is not always sufficient to attach the sensor to the refrigerator itself because there may be a significant temperature difference between the sample and the cold point of the refrigerator, especially when the experimental heat load is high. It is also possible that there will be significant temperature differences across the sample itself. The important parameter is the effectiveness of the heat transfer from the sample to the sensor.

In general good thermal contact (to a solid thermometer or holder) is obtained by face to face contact between two clean copper surfaces. Gold-plating the copper surfaces will improve thermal contact. The surfaces should be pressed together using a screw thread (or similar clamping method), so that there is a large force between them. It is important to avoid the presence of any superconducting materials in the thermal path because they are very good thermal insulators. Many solders become superconducting at milli-kelvin temperatures. In some cases it may be acceptable to suppress the superconductivity using a small magnetic field (<0.1 T). Superconducting transitions of a few common materials are listed in the Cryogenic Reference section. Non-superconducting solder is available.

At very low temperatures there is a large thermal resistance ("Kapitza resistance") between liquid helium and any solid. When even a small amount of heat is supplied to the sample, its temperature quickly rises to a value much higher than that of the $^3He/^4He$ mixture. The most effective way to ensure good thermal contact between the sample and the mixture is to mount the sample directly onto a mixing chamber that has been designed with a very large surface area to make good thermal contact with the mixture.

Twisted pairs

Electrical noise is often picked up by an electrical circuit, and if sensitive measurements are being made the noise may make it difficult to detect a signal. The noise can also contribute to radio frequency heating of the sensor in ultra low temperature systems. One way of reducing the electrical noise pick up is to arrange the wires in twisted pairs. The wires are twisted together for their whole length, so that the currents induced by flux passing between the wires in each twist is cancelled by that in the next twist.

Thermo-electric voltages

If two dissimilar metals are joined together they act as a thermocouple, and small voltages (typically microvolts) can be generated. If very low voltage signals are being measured steps have to be taken to reduce the thermal voltages, so that they do not affect the readings. This is especially important at temperatures below 4 K, when very small excitation currents are required to prevent self-heating. As there are always some joints, it is important to ensure that the joints in all the wires are at exactly the same temperature. The dependence on temperature (near room temperature) of thermoelectric voltage with respect to copper (relative thermopower) is given in the table. These figures should be treated with caution, as the thermolectric properties of copper are very sensitive to purity.

Thermoelectic voltage coefficient with respect to copper

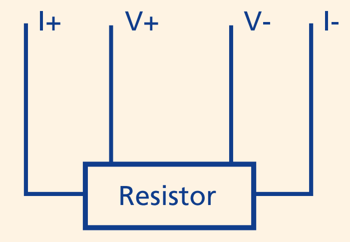
Metal	μV/K
Copper	<0.3
Constantan (copper-nickel)	40
Gold	0.5
Silver	0.5
Brass	3
Beryllium Copper	5
Aluminum	5
Kovar or Alloy 42	40
Silicon	500
Copper-Oxide	1000
Cadmium-Tin Solder	0.2
Tin-Lead Solder	5

Four wire measurements

Cryogenic resistance thermometry requires the use of the four-wire technique. Using this technique a sensor with a resistance of a few ohms can be measured accurately through leads with a resistances of several hundred ohms. Two wires are used to supply the excitation current. The other two wires are used to measure the voltage across the sensor. Since there is almost no current flowing in these wires the voltage drop along them is tiny, and their resistance can also be neglected.

All Oxford Instruments temperature controllers and monitors use the four-wire technique.

Four-wire measurements



Ultra-High Vacuum (UHV) systems

While some sensors in bare chip form or hermetic packages are reported to be suitable for use in UHV, it is always advisable to mount the sensor and wiring outside the UHV space if possible. Mounting sensors and thermally anchoring the wires is made much easier by use of greases, adhesives, varnish, insulating sleeving and fishing line, none of which are advisable in UHV.

Accuracy in temperature measurement

The Oxford Instruments ITC500 series of temperature controllers and monitors has designated excitation currents for each sensor offered which ensure negligible self-heating over the recommended temperature range.

Semiconductor resistance sensors have a resistance which rises rapidly with decreasing temperature. In the ITC500 series the sensor current is measured at constant voltage for these sensors. This reduces the risk of self-heating since the current is automatically reduced with decreasing temperature.

The tables below summarise the capabilities of the ITC500 series temperature controllers and monitors when used with fully calibrated sensors.

Sensor	Rhodium-Iron	Cernox
Temperature range for which these figures have been estimated	1.4 – 300 K	1.4 – 300 K
Display resolution	0.1 K	0.1 K
Accuracy	0.1 K	0.1 K

Accuracy of measurement for sensors used with the ITC501 monitor or the ITC502 controller

Sensor	Rhodium-Iron	Cernox
Temperature range	1.4 – 300 K	1.4 – 300 K
Display resolution		
T≤19.99K 20 K≤T≤199.99 K T≥200 K	1 mK 10 mK 100 mK	1 mK 10 mK 100 mK
Accuracy		
T≤19.99K 20 K≤T≤199.99 K T≥200 K	30 mK 30 mK 100 mK	30 mK 30 mK 100 mK

Accuracy of measurement for sensors used with the ITC503 temperature controller

References

"Cryogenic Thermometry: A Review of Recent Progress ", L. G. Rubin, Cryogenics, Vol 10, 14-20, (1970).
"Cryogenic Thermometry: A Review of Progress Since 1970", L. G. Rubin, B.L. Brandt and H.H. Sample, Cryogenics, Vol 22, 491 (1982).
"Cryogenic Thermometry: A Review of Progress Since 1982", L. G. Rubin, Cryogenics, Vol 37, 341-356, (1997).

reference