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SMR/543 - 7

EXPERIMENTAL WORKSHOP ON HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED MATERIALS (BASIC ACTIVITIES)

(11 February - 1 March 1991)

" Temperature Measurements and Control in the 4K - 150K Range "

presented by:

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Temperature measurements and control in the 4 K – 150 K range

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4 and 5 short remarks only

3 Thermometers:
vapour pressure
resistance : platinum
Rh 0.03 %Fe
Germanium
Carbon radio resistors
carbon-in-glass
Thermistors
diode Silicon
GaAs
thermocouples ordinary
low temp.

Thermodynamic temperature, and its unit the kelvin

The basic temperature in physics is the thermodynamic temperature T

This is, of course, the temperature which occurs in such fundamental relations as

- $q = T dS$ (second law of thermodynamics)
- $n_i \propto e^{-\varepsilon_i/kT}$ (Boltzmann distribution)

The thermodynamic temperature has an absolute zero (lowest energy state of a system) as can easily be seen from a simple example

$$\begin{array}{l} \text{——} \; \varepsilon_2 \;\; n_2 \\ \text{——} \; \varepsilon_1 \;\; n_1 \end{array} \qquad \frac{n_2}{n_1} = e^{-(\varepsilon_2 - \varepsilon_1)/kT}$$

the state $n_2 = 0$ corresponds to $T = 0$

(with $n_2 > n_1$ negative T's, which are higher than pos T's)

With one more reference point the unit of thermodynamic temperature, the kelvin, is defined. One has chosen the triple point of water, and defined it as 273.16 K. Thus:

$$1 \text{ kelvin} = \frac{\text{therm. temp tr. point } H_2O}{273.16} = \frac{T_{trp}}{273.16}$$

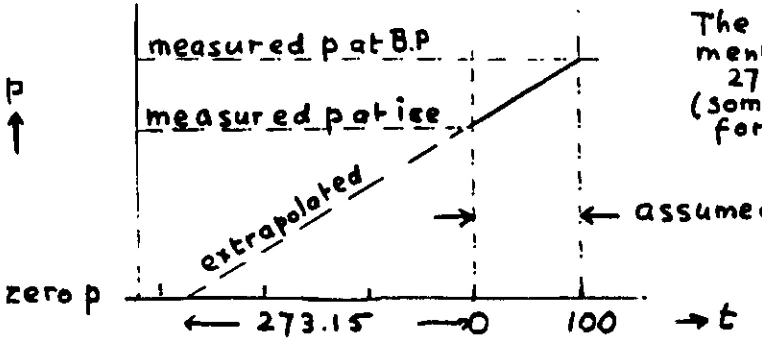
For convenience one also uses the Celsius temperature t, now defined as

$$\frac{t}{°C} = \frac{T}{K} - 273.15$$

the difference between the actual thermodynamic temperature and the thermodynamic temperature of the "ice point".

There is an interesting history in this choice of 273.16 for the triple point of water

- When I came as a student in the thermometry group around 1950 there were many discussions on the best value of the ice-point, at that time deduced from the assumption that $t_{\text{boiling point } H_2O, 1atm} - t_{ice} = 100°C$. The experiments that were assessed were all gas thermometer measurements



The general agreement was 273.15 (some people fought for 273.155)

- When later it was decided on good grounds to use the water triple point ($t_{trp} - t_{ice} = 0.00996°c \approx 0.01°c$) the triple point was set at 273.16 K.
- Recent gasthermometry and total radion thermometry gave, starting from $T_{trp} = 273.16$ K $T_{BP} = 373.124$ K in stead of the expected 373.15 K which means that $t_{BP} - t_{ice}$ is now 99.974 K ($t_{BP} = 99.974°C$)

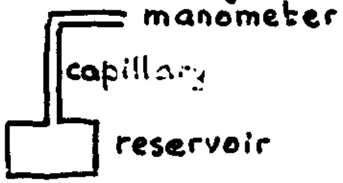
The right value for T_{ice} should have been 273.22 K !

Measurements of thermodynamic temperature

It is "difficult" and therefore mostly done in national standards laboratories

In our range of interest (1 K - 273 K) one uses:

1 Gas thermometer (constant volume, constant amount of gas)



ideally $pV = NRT$

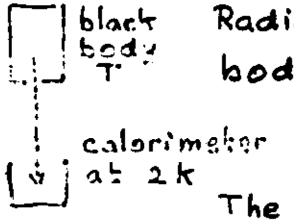
$$\frac{p}{p_{ref}} = \frac{T}{T_{ref}} \Rightarrow T = \frac{p}{p_{ref}} T_{ref}$$

Ideally $T_{ref} = T_{tr.p.H_2O}$, but in practice one chooses a T_{ref} in the temp. range of interest.

Problems:
1 non-ideality of gas
2 adsorption of gas
3 gas in capillary and manometer
4 pressure in cell differs from that in manometer

3 and 4 can be solved by measuring the pressure directly in the reservoir (low temp. pressure transducer)

2 Total radiation thermometer



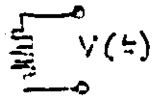
Radiative energy coming from black body: $U = \sigma T^4$

$$\sigma = \frac{2\pi^5 k^4}{15 c^2 h^3} \approx 5.67 \frac{W}{m^2 K^4}$$

The radiation is collected in low temp

Measurements of therm. temperature (cont.)

3 Thermal noise thermometer

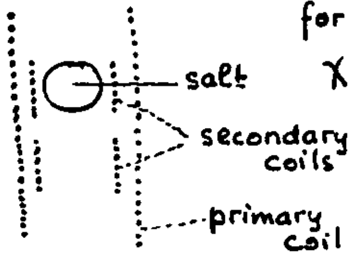


$$\langle V(t)\rangle = 0$$
$$\langle V(t)^2\rangle = 4kTR\,\Delta\nu$$

Used at 84 K and 4 K and below and sometimes at higher temperatures. At very low temperature down to 1 mK, superconductive amplifiers are used for measuring the low voltages. Long measuring times are required for averaging

We can include here two types of semi-thermodynamic thermometers:

Magnetic thermometer makes use of Curie-law for a paramagnetic salt



$$\chi = C/T$$

due to several factors:

non-ideality of salt

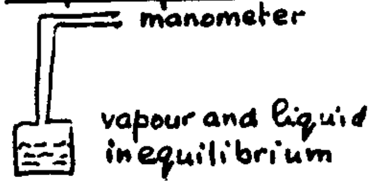
filling factor of coils etc

the thermometer is not really thermodynamic

Mutual inductance

$$M = A + \frac{BC}{T}$$

Vapour pressure thermometers



^3He	0.5 K	– 3.3 K
^4He	1.5	– 5
H_2	14	– 20
Ne	25	– 27
N_2	63	– 77
O_2	54	– 90

Thermodynamics gives shape of the vapour pressure vs T curve

2 The International Temperature Scale of 1990

ITS-90

The question is, of course, how to get from these fundamental temp. measurements to reliable temp. measurements in science and industry

Fundamental temp. measurements

calibrated:

1 Pt resistance thermometers — 273.16 K … 24.5561 K tr. point of Ne; 13.8033 K tr. point of e-H_2

2 RhFe resistance thermometers — 24.5561 K … 0.65

3 ^4He, ^3He vapour pressure thermometers — 4.2221 K … 0.65

4 temperatures of reference points (triple points of Hg (234.315 K), Ar (83.8058 K) O_2 (54.3584 K), Ne (24.5561 K) e-H_2 (13.8033 K)

5 Superconductive transition temperatures

of Pb	7.1999 K	Zn	0.851 K
In	3.4145	Cd	0.519 K
Al	1.1796		

The International Temperature Scale of 1990 gives:

1 A detailed prescription how to calibrate standard platinum resistance thermometers down to 13.8033 K

2 Describes interpolation gas thermometer 24.5561 – ~4.2 K

3 ^4He and ^3He vapour pressure equations

The ITS-90

Defining fixed points

T_{90}/K	$t_{90}/°C$	Substance	State
3 to 5	-270.15 to -268.15	He	V
13.8033	-259.3467	$e\text{-}H_2$	T
≈ 17	≈ -256.15	$e\text{-}H_2$ (or He)	V (or G)
≈ 20.3	≈ -252.85	$e\text{-}H_2$ (or He)	V (or G)
24.5561	-248.5939	Ne	T
54.3584	-218.7916	O_2	T
83.8058	-189.3442	Ar	T
234.3156	- 38.8344	Hg	T
273.16	0.01	H_2O	T
302.9146	29.7646	Ga	M
429.7485	156.5985	In	F
505.078	231.928	Sn	F
692.677	419.527	Zn	F
933.473	660.323	Al	F
1234.93	961.78	Ag	F
1337.33	1064.18	Au	F
1357.77	1084.62	Cu	F

interpolating gas therm.

Platinum resistance thermometer

All substances except ^3He are of natural isotopic composition

$e\text{-}H_2$ is hydrogen at equilibrium concentration of ortho and para forms

V = vapour pressure point ; T = triple point

G = gas thermometer point ; M, F = melting, freezing point at 101 325 Pa

0.65 K – 3.2 K ^3He vapour pressure – T_{90} equation

1.25 K – 5.0 K ^4He " " – T_{90} "

The International Temperature Scale of 1990 (ITS-90) cont.

The national standards laboratories provide to users who need accurate temperature determinations, or to manufacturers of thermometers, thermometers calibrated on ITS-90, i.e:

For the range 13.033 K – 273.15 K
calibrated against a standard Pt resistance thermometer

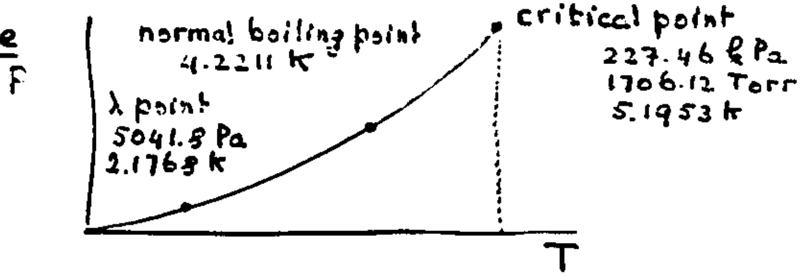
For the range ~4 K – 24.5561 K
calibrated against an interpolating gas-thermometer

For the range below 4 K
calibrated against ^4He or ^3He vapour pressure

3 Thermometers

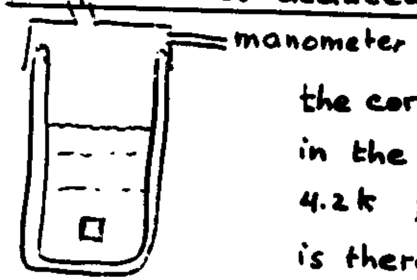
1 Vapour pressure thermometers

^4He



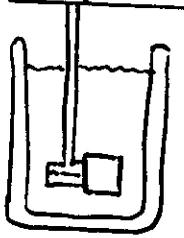
at 4.2 K extremely sensitive $\frac{dp}{dT} \approx \frac{0.7\,\text{Torr}}{\text{mK}} \approx \frac{100\,\text{Pa}}{\text{mK}} \approx \frac{0.1\%}{\text{mK}}$

Temperatures deduced from bath pressure



the correction for hydrostatic head in the liquid is ~ 1 mK per 7cm at 4.2K ; 1 mK per cm at 2.2K (but is there not, in general, realized) and zero below T_λ

Temperatures deduced using vapour pressure bulb

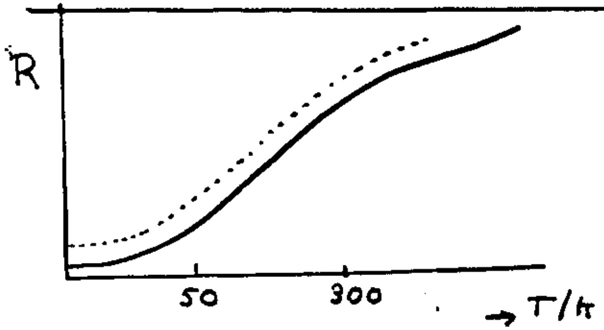


this method gives more reliable results but one has to avoid "cold spots" (which would give a too low pressure) and heat influx

No measurable effect of magnetic fields

^3He Similar to ^4He. Only vapour pressure bulb
No λ transition (except at mK temperatures)
Even more sensitive

Platinum resistance thermometers

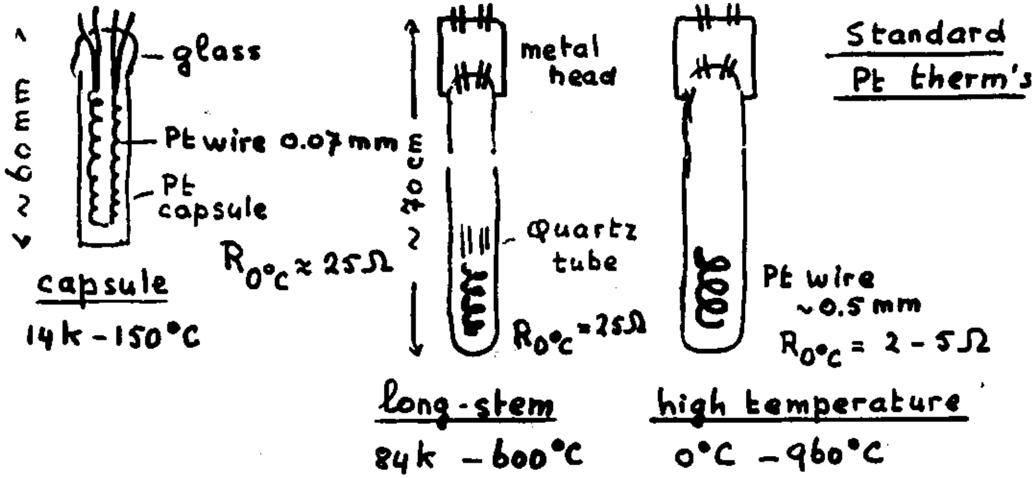


The resistance increases approx. proportional with T . . $\alpha = \frac{1}{R}\frac{dR}{dT} \approx 0.004/\text{K}$ but flattens of below ~ 50 K

According to Matthiessen's Law $R = R_{ideal}^{(T)} + \Delta R$
For good Pt thermometers $R_{4K}/R_{273K} \leqslant 500 \cdot 10^{-6}$

Types of Pt-thermometers

Standard Pt therm's



Expensive ($ 2000 - $ 4000); delicate (0.1 mK/...knock:
highly stable 0.1 mK ; low resistance

Laboratory (industrial) Pt thermometers

Cheap ($ 30) ; not delicate ; stability "± 10 mK at 77K".
resistances up to 1000 Ω at 0°C ; small sizes are available

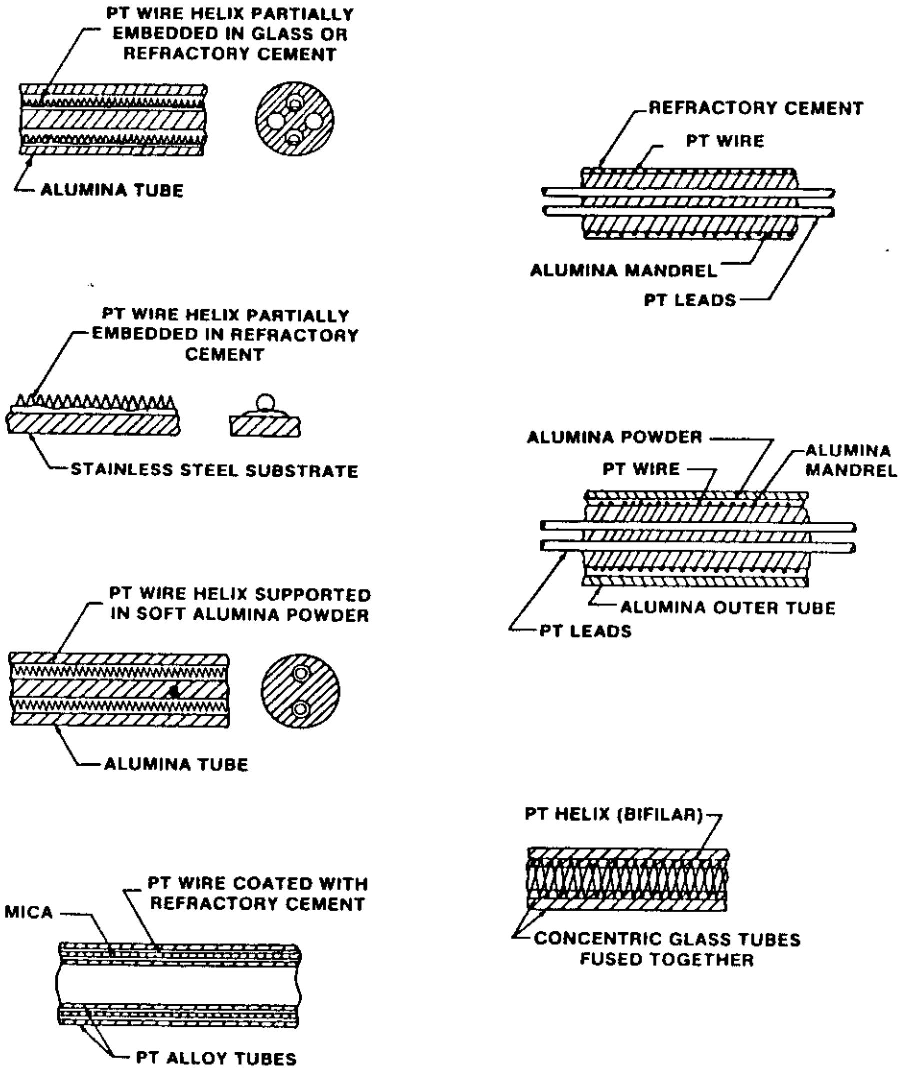


Fig. 16.1: (a) Fabrication of IPRTs: wire-wound;

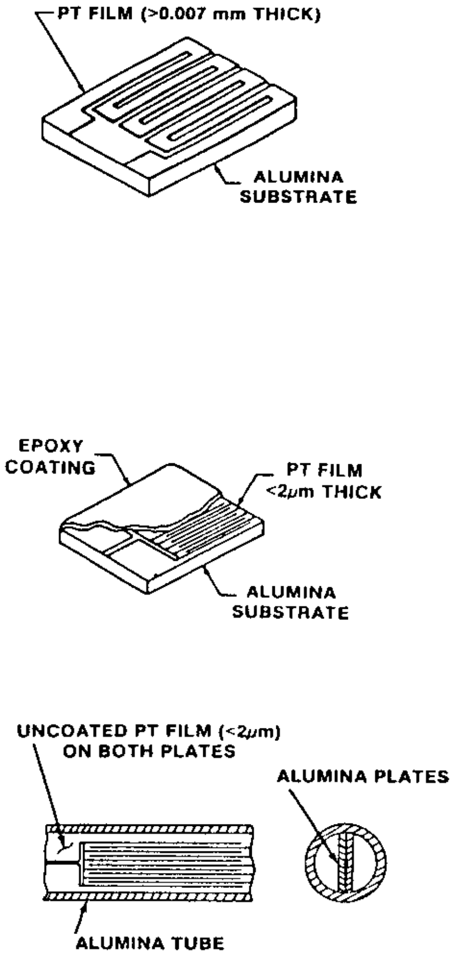


Fig. 16.1: (b) Fabrication of IPRTs: thick film [Curtis (1982)].

RhFe (rhodium with 0.03% iron) resistance thermometers

Especially used below 30K (down to 0.5K) where the Pt resistance thermometer looses sensitivity

R approximately linear in T between 0.5K and 30K ; above 30K behaviour like pure metal (platinum) (see p 10)

standand RhFe-therm (capsule type like Pt) highly stable (0.1 mK), delicate and expensive

Smaller types also thin film RhFe therm's are available which are in general less stable

Germanium (doped) resistance thermometers

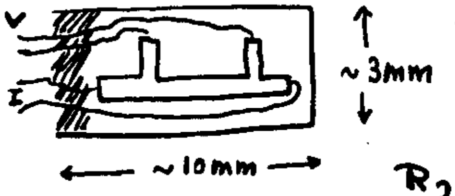
These are semiconductors : R increases with decreasing temperature.

Very useful below 30K (100K) as laboratory standards and as practical thermometers

Sometimes specified according to their resistance at 4.2K (Ge 1000, Ge 200 .... Ge 30)

High resistance (compared to Pt and RhFe); high sensitivity

Mostly as "dead horse" encapsulated units



copper capsule filled with ^{4}He or ^{3}He gas although most of the heat contact comes through leads

$R_{2\text{-points}} \neq R_{4\text{-points}}$

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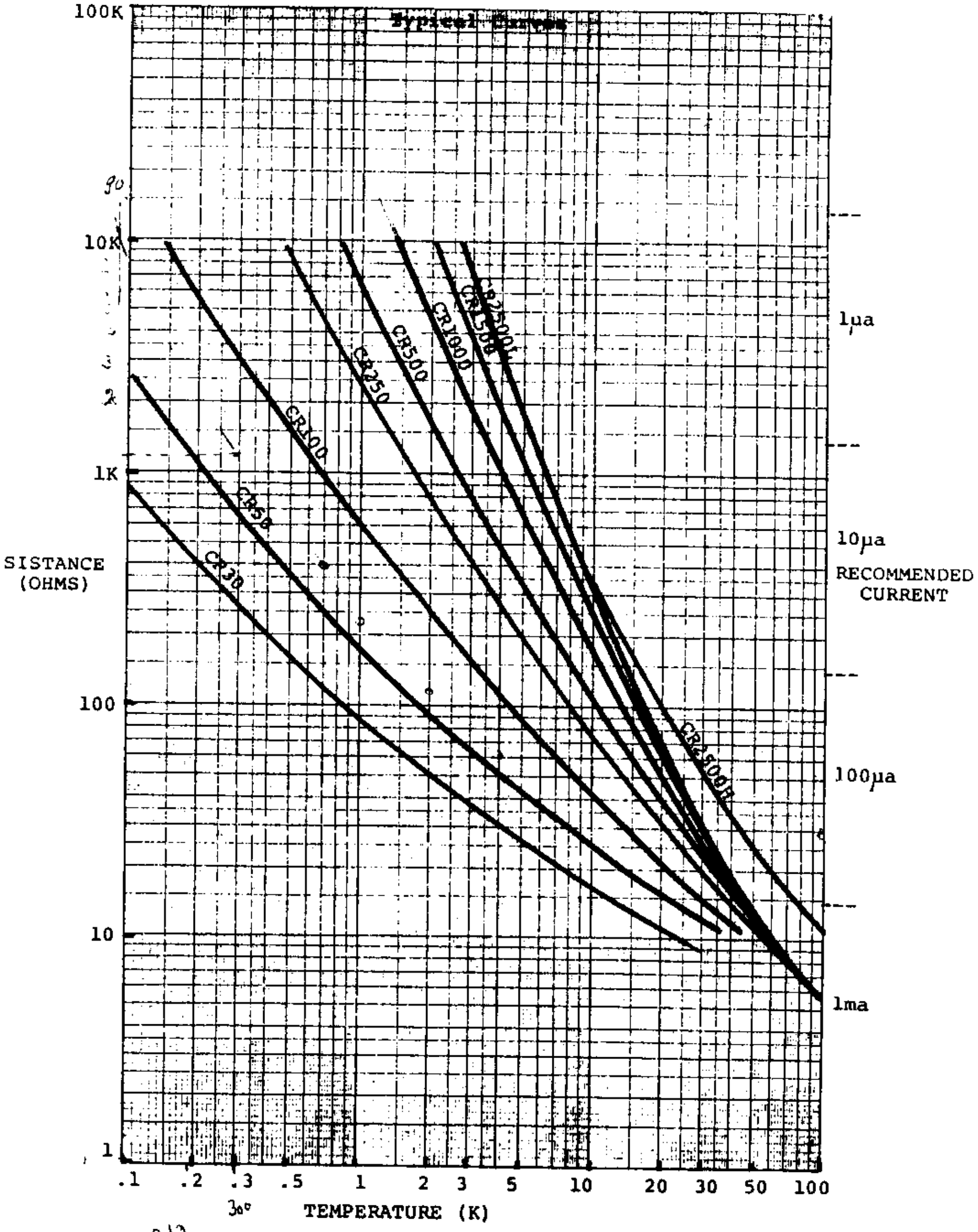
CRYO RESISTOR GERMANIUM SENSORS
TEMPERATURE vs RESISTANCE



Carbon resistance thermometers

Conduction believed to be by hopping of electron over energy barriers (hopping between grains. Resistance increases exponentially towards lower temperatures.

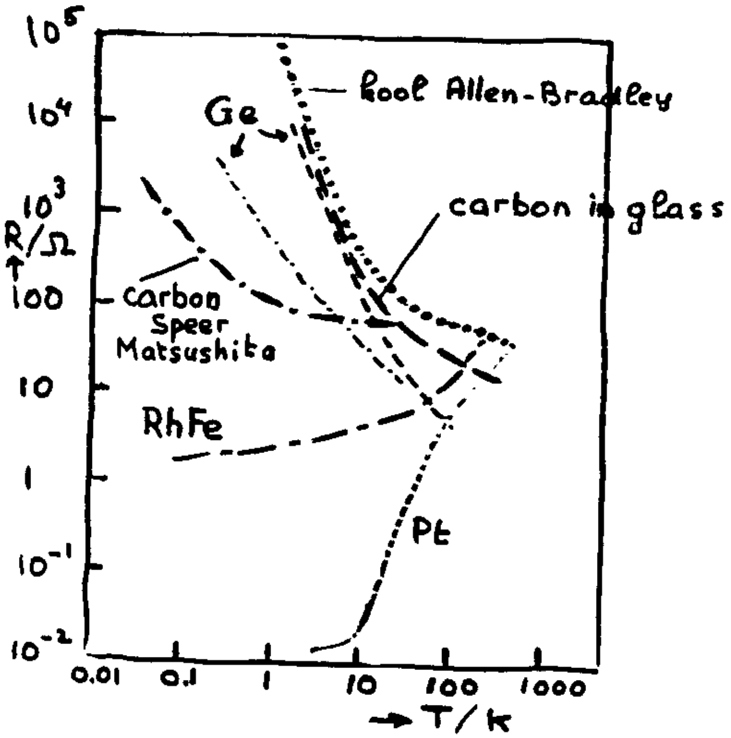
ommercial "radio resistors"

Allen Bradley ~1 K – 100 K cheap and sensitive stability on thermal cycling to 300 K may be problem; sometimes to overcome by repeated calibration at one temp to determine ΔR, the change in the calibration, at this temperature and assuming ΔR/R to be independent of T

Matsushita < 1 K where Allen Bradley's resistances become very high

Carbon-in-glass

Prepared by heating porous glass with organic liquid in the pores. The remaining carbon particles are now fixed in the holes. This, and encapsulation (like for Ge thermometers) considerably improves stability of calibration



Electrical resistance of some typical thermometers

Pt Standard Pt resistance therm. $R_{0°C} \approx 25\,\Omega$ (Industrial Pt therm. with $R_{0°C}$ up to 1000 Ω are available but sensitity remains low below ~20 K)

Pt and RhFe standard therm's are highly stable

Smaller and metal film RhFe therm's are available

Ge Germanium resistance thermometer

Different types of carbon therm's are indicated carbon-in-glass is more stable

17. Thermistors

The term thermistor refers to semiconducting ceramic materials, generally oxides, acting as sensing elements of devices for measuring temperature. A very extensive literature is available on this subject: especially valuable is a book by Sachse (1975), and many papers in Temperature, Its Measurement and Control in Science and Industry, Vol. 4 (1972) and Vol. 5 (1982).

It is difficult to discuss thermistors within the framework of this document; their characteristics are much more device-dependent than those of other thermometers, so their properties must be related to specific commercial devices and a general description cannot be given in terms of materials, at least for a moderately high level of accuracy. On the other hand, the thermistor is very widely used and may show a stability comparable with that of an IPRT.

The range of use of each particular thermistor is narrow since the resistance/temperature relationship is exponential of the form

$$R = R_0 \exp[-b((1/T) - (1/T_0))] \qquad (17.1)$$

where R_0 is the zero-power resistance (typically between 2 and 30 kΩ) of the thermistor at some reference temperature T_0 (kelvins), frequently 298 K (zero power resistance is the resistance when the current is low enough to produce negligibly small self-heating). The constant b is such that R changes about 4 percent per kelvin. Therefore a suitable type of thermistor must be chosen for each specific application.

Although thermistors can be used at very low temperatures (liquid helium [Schlosser and Munnings (1972)]) and at high temperatures (above 500 °C [Sachse (1975)]), the main area of application is between about -80 °C and 250 °C. They may be considered as secondary thermometers (accurate to within 50 mK to 5 mK) only in an even narrower range, between 0 °C and 100 °C. The following discussion is restricted to this latter range.

Both disk and bead types can have this quality when they are glass-coated to limit the deleterious effect of moisture. Apart from the effect of moisture on the thermistor itself, the probe where the thermistor is usually mounted can also be moisture-sensitive; for example, moisture can cause shunting between the connecting leads.

Interchangeability of thermistors can be within 50 mK, especially with disk types because the larger sensing element more easily allows constancy in the unit-to-unit distribution of materials in the mixture of oxides.

Stability on thermal cycling is the main guide to thermometer quality. Several studies [LaMers et al. (1982), Wood et al. (1978), Edwards (1983), Mangum (1986)] reveal a large variety of behaviours. As with germanium thermometers, it is difficult to express a general rule on stability or even on drift trends. In the most extensive of these studies, Wood et al. (1978) present a large number of figures that show the aging of a large variety of thermistors at various temperatures. The reader is referred to these figures for the details. Some types from two manufacturers appear to show a stability better than 10 mK/year.

Mangum (1986) found the bead-in-glass thermistors to be much more stable than the disk type. During about 4000 h aging at 100 °C, 11 of 12 bead-type thermistors were stable to within 5 mK but 10 of 11 disk-type thermistors changed several tenths of a degree. The bead-type sensors became much less stable if subjected to heating at 300 °C. When they were thermally cycled to 150 °C, about 30% of a sample of 20 changed by 50 to 250 mK. Mangum found no significant differences between the products of various manufacturers.

Moderately large calibration changes due to drift are reported [Code (1985)] to be retrievable by a single-point recalibration, since the whole characteristic shifts by the same amount in the whole temperature range.

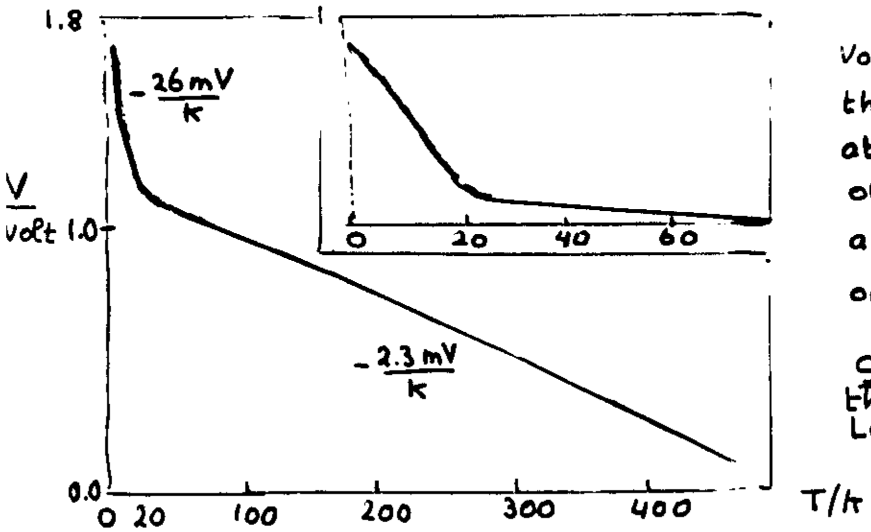
Since the sensing element is generally mounted in a stem, the self-heating effect, dynamic response, and immersion error are determined essentially by the stem; therefore the magnitudes of these are common to those of other types of thermometers used in the same temperature range, such as IPRTs (see Section 16.3).

Interpolation equations of the exponential type, with two or more exponential terms, or the following inverse equation:

$$T^{-1} = A + B \ln R + C (\ln R)^3 \qquad (17.2)$$

can be used for approximation of the thermistor R-T characteristics within a few millikelvins over several tens of kelvins [Sapoff et al. (1982), Steinhart and Hart (1968)].

Diode thermometers



Voltage over the diode at a current of 10 μA as a function of T

Si-diode thermometer Lake Shore

These are not resistance thermometers, because the voltage over the diode is not proportional to the current

Very sensitive and in large temperature range linear in T. Much used in commercial and laboratory applications

Stability:

Lake Shore: repeatability over last 4 cycles has to be better than ± 50 mK at 4.2 K' for device acceptance

Bedford: No general statement can be made regarding the stability of diode therm's; selected ones can be as stable as 0.01 K but much larger instabilities can occur unpredictably

GaAs diode thermometers have lower magnetic field dependence. Repeatability typically ± 10 mK

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14. Diode Thermometers

Diodes can be used above room temperature (e.g. in clinical thermometry) but not with sufficiently-high accuracy to be considered in this monograph. There is an extensive literature on semiconducting diodes with possible application as cryogenic thermometers [e.g. Swartz and Swartz (1974), Lengerer (1974), and Rubin and Brandt (1982)] but only two types intended for use as thermometers are commercially available: GaAs and Si. The temperature-indicating parameter is the forward-biased junction voltage, which decreases approximately linearly with increasing temperature when the current is kept constant.

Because of their almost trivial cost, silicon diodes mass-produced for the electronics industry have been widely tested as thermometers. They would have particular appeal in large engineering projects requiring hundreds of sensors. It turns out, however, to be very costly to select the very small percentage that are adequate for thermometric use. The following discussion does not apply to these devices, but to diodes that are manufactured for specific use as thermometers. There are some specific drawbacks to diode thermometers:

a) The typical I-V characteristic is such as to make the internal impedance of the device very high (easily greater than 100 kΩ) at small currents; or else - using a larger current - one encounters unacceptably high power dissipation at low temperatures.

b) There is a transition region in the conduction mechanism around 20 K that makes fitting a V-T characteristic over the whole temperature range difficult for GaAs and impossible for Si (Figs. 14.1 and 14.2).

For GaAs the least-squares fitted equation [Pavese (1974)]

$$V = \sum_{i=0}^{7} A_i (\ln T')^i \quad , \qquad (14.1)$$

(where $T' = (T/T_1) + 1$) fits to within about ± 0.1 K (~ ± 100 parts per million in voltage) from 4 K to 300 K. For higher accuracy, the range is subdivided into two sections with the junction near 90 K. An effective equation for the two-range fitting is [Swartz and Gaines (1972)]:

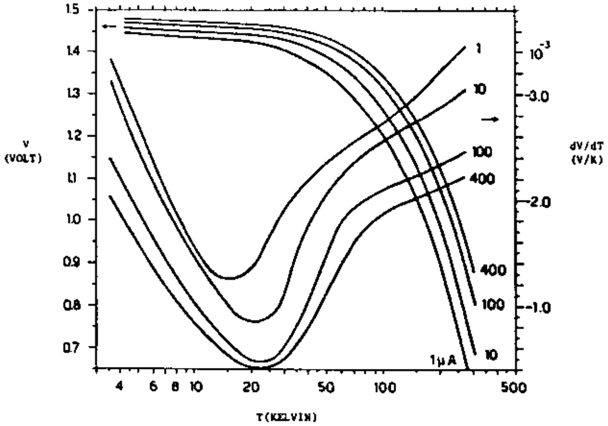


Fig. 14.1: Voltage and sensitivity of a gallium arsenide diode as a function of temperature and current (labels on curves) [after Pavese and Limbarinu (1972)].

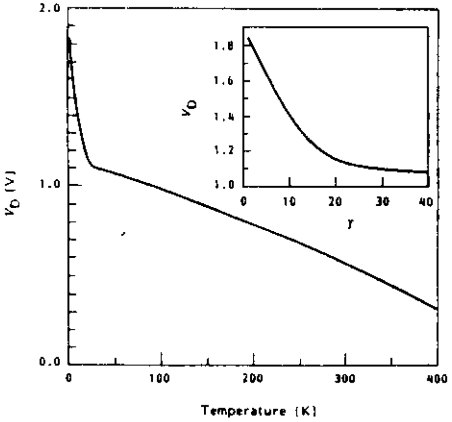
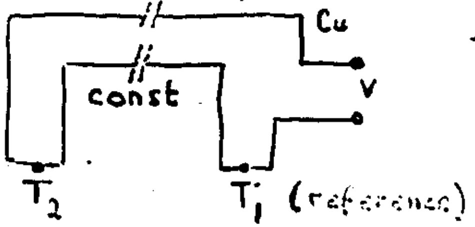


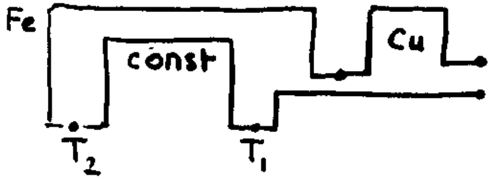
Fig. 14.2: Forward biased voltage of a silicon diode as a function of temperature. The lower temperature region is shown to larger scale in the inset [Lanchester (1989)].

Thermocouples



copper-constantan thermocouple

at room temp ~ 40µV/K



iron-constantan

at room temp ~ 50µV/K

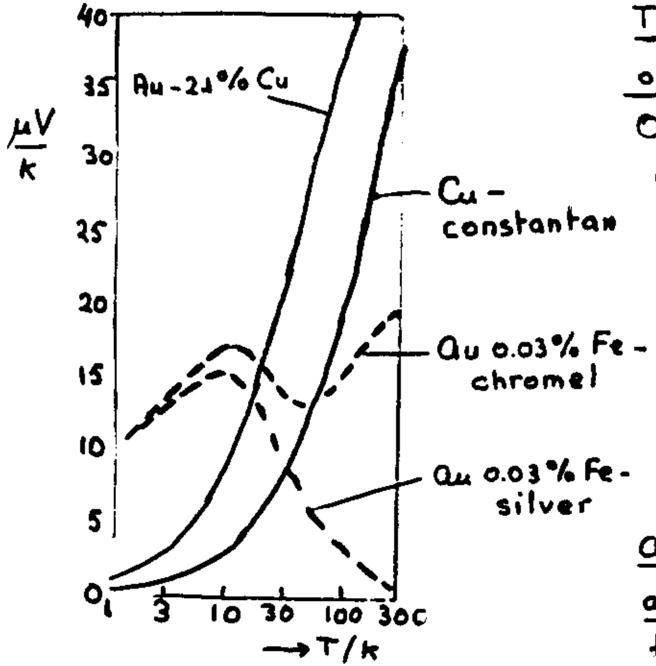
Thermocouples are cheap and fast, in particular useful for measuring temperature differences

Above say 600°C the only practical thermometers

Types of thermocouples

	range	stability	thermopower 273 K
Pt 10%Rh - Pt	<1500°C	± 0.2 K	10 µV/K
Pt 13%Rh - Pt	"	"	"
"Base metal"			
Type E NiCr - CuNi	< 800°C	± 1 K	60
J FeCu - Ni	< 800°C	± 1 K	60
K NiCr - NiAl	<1200°C	± 1 K	
T Cu - CuNi constantan	< 800 < 800°C	± 1 K	40
Fe - constantan	< 800°C	± 1 K	50

All these thermocouples loose sensitivity at low temperatures



Thermoelectic power of thermocouples

Ordinary thermocouples (Cu-constantan and Fe-constantan) which have sensitivities of ~40 $\mu V/k$ at room-temperatures, loose sensitivity at low temperatures

Au-Fe – chromel has at least 10 $\mu V/k$ down to 10 k

Compare these voltage sensitivities with those of platinum or germanium resistance therm's

Eg: Pt 100 Ω at 0°C at 100 k

$R \approx 30\,\Omega \qquad \frac{dR}{dT} = 0.4\,\frac{\Omega}{k}$

with measuring current of 2 mA → $\frac{dV}{dT} = 0.8\,\frac{mV}{k}$

(this current will keep self-heating below a few mk)

Ge 1000 Ω at 4 k

$R \approx 1000\,\Omega \qquad \frac{dR}{dT} \approx 300\,\frac{\Omega}{k}$

with measuring current of 50 μA → $\frac{dV}{dT} = 1.5\,\frac{mV}{k}$

(self-heating for (0.25 μW) will be 1 mk or less)

With all thermocouples DC voltages must be measured which makes mk-work impossible, but changes in temperature differences can be measured precisely (even within μk's)

Magnetic field effect given as errors in measured temperatures and repeatability (in zero field for various thermometers

	10 k		100 k		repeatability
	2.5 T	8 T	2.5 T	8 T	
Pt 100 Ω resistance	20 %	100 % (20 k)	0.04 %	0.4 %	±10 mk (77 k)
RhFe "	7	>10	0.1	0.9	"
Ge "	4-15	25-60	3-10	15-30	±0.8 mk 4 k ±2 mk 20 k
Carbon-in-glass "	0.5	2.3 (4 k)	0.05	0.05	±0.8 mk 4 k
Carbon "	1-5	5-20			
Silicon diode	10	30 (20 k)	0.2	0.5	±10 mk 4 k
GaAs "	2.9 0.2	3.8 (4 k) 0.2 (30 k)	0.1-0.2	0.5	"
Capacitance	<0.01	<0.01	<0.01	<0.01	± 1 k or more
Thermocouples:					
Chromel-constantan	1	3	<1	<1	0.1 k
Chromel-AuFe (0.07%)	3	20	0.1	0.8	0.1 k
RuO$_2$ resistance	?				

Standard Pt resistance thermometers have a repeatability from $\overset{0.1}{0.2}$ mk (273 k ~ 24 k) to ~ 0.3 mk at 14 k

Standard RhFe: 0.1 mk 0.5 k - 30 k

Note that a repeatability of ±10 mk at 77 k for "industrial" Pt thermometers could mean ±30 mk at 20 k

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Reference Section

Lake Shore Catalog

Typical Magnetic Field-Dependent Temperature Errors for for Selected Cryogenic Temperature Sensors $\Delta T/T(\%)$ at ß (magnetic field)

Sensor Type	T(K)	ß (tesla units)				Comments
		2.5	8	14	19	
Carbon Glass Resistors	4.2	-0.5	-2.3	-4.9	-6.6	*Negative ΔR/R when T ≥ 60K.* *Good reproducibility.* *Reduced sensitivity above 100K.* *Errors negative below 20K.*
	10	-0.2	-1.1	-2.6	-3.8	
	25	0.02	0.22	0.54	0.79	
	45	0.07	0.48	1.32	2.16	
	88	0.05	0.45	1.32	2.30	
	306	<0.01	0.22	0.62	1.14	
Platinum Resistors	20	20	100	250	---	*Recommended for use when T ≥ 30K.*
	40	0.5	3	6	8.84	
	87	0.04	0.4	1	1.74	
	300	<0.01	0.02	0.07	0.13	
Rhodium-Iron Resistors	4.2	11	40 (6 tesla)	---	---	*Not recommended for use below 77K in magnetic fields.*
	40	1.5	12	30	46.76	
	87	0.2	1.5	4	6	
	300	<0.01	0.1	0.4	---	
CS-401	2.2	<0.02	<0.02	0.02	---	*Probably zero field-induced temperature error. Recommended for control purposes.*
	4.2	<0.01	<0.01	0.01	---	
(SrTiO$_3$) Capacitors	88	<0.01	<0.01	<0.01	≤0.01	
	190	<0.01	<0.01	<0.01	≤0.01	
	300	---	---	---	---	
CS-501 (multilayer ceramic element Capacitors	ΔT/T(%) < 0.15 at 4.2K and 18.7 tesla. ΔT/T(%) <0.05 at 77K and 305K and 18.7 tesla.					*Recommended for control purposes.* *Monotonic in C vs. T to nearly room temperature.*
Germanium Resistors	2.0	-8	-60	---	---	*Not recommended except at low "ß" owing to large, orientation-dependent temperature effect.*
	4.2	-5 to -20	-30 to -55	-60 to -75	---	
	10	-4 to -15	-25 to -60	-60 to -75	---	
	20	-3 to -20	-15 to -35	-50 to -80	---	
Chromel-AuFe (0.07%) Thermocouples	10	3	20	30	---	*Data taken with entire thermocouple in field, cold junction at 4.2K, errors in hot junction temperature.*
	45	1	5	7	---	
	100	0.1	0.8	---	---	
Type E (Chromel-CuNi) Thermocouples	10	1	3	7	---	*Useful when T ≥ 10K.* *Refer to comments for Chromel-AuFe (0.07%)*
	20	<1	2	4	---	
	45	<1	<1	2	---	

Table 33. L. G. Rubin, B. L. Brandt and H. H. Sample, some Practical Solutions to Measurement Problems Encountered at Low Temperatures and High Magnetic Fields, Advances in Cryogenic Engineering, Vol. 31, Plenum Press, New York (1986), p. 1221.

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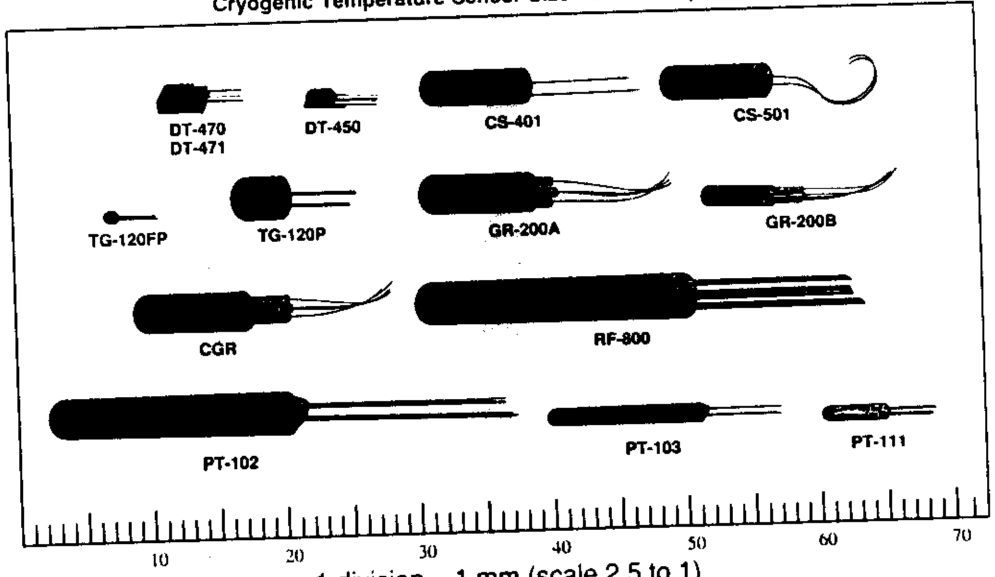
Typical Magnetic Field-Dependent Temperature Errors for Diode Temperature Sensors $\Delta T/T(\%)$ at ß (magnetic field)

Sensor Type	T(K)	ß (tesla units)					Comments
		1	2	3	4	5	
GaAlAs Diodes	4.2	2.9	3.8	3.7	2.8	1	*Shown with junction perpendicular to applied field H. (When junction is parallel to H, induced errors are typically less than, or on the order of, those shown.)*
	30	0.2	0.2	0.3	0.3	0.2	
	78	< 0.1	< 0.1	0.17	0.16	0.1	
	300	≤ 0.1	< 0.1	< 0.1	< 0.1	< 0.1	
Silicon Diodes	4.2	-200	-300	-350	-400	-500	*Strongly orientation dependent.* *Junction parallel to field.*
	20	-10	-20	-25	-30	-40	
	40	-4	-6	-8	-10	-12	
	60	-0.5	-1	-2	-3	-3.5	
	80	< 0.1	-0.5	-0.8	-1.1	-1.5	
	300	< -0.1	<-0.1	<-0.1	<-0.1	<-0.1	
Silicon Diodes	4.2	-8	-9	-11	-15	-20	*Junction perpendicular to field.*
	20	-4	-5	-5	-0.5	10	
	40	1.5	-3	-4	-5	-5.5	
	60	-0.5	-0.7	-0.8	-1	-1.1	
	80	-0.1	-0.3	-0.5	-0.6	-0.7	
	300	< 0.1	0.2	0.5	0.6	0.6	

Table 34.

Cryogenic Temperature Sensor Size Relationship Scale



1 division = 1 mm (scale 2.5 to 1)

Figure 28.

Cryogenic Temperature Sensor Characteristics

Sensor Type	Useful Temperature Range (K)	Reproductivity (+/- value)	Sensitivity (Typical)	Accuracy[note1] (+/- value)	Use in Magnetic Field
Silicon Diodes DT-470 DT-471 DT-450	 1.4 to 475 10 to 425 1.4 to 325	10mK at 4.2K	30 mV/K at 4.2K 2.4mV/K at 300K 2.2mV/K at 475K	20mK <10K 50mK to 340K 0.1K > 300K	Relatively low magnetic field dependence for $T > 60K$ and $\beta < 5$ tesla.
GaAlAs Diodes TG-120	1.4 to 325	10mK at 4.2K	180mV/K at 4.2K 100mV/K at 20K	50mK	Relatively low magnetic field dependence $\Delta T/T(\%) \le 4\%$ for $\beta \le 5$ tesla and $T \ge 4.2K$
Platinum Resistance Thermometer PT-102 PT-103 PT-111	 14 to 873 14 to 873 14 to 673	10mK at 77K	0.084 ohms/K at 20K 0.414 ohms/K at 70K 0.388 ohms/K at 300K	20mK at 20K 35mK at 300K 0.1K (340 to 480K) 0.2K > 480K	Moderately orientation-dependent. Suggested use only when $T \ge 30K$.
Rhodium-Iron Resistor RF-800	1 to 500	10mK < 400K	0.1 ohms/K < 4.2K & > 100K	35mK (20K to 300K) 0.1K (340K to 480K) 0.2K > 480K	Moderate magnetic field dependence from 77K to 500K.
Carbon-Glass Resistor CGR-1 series	1.4 to 325	0.75mK at 4.2K	706.6 ohms/K at 4.2K 0.092 ohms/K at 100K (CGR-1-1000)	5mK < 10K 20mK at 20K 55mK at 50K	$\Delta R/Ro$ positive and monotonic in β field and T. Useful to 300K.
Germanium Resisors GR-200 series	0.05 to 100	0.5mK at 4.2K	66.803 ohms/K at 1.4K 595.2 ohms/K at 4.2K (GR-200A-1000)	5mK < 10K 15mK at 20 K 35mK at 50 K	Not recommended except at low β due to large, orientation-dependent temperature effect.
Capacitance Sensors CS-401 CS-501	1 to 60 (80 to 300) 1 to 290	Very stable when used as control element in magnetic field	26pf/K at 4.2K (CS-501)	Recommended for use as a transfer control element, not for absolute measurements	Probably zero field-induced temperature error. Recommended for control purposes.
Thermocouples Type K (Chromel-CuAl) Type E (Chromel-CuNi) Type T (Cu-CuNi) Chromel-AuFe (0.07%) Chromel-AuFe (0.03%) Chromel-CuFe (0.15%)	 3 to 575[note 4] 3 to 475 3 to 575 1.4 to 325 4 to 325 4 to 300	 20mK at 77K 20mK at 77K 20mK at 77K	(K)4.1μV/K at 20K (E)8.5μV/K at 20K (T)4.6μV/K at 20K 15μV/K > 10K 15μV/K > 10K 15μV/K > 10K (or higher)	2.2K (73K to 273K)[note 2] 1.7K (73K to 273K) 1.0K (73K to 273K) see note 3 see note 3 2.0K	Generally difficult to use as low temperature thermometers in the presence of magnetic field. AuFe combination strongly field dependent for $T \le 20K$. (Field dependence can vary for specimens from the same spool.) Type E thermocouples useful in magnetic field when $T \ge 10K$

Table 35.

1 Typical Accuracy of Lake Shore calibrations

2 Limits of error ASTM E230 for standardized thermocouple types

3 Refer to Sparks, L.L., and Powell, R.I. (1973) "Low Temperature Thermocouples KP Normal Silver, Copper vs Au-0.02 at %Fe and Au-0.07 at %Fe." J. Res. Natl. Bur. Std 76A, 263-283.

4 Range of use with Lake Shore instruments

Composite Range of Use for Cryogenic Temperature Sensors With Lake Shore Instruments

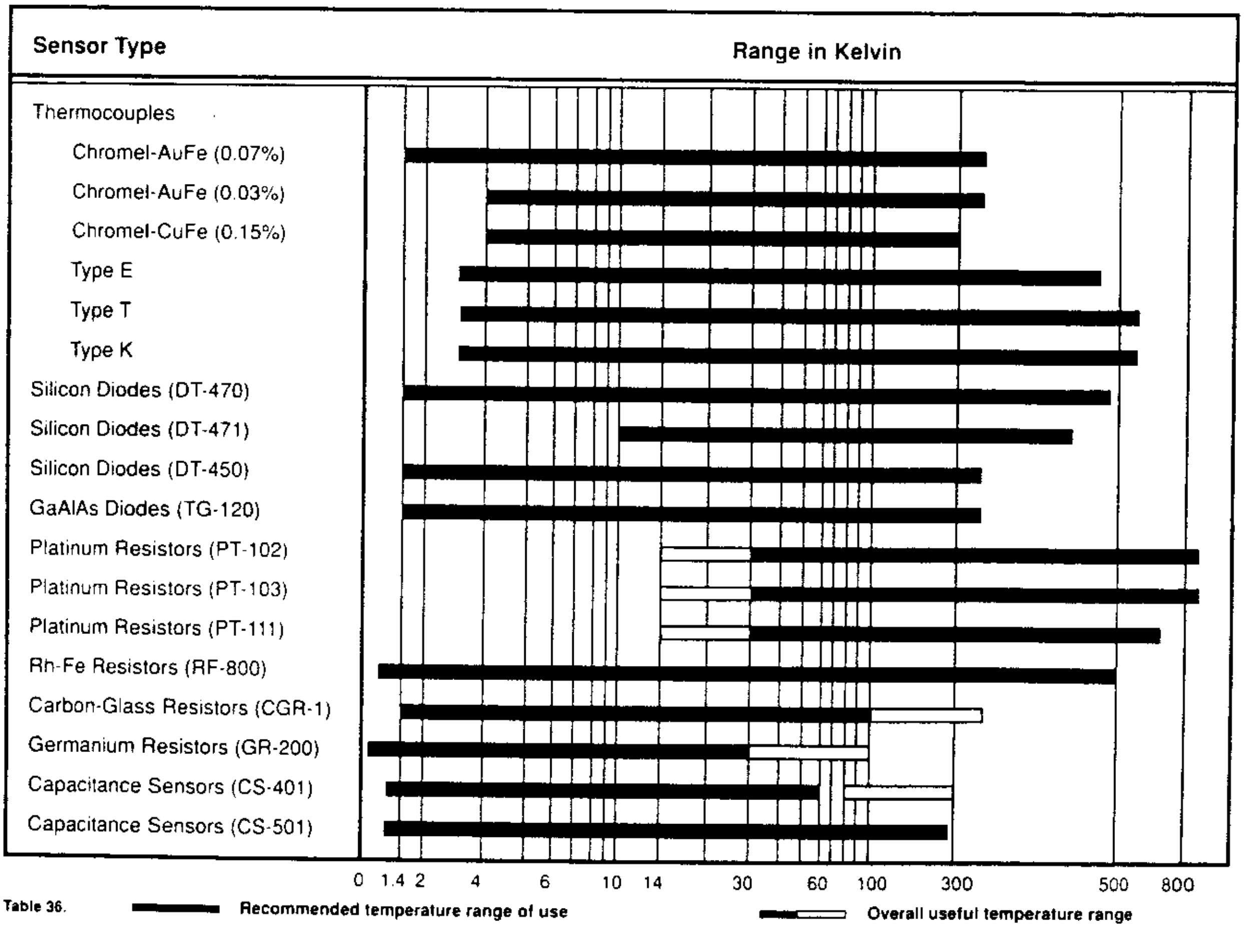
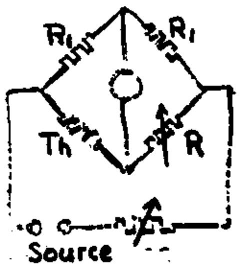


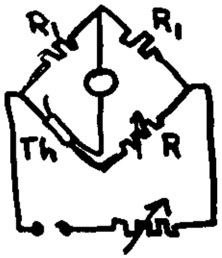
Table 36.

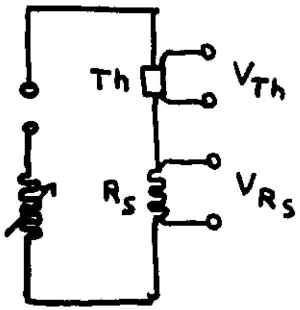
Measuring methods and equipment

We will restrict ourselves to the measurement of resistances of resistance thermometers.
In general electrical resistances can relatively easily be measured with high accuracy

2 - 3 and 4 leads. measurements







Wheatstone Bridge
$R_{Th} = R$

2-leads 3-leads

Potentiometric
$$R_{Th} = \frac{V_{Th}}{V_{R_s}} \cdot R_s$$
4-leads

Only in the 4 leads measurements the resistance of the leads do not play a role. This is important for low resistance thermometers where the lead resistances are not small compared to the thermometer resistance
Also important for Ge-thermometers

In the potentiometric method the current has to be kept constant during the meas. of V_{Th} and V_{R_s}
One can use either a DC or an AC source; in case of DC the measurement should be repeated after current reversal in order to cancel the effects of spurious thermal EMF's.

Most standards laboratories use for highest accuracy resistance measurements of low resistance Pt and RhFe thermometers hand operated DC potentiometers (Guildline accuracy 1 in 10^6

Automatic AC-potentiometers are available with similar accuracy

Special purpose AC-potentiometers with very low current through the thermometer (to avoid selfheating) are available especially for very low T

More expensive digital meters have provisions for 4-leads resistance meausements; but self-heating of several mK's can occur if the measuring current is not low enough.

A simple Wheatstone bridge (self-made) with a lock-in amplifier as detector is often useful

For 4-leads measurements the circuit given before can simply be made with either DC or AC and a mV, µV or nV meter.

Self heating of resistance thermometers by the measuring current depend much on model of sensor and temperature. Most manufacturers give data.
Even better determine it yourself
Eg small 100Ω Pt therm.(ceramic) down to 20K ~ 0.2°C/mW
which means that 2 mA give (in 2.5 Ω) 2 mK self-heating

References

- The only general book on temperature measurements as far as I know is
  T.J. Quinn Temperature Academic Press (London) 1983 (A new Edition adopted to ITS-90 is in preparation) Emphasis is on standard thermometry
- Useful information in Chapter Thermometry in
  G.K. White Techniques in Low Temperatures Oxford Univ Press (1975 ?)
- The following guides have appeared from the Bureau International des Poids et Mesures
  - The International Temperature Scale of 1990 (ITS-90). also published in "Metrologia"
    Metrologia ... (1990) 1. , H. Preston-Thomas, The International Temperature Scale of 1990
  - Supplementary Information for the ITS-90 *
    (will appear shortly)
  - Techniques for approximating the ITS-90 *
    1st Edition July 1990 (R.E. Bedford et al)

  * will be updated every ~5 years
  books from BIPM may be available from your national standard lab or directly from BIPM, Pavillon de Breteuil, F 92310, Sèvres, France.
- Manufactures Catalogs, eg from Lake Shore Cryotronics, 64 East Walnut Str, Westerville, Ohio 43081-2399 US

THE INTERNATIONAL TEMPERATURE SCALE OF 1990
(ITS-90)

It should be noted that the official version of the scale is the French one. The English version, published for convenience, has been authorized by the Comité Consultatif de Thermométrie and approved by the Comité International des Poids et Mesures.

The International Temperature Scale of 1990 was adopted by the Comité International des Poids et Mesures at its meeting in 1989, in accordance with the request embodied in Resolution 7 of the 18th Conférence Générale des Poids et Mesures of 1987. This scale supersedes the International Practical Temperature Scale of 1968 (amended edition of 1975) and the 1976 Provisional 0,5 K to 30 K Temperature Scale.

1. Units of temperature

The unit of the fundamental physical quantity known as thermodynamic temperature, symbol T, is the kelvin, symbol K, defined as the fraction 1/273,16 of the thermodynamic temperature of the triple point of water (1).

Because of the way earlier temperature scales were defined, it remains common practice to express a temperature in terms of its difference from 273,15 K, the ice point. A thermodynamic temperature, T, expressed in this way is known as a Celsius temperature, symbol t, defined by:

$$t/{}^\circ\mathrm{C} = T/\mathrm{K} - 273{,}15. \qquad (1)$$

The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the kelvin. A difference of temperature may be expressed in kelvins or degrees Celsius.

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(1) Comptes Rendus des Séances de la Treizième Conférence Générale des Poids et Mesures (1967-1968), Resolutions 3 and 4, p. 104.

The International Temperature Scale of 1990 (ITS-90) defines both International Kelvin Temperatures, symbol T_{90}, and International Celsius Temperatures, symbol t_{90}. The relation between T_{90} and t_{90} is the same as that between T and t, i.e. :

$$t_{90}/{}^{\circ}\mathrm{C} = T_{90}/\mathrm{K} - 273{,}15. \tag{2}$$

The unit of the physical quantity T_{90} is the kelvin, symbol K, and the unit of the physical quantity t_{90} is the degree Celsius, symbol °C, as is the case for the thermodynamic temperature T and the Celsius temperature t.

2. Principles of the International Temperature Scale of 1990 (ITS-90)

The ITS-90 extends upwards from 0,65 K to the highest temperature practicably measurable in terms of the Planck radiation law using monochromatic radiation. The ITS-90 comprises a number of ranges and sub-ranges throughout each of which temperatures T_{90} are defined. Several of these ranges or sub-ranges overlap, and where such overlapping occurs, differing definitions of T_{90} exist : these differing definitions have equal status. For measurements of the very highest precision there may be detectable numerical differences between measurements made at the same temperature but in accordance with differing definitions. Similarly, even using one definition, at a temperature between defining fixed points two acceptable interpolating instruments (e.g. resistance thermometers) may give detectably differing numerical values of T_{90}. In virtually all cases these differences are of negligible practical importance and are at the minimum level consistent with a scale of no more than reasonable complexity : for further information on this point, *see* « Supplementary Information for the ITS-90 » *.

The ITS-90 has been constructed in such a way that, throughout its range, for any given temperature the numerical value of T_{90} is a close approximation to the numerical value of T according to best estimates at the time the scale was adopted. By comparison with direct measurements of thermodynamic temperatures, measurements of T_{90} are more easily made, are more precise and are highly reproducible.

There are significant numerical differences between the values of T_{90} and the corresponding values of T_{68} measured on the International Practical Temperature Scale of 1968 (IPTS-68), *see* Fig. 1 and Table VI. Similarly there were differences between the IPTS-68 and the International Practical Temperature Scale of 1948 (IPTS-48), and between the International Temperature Scale of 1948 (ITS-48) and the International Temperature Scale of 1927 (ITS-27). *See* the Appendix and, for more detailed information, « Supplementary Information for the ITS-90 ».

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* See Monography BIPM/1990.

3. Definition of the International Temperature Scale of 1990

Between 0,65 K and 5,0 K T_{90} is defined in terms of the vapour-pressure temperature relations of ^{3}He and ^{4}He.

Between 3,0 K and the triple point of neon (24,5561 K) T_{90} is defined by means of a helium gas thermometer calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13,8033 K) and the freezing point of silver (961,78 °C) T_{90} is defined by means of platinum resistance thermometers calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Above the freezing point of silver (961,78 °C) T_{90} is defined in terms of a defining fixed point and the Planck radiation law.

The defining fixed points of the ITS-90 are listed in Table I. The effects of pressure, arising from significant depths of immersion of the sensor or from other causes, on the temperature of most of these points are given in Table II.

3.1. From 0,65 K to 5,0 K : helium vapour-pressure temperature equations

In this range T_{90} is defined in terms of the vapour pressure p of ^{3}He and ^{4}He using equations of the form :

$$T_{90}/\mathrm{K} = A_0 + \sum_{i=1}^{9} A_i[(\ln(p/\mathrm{Pa}) - B)/C]^i. \tag{3}$$

The values of the constants A_0, A_i, B and C are given in Table III for ^{3}He in the range of 0,65 K to 3,2 K, and for ^{4}He in the ranges 1,25 K to 2,1768 K (the λ point) and 2,1768 K to 5,0 K.

3.2. From 3,0 K to the triple point of neon (24,5561 K) : gas thermometer

In this range T_{90} is defined in terms of a ^{3}He or a ^{4}He gas thermometer of the constant-volume type that has been calibrated at three temperatures. These are the triple point of neon (24,5561 K), the

Table I

Defining fixed points of the ITS-90

Number	Temperature		Substance^(a)	State^(b)	$W_r(T_{90})$
	T_{90}/K	t_{90}/°C			
1	3 to 5	− 270,15 to − 268,15	He	V	
2	13,803 3	− 259,346 7	e-H_2	T	0,001 190 07
3	≈ 17	≈ − 256,15	e-H_2 (or He)	V (or G)	
4	≈ 20,3	≈ − 252,85	e-H_2 (or He)	V (or G)	
5	24,556 1	− 248,593 9	Ne	T	0,008 449 74
6	54,358 4	− 218,791 6	O_2	T	0,091 718 04
7	83,805 8	− 189,344 2	Ar	T	0,215 859 75
8	234,315 6	− 38,834 4	Hg	T	0,844 142 11
9	273,16	0,01	H_2O	T	1,000 000 00
10	302,914 6	29,764 6	Ga	M	1,118 138 89
11	429,748 5	156,598 5	In	F	1,609 801 85
12	505,078	231,928	Sn	F	1,892 797 68
13	692,677	419,527	Zn	F	2,568 917 30
14	933,473	660,323	Al	F	3,376 008 60
15	1 234,93	961,78	Ag	F	4,286 420 53
16	1 337,33	1 064,18	Au	F	
17	1 357,77	1 084,62	Cu	F	

:
— All substances except ^{3}He are of natural isotopic composition ;
— e-H_2 is hydrogen at the equilibrium concentration of the ortho- and para-molecular forms.

:
— For advice on the realization of these various states, *see* « Supplementary Information for the ITS-90 ».
— Symbols have the following meanings : V : vapour pressure point ; T : triple point (temperature at which the solid, liquid and vapour phases in equilibrium) ; G : gas thermometer point ; M, F : melting point, freezing point (temperature, at a pressure of 101 325 Pa, at which the solid d liquid phases are in equilibrium).

Table II

Effect of pressure on the temperatures of some defining fixed points *

Substance	Assigned value of equilibrium temperature T_{90}/K	Temperature variation	
		with pressure p $(dT/dp)/(10^{-8}\text{K}\cdot\text{Pa}^{-1})$**	with depth h $(dT/dh)/(10^{-3}\text{K}\cdot\text{m}^{-1})$***
e-Hydrogen (T)	13,803 3	34	0,25
Neon (T)	24,556 1	16	1,9
Oxygen (T)	54,358 4	12	1,5
Argon (T)	83,805 8	25	3,3
Mercury (T)	234,315 6	5,4	7,1
Water (T)	273,16	− 7,5	− 0,73
Gallium	302,914 6	− 2,0	− 1,2
Indium	429,748 5	4,9	3,3
Tin	505,078	3,3	2,2
Zinc	692,677	4,3	2,7
Aluminium	933,473	7,0	1,6
Silver	1 234,93	6,0	5,4
Gold	1 337,33	6,1	10
Copper	1 357,77	3,3	2,6

* The reference pressure for melting and freezing points is the standard atmosphere (p_0 = 101 325 Pa). For triple points (T) the pressure effect is a consequence only of the hydrostatic head of liquid in the cell.

** Equivalent to millikelvins per standard atmosphere.

*** Equivalent to millikelvins per metre of liquid.

Table III

Values of the constants for the helium vapour pressure Eq. (3), and the temperature range for which each equation, identified by its set of constants, is valid

	^{3}He 0,65 K to 3,2 K	^{4}He 1,25 K to 2,1768 K	^{4}He 2,1768 K to 5,0 K
A_0	1,053 447	1,392 408	3,146 631
A_1	0,980 106	0,527 153	1,357 655
A_2	0,676 380	0,166 756	0,413 923
A_3	0,372 692	0,050 988	0,091 159
A_4	0,151 656	0,026 514	0,016 349
A_5	− 0,002 263	0,001 975	0,001 826
A_6	0,006 596	− 0,017 976	− 0,004 325
A_7	0,088 966	0,005 409	− 0,004 973
A_8	− 0,004 770	0,013 259	0
A_9	− 0,054 943	0	0
B	7,3	5,6	10,3

triple point of equilibrium hydrogen (13,8033 K), and a temperature between 3,0 K and 5,0 K. This last temperature is determined using a ^{3}He or a ^{4}He vapour pressure thermometer as specified in Sect. 3.1.

3.2.1. From 4,2 K to the triple point of neon (24,5561 K) with ^{4}He as the thermometric gas

In this range T_{90} is defined by the relation:

$$T_{90} = a + bp + cp^2, \tag{4}$$

where p is the pressure in the gas thermometer and a, b and c are coefficients the numerical values of which are obtained from measurements made at the three defining fixed points given in Sect. 3.2, but with the further restriction that the lowest one of these points lies between 4,2 K and 5,0 K.

3.2.2. From 3,0 K to the triple point of neon (24,5561 K) with ^{3}He or ^{4}He as the thermometric gas

For a ^{3}He gas thermometer, and for a ^{4}He gas thermometer used below 4,2 K, the non-ideality of the gas must be accounted for explicitly, using the appropriate second virial coefficient $B_3(T_{90})$ or $B_4(T_{90})$. In this range T_{90} is defined by the relation:

$$T_{90} = \frac{a + bp + cp^2}{1 + B_x(T_{90})\, N/V}, \tag{5}$$

where p is the pressure in the gas thermometer, a, b and c are coefficients the numerical values of which are obtained from measurements at three defining temperatures as given in Sect. 3.2, N/V is the gas density with N being the quantity of gas and V the volume of the bulb, x is 3 or 4 according to the isotope used, and the values of the second virial coefficients are given by the relations:

For ^{3}He,

$$\begin{aligned} B_3(T_{90})/\mathrm{m}^3\ \mathrm{mol}^{-1} = \{&16{,}69 - 336{,}98(T_{90}/\mathrm{K})^{-1} \\ &+ 91{,}04(T_{90}/\mathrm{K})^{-2} - 13{,}82(T_{90}/\mathrm{K})^{-3}\}\, 10^{-6}. \end{aligned} \tag{6 a}$$

For ^{4}He,

$$\begin{aligned} B_4(T_{90})/\mathrm{m}^3\ \mathrm{mol}^{-1} = \{&16{,}708 - 374{,}05(T_{90}/\mathrm{K})^{-1} \\ &- 383{,}53(T_{90}/\mathrm{K})^{-2} + 1\,799{,}2(T_{90}/\mathrm{K})^{-3} \\ &- 4\,033{,}2(T_{90}/\mathrm{K})^{-4} + 3\,252{,}8(T_{90}/\mathrm{K})^{-5}\}\, 10^{-6}. \end{aligned} \tag{6 b}$$

The accuracy with which T_{90} can be realized using Eqs. (4) and (5) depends on the design of the gas thermometer and the gas density used. Design criteria and current good practice required to achieve a selected accuracy are given in « Supplementary Information for the ITS-90 ».

3.3. The triple point of equilibrium hydrogen (13,8033 K) to the freezing point of silver (961,78 °C): platinum resistance thermometer

In this range T_{90} is defined by means of a platinum resistance thermometer calibrated at specified sets of defining fixed points, and using specified reference and deviation functions for interpolation at intervening temperatures.

No single platinum resistance thermometer can provide high accuracy, or is even likely to be usable, over all of the temperature range 13,8033 K to 961,78 °C. The choice of temperature range, or ranges, from among those listed below for which a particular thermometer can be used is normally limited by its construction.

For practical details and current good practice, in particular concerning types of thermometer available, their acceptable operating ranges, probable accuracies, permissible leakage resistance, resistance values, and thermal treatment, *see* « Supplementary Information for the ITS-90 ». It is particularly important to take account of the appropriate heat treatments that should be followed each time a platinum resistance thermometer is subjected to a temperature above about 420 °C.

Temperatures are determined in terms of the ratio of the resistance $R(T_{90})$ at a temperature T_{90} and the resistance $R(273{,}16\ \mathrm{K})$ at the triple point of water. This ratio, $W(T_{90})$, is (2):

$$W(T_{90}) = R(T_{90})/R(273{,}16\ \mathrm{K}). \tag{7}$$

An acceptable platinum resistance thermometer must be made from pure, strain-free platinum, and it must satisfy at least one of the following two relations:

$$W(29{,}7646\ ^\circ\mathrm{C}) \geqslant 1{,}118\,07, \tag{8 a}$$

$$W(-38{,}8344\ ^\circ\mathrm{C}) \leqslant 0{,}844\,235. \tag{8 b}$$

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(2) Note that this definition of $W(T_{90})$ differs from the corresponding definition used in the ITS-27, ITS-48, IPTS-48 and IPTS-68: for all of these earlier scales $W(T)$ was defined in terms of a reference temperature of 0 °C, which since 1954 has itself been defined as 273,15 K.

An acceptable platinum resistance thermometer that is to be used up to the freezing point of silver must also satisfy the relation:

$$W(961{,}78\ ^\circ\mathrm{C}) \geqslant 4{,}2844. \qquad (8\ \mathrm{c})$$

In each of the resistance thermometer ranges, T_{90} is obtained from $W_r(T_{90})$ as given by the appropriate reference function {Eqs. (9 b) or (10 b)}, and the deviation $W(T_{90}) - W_r(T_{90})$. At the defining fixed points this deviation is obtained directly from the calibration of the thermometer; at intermediate temperatures it is obtained by means of the appropriate deviation function {Eqs. (12), (13) and (14)}.

(i) For the range 13,8033 K to 273,16 K the following reference function is defined:

$$\ln\left[W_r(T_{90})\right] = A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln(T_{90}/273{,}16\ \mathrm{K}) + 1{,}5}{1{,}5}\right]^i. \qquad (9\ \mathrm{a})$$

An inverse function, equivalent to Eq. (9 a) to within 0,1 mK, is:

$$T_{90}/273{,}16\ \mathrm{K} = B_0 + \sum_{i=1}^{15} B_i \left[\frac{W_r(T_{90})^{1/6} - 0{,}65}{0{,}35}\right]^i. \qquad (9\ \mathrm{b})$$

The values of the constants A_0, A_i, B_0 and B_i are given in Table IV.

A thermometer may be calibrated for use throughout this range or, using progressively fewer calibration points, for ranges with low temperature limits of 24,5561 K, 54,3584 K and 83,8058 K, all having an upper limit of 273,16 K.

(ii) For the range 0 °C to 961,78 °C the following reference function is defined:

$$W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \left[\frac{T_{90}/\mathrm{K} - 754{,}15}{481}\right]^i. \qquad (10\ \mathrm{a})$$

An inverse function, equivalent to equation (10 a) to within 0,13 mK, is:

$$T_{90}/\mathrm{K} - 273{,}15 = D_0 + \sum_{i=1}^{9} D_i \left[\frac{W_r(T_{90}) - 2{,}64}{1{,}64}\right]^i. \qquad (10\ \mathrm{b})$$

The values of the constants C_0, C_i, D_0 and D_i are given in Table IV.

TABLE IV

Platinum resistance thermometer

The constants A_0, A_i; B_0, B_i; C_0, C_i; D_0 and D_i in the reference function of equations (9 a); (9 b); (10 a); and (10 b) respectively

A_0	− 2,135 347 29	B_0	0,183 324 722
A_1	3,183 247 20	B_1	0,240 975 303
A_2	− 1,801 435 97	B_2	0,209 108 771
A_3	0,717 272 04	B_3	0,190 439 972
A_4	0,503 440 27	B_4	0,142 648 498
A_5	− 0,618 993 95	B_5	0,077 993 465
A_6	− 0,053 323 22	B_6	0,012 475 611
A_7	0,280 213 62	B_7	− 0,032 267 127
A_8	0,107 152 24	B_8	− 0,075 291 522
A_9	− 0,293 028 65	B_9	− 0,056 470 670
A_{10}	0,044 598 72	B_{10}	0,076 201 285
A_{11}	0,118 686 32	B_{11}	0,123 893 204
A_{12}	− 0,052 481 34	B_{12}	− 0,029 201 193
		B_{13}	− 0,091 173 542
		B_{14}	0,001 317 696
		B_{15}	0,026 025 526
C_0	2,781 572 54	D_0	439,932 854
C_1	1,646 509 16	D_1	472,418 020
C_2	− 0,137 143 90	D_2	37,684 494
C_3	− 0,006 497 67	D_3	7,472 018
C_4	− 0,002 344 44	D_4	2,920 828
C_5	0,005 118 68	D_5	0,005 184
C_6	0,001 879 82	D_6	− 0,963 864
C_7	− 0,002 044 72	D_7	− 0,188 732
C_8	− 0,000 461 22	D_8	0,191 203
C_9	0,000 457 24	D_9	0,049 025

A thermometer may be calibrated for use throughout this range or, 419,527 °C, 231,928 °C, 156,5985 °C or 29,7646 °C, all having a lower limit of 0 °C.

(iii) A thermometer may be calibrated for use in the range 234,3156 K (− 38,8344 °C) to 29,7646 °C, the calibration being made at these temperatures and at the triple point of water. Both reference functions {Eqs. (9) and (10)} are required to cover this range.

The defining fixed points and deviation functions for the various

TABLE V

Deviation functions and calibration points for platinum resistance thermometers in the various ranges in which they define T_{90}

(a) Ranges with an upper limit of 273,16 K			
Section	Lower limit	Deviation functions	Calibration points**
3.3.1	13,803 3 K	$a[W(T_{90})-1] + b[W(T_{90})-1]^2 + \sum_{i=1}^{5} c_i[\ln W(T_{90})]^{i+n}$, $n = 2$	2 to 9
3.3.1.1	24,556 1 K	As for 3.3.1 with $c_4 = c_5 = 0$ and $n = 0$	2, 5 to 9
3.3.1.2	54,358 4 K	As for 3.3.1 with $c_2 = c_3 = c_4 = c_5 = 0$ and $n = 1$	6 to 9
3.3.1.3	83,805 8 K	$a[W(T_{90}) - 1] + b[W(T_{90}) - 1] \ln W(T_{90})$	7 to 9
(b) Ranges with a lower limit of 0 °C			
Section	Upper limit	Deviation functions	Calibration points **
3.3.2 *	961,78 °C	$a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c[W(T_{90}) - 1]^3 + d[W(T_{90}) - W(660{,}323\ ^\circ\text{C})]^2$	9, 12 to 15
3.3.2.1	660,323 °C	As for 3.3.2 with $d = 0$	9, 12 to 14
3.3.2.2	419,527 °C	As for 3.3.2 with $c = d = 0$	9, 12, 13
3.3.2.3	231,928 °C	As for 3.3.2 with $c = d = 0$	9, 11, 12
3.3.2.4	156,598 5 °C	As for 3.3.2 with $b = c = d = 0$	9, 11
3.3.2.5	29,764 6 °C	As for 3.3.2 with $b = c = d = 0$	9, 10
(c) Range from 234,315 6 K (− 38,834 4 °C) to 29,764 6 °C			
3.3.3		As for 3.3.2 with $c = d = 0$	8 to 10

* Calibration points 9, 12 to 14 are used with $d = 0$ for $t_{90} \leqslant 660{,}323$ °C ; the values of a, b and c thus obtained are retained for $t_{90} \geqslant 660{,}323$ °C, ith d being determined from calibration point 15.

** *See* Table I.

3.3.1. The triple point of equilibrium hydrogen (13,8033 K) to the triple point of water (273,16 K)

The thermometer is calibrated at the triple points of equilibrium hydrogen (13,8033 K), neon (24,5561 K), oxygen (54,3584 K), argon (83,8058 K), mercury (234,3156 K), and water (273,16 K), and at two additional temperatures close to 17,0 K and 20,3 K. These last two may be determined either : by using a gas thermometer as described in Sect. 3.2, in which case the two temperatures must lie within the ranges 16,9 K to 17,1 K and 20,2 K to 20,4 K respectively ; or by using the vapour pressure-temperature relation of equilibrium hydrogen, in which case the two temperatures must lie within the ranges 17,025 K to 17,045 K and 20,26 K to 20,28 K respectively, with the precise values being determined from Eqs. (11 a) and (11 b) respectively :

$$T_{90}/\text{K} - 17{,}035 = (p/\text{kPa} - 33{,}3213)/13{,}32, \qquad (11\text{ a})$$
$$T_{90}/\text{K} - 20{,}27 = (p/\text{kPa} - 101{,}292)/30. \qquad (11\text{ b})$$

The deviation function is (3) :

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + \sum_{i=1}^{5} c_i[\ln W(T_{90})]^{i+n}, \qquad (12)$$

with values for the coefficients a, b and c_i being obtained from measurements at the defining fixed points and with $n = 2$.

For this range and for the sub-ranges 3.3.1.1 to 3.3.1.3 the required values of $W_r(T_{90})$ are obtained from Eq. (9 a) or from Table I.

3.3.1.1. The triple point of neon (24,5561 K) to the triple point of water (273,16 K)

The thermometer is calibrated at the triple points of equilibrium hydrogen (13,8033 K), neon (24,5561 K), oxygen (54,3584 K), argon (83,8058 K), mercury (234,3156 K) and water (273,16 K).

The deviation function is given by Eq. (12) with values for the coefficients a, b, c_1, c_2 and c_3 being obtained from measurements at the defining fixed points and with $c_4 = c_5 = n = 0$.

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(3) This deviation function (and also those of Eqs (13) and (14)) may be expressed in terms of W_r rather than W ; for this procedure *see* « Supplementary Information for ITS-90 ».

3.3.1.2. The triple point of oxygen (54,3584 K) to the triple point of water (273,16 K)

The thermometer is calibrated at the triple points of oxygen (54,3584 K), argon (83,8058 K), mercury (234,3156 K) and water (273,16 K).

The deviation function is given by Eq. (12) with values for the coefficients a, b and c_1 being obtained from measurements at the defining fixed points, with $c_2 = c_3 = c_4 = c_5 = 0$ and with $n = 1$.

3.3.1.3. The triple point of argon (83,8058 K) to the triple point of water (273,16 K)

The thermometer is calibrated at the triple points of argon (83,8058 K), mercury (234,3156 K) and water (273,16 K).

The deviation function is:

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]\ln W(T_{90}) \qquad (13)$$

with the values of a and b being obtained from measurements at the defining fixed points.

3.3.2. From 0 °C to the freezing point of silver (961,78 °C)

The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of tin (231,928 °C), zinc (419,527 °C), aluminium (660,323 °C) and silver (961,78 °C).

The deviation function is:

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c[W(T_{90}) - 1]^3 + d[W(T_{90}) - W(660{,}323\ ^\circ\mathrm{C})]^2. \qquad (14)$$

For temperatures below the freezing point of aluminium $d = 0$, with the values of a, b and c being determined from the measured deviations from $W_r(T_{90})$ at the freezing points of tin, zinc and aluminium. From the freezing point of aluminium to the freezing point of silver the above values of a, b and c are retained and the value of d is determined from the measured deviation from $W_r(T_{90})$ at the freezing point of silver.

For this range and for the sub-ranges 3.3.2.1 to 3.3.2.5 the required values for $W_r(T_{90})$ are obtained from Eq. (10 a) or from Table I.

3.3.2.1. From 0 °C to the freezing point of aluminium (660,323 °C)

The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of tin (231,928 °C), zinc (419,527 °C) and aluminium (660,323 °C).

The deviation function is given by Eq. (14), with the values of a, b and c being determined from measurements at the defining fixed points and with $d = 0$.

3.3.2.2. From 0 °C to the freezing point of zinc (419,527 °C)

The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of tin (231,928 °C) and zinc (419,527 °C).

The deviation function is given by Eq. (14), with the values of a and b being obtained from measurements at the defining fixed points and with $c = d = 0$.

3.3.2.3. From 0 °C to the freezing point of tin (231,928 °C)

The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of indium (156,5985 °C), and tin (231,928 °C).

The deviation function is given by Eq. (14), with the values of a and b being obtained from measurements at the defining fixed points and with $c = d = 0$.

3.3.2.4. From 0 °C to the freezing point of indium (156,5985 °C)

The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing point of indium (156,5985 °C).

The deviation function is given by Eq. (14), with the value of a being obtained from measurements at the defining fixed points and with $b = c = d = 0$.

3.3.2.5. From 0 °C to the melting point of gallium (29,7646 °C)

The thermometer is calibrated at the triple point of water (0,01 °C), and at the melting point of gallium (29,7646 °C).

The deviation function is given by Eq. (14), with the value of a being obtained from measurements at the defining fixed points and with $b = c = d = 0$.

3.3.3. The triple point of mercury (− 38,8344 °C) to the melting point of gallium (29,7646 °C)

The thermometer is calibrated at the triple points of mercury (− 38,8344 °C), and water (0,01 °C), and at the melting point of gallium (29,7646 °C).

The deviation function is given by Eq. (14), with the values of a and b being obtained from measurements at the defining fixed points and with $c = d = 0$.

The required values of $W_r(T_{90})$ are obtained from Eqs. (9 a) and (10 a) for measurements below and above 273,16 K respectively, or

3.4. The range above the freezing point of silver (961,78 °C): Planck radiation law

Above the freezing point of silver the temperature T_{90} is defined by the equation:

$$\frac{L_\lambda(T_{90})}{L_\lambda[T_{90}(X)]} = \frac{\exp\left(c_2[\lambda T_{90}(X)]^{-1}\right) - 1}{\exp\left(c_2[\lambda T_{90}]^{-1}\right) - 1}, \qquad (15)$$

where $T_{90}(X)$ refers to any one of the silver $\{T_{90}(\mathrm{Ag}) = 1\,234{,}93\ \mathrm{K}\}$, the gold $\{T_{90}(\mathrm{Au}) = 1\,337{,}33\ \mathrm{K}\}$ or the copper $\{T_{90}(\mathrm{Cu}) = 1\,357{,}77\ \mathrm{K}\}$ freezing points (4) and in which $L_\lambda(T_{90})$ and $L_\lambda[T_{90}(X)]$ are the spectral concentrations of the radiance of a blackbody at the wavelength (in vacuo) λ at T_{90} and at $T_{90}(X)$ respectively, and $c_2 = 0{,}014388\ \mathrm{m \cdot K}$.

For practical details and current good practice for optical pyrometry, *see* « Supplementary Information for the ITS-90 ».

4. Supplementary information and differences from earlier scales

The apparatus, methods and procedures that will serve to realize the ITS-90 are given in « Supplementary Information for the ITS-90 ». This document also gives an account of the earlier International Temperature Scales and the numerical differences between successive scales that include, where practicable, mathematical functions for the differences $T_{90} - T_{68}$. A number of useful approximations to the ITS-90 are given in « Techniques for Approximating the ITS-90 » *.

The two documents have been prepared by the Comité Consultatif de Thermométrie and are published by the BIPM; they are revised and updated periodically.

The differences $T_{90} - T_{68}$ are shown in Fig. 1 and Table VI. The number of significant figures given in Table VI allows smooth interpolations to be made. However, the reproducibility of the IPTS-68 is, in many areas, substantially worse than is implied by this number.

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(4) The T_{90} values of the freezing points of silver, gold and copper are believed to be self consistent to such a degree that the substitution of any one of them in place of one of the other two as the reference temperature $T_{90}(X)$ will not result in significant differences in the measured values of T_{90}.

* *See* Monography BIPM/1990.

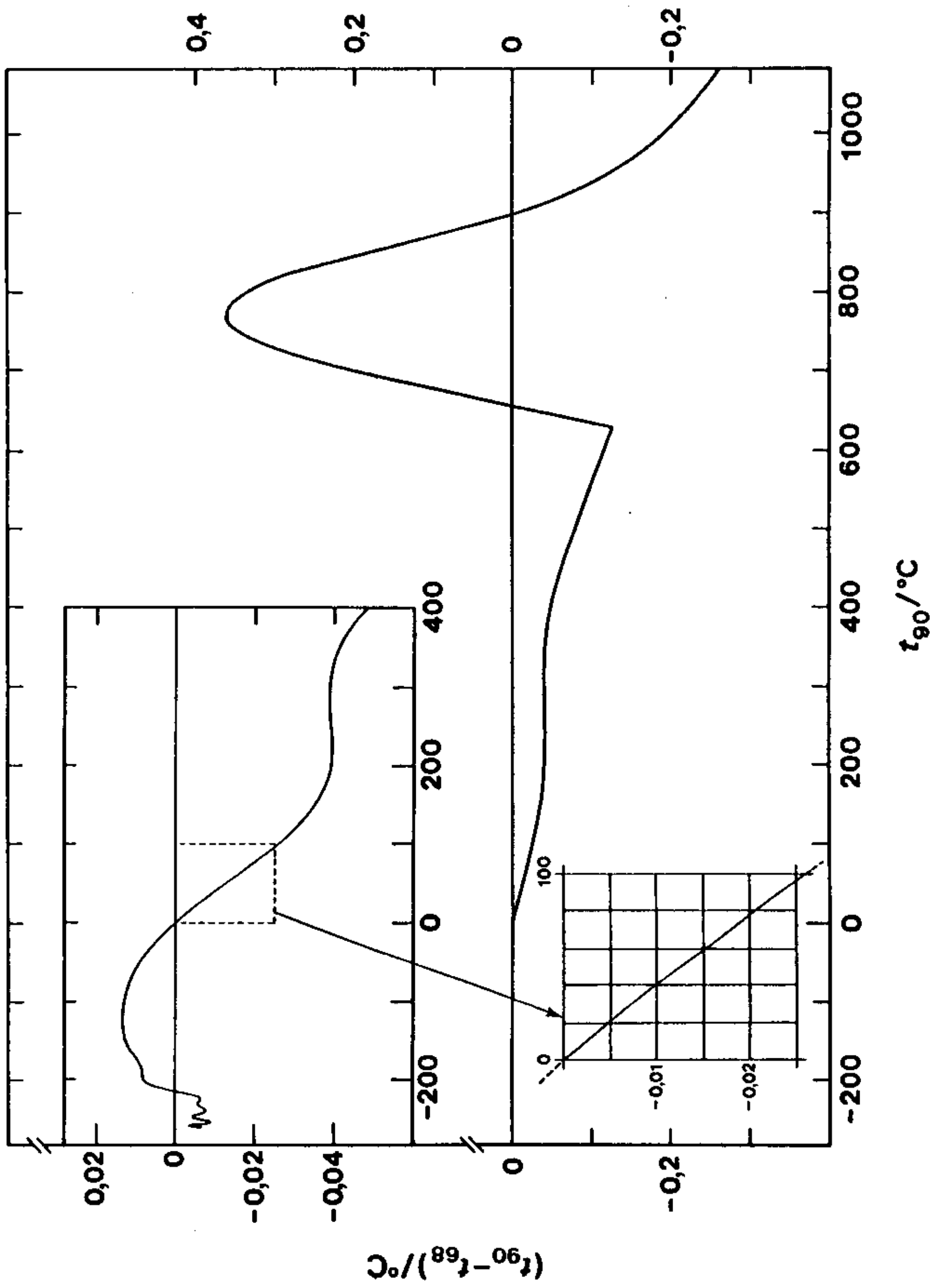

TABLEAU VI

Differences between ITS-90 and EPT-76, and between ITS-90 and IPTS-68 for specified values of T_{90} and t_{90}

$_{90} - T_{76})$/mK

T_{90}/K	0	1	2	3	4	5	6	7	8	9
0						− 0,1	− 0,2	− 0.3	− 0.4	− 0,5
10	− 0.6	− 0.7	− 0.8	− 1,0	− 1,1	− 1,3	− 1,4	− 1.6	− 1.8	− 2.0
20	− 2.2	− 2.5	− 2,7	− 3,0	− 3,2	− 3,5	− 3.8	− 4,1		

$_{90} - T_{68})$/K

T_{90}/K	0	1	2	3	4	5	6	7	8	9
10					− 0,006	− 0,003	− 0,004	− 0,006	− 0,008	− 0,009
20	− 0,009	− 0,008	− 0,007	− 0,007	− 0,006	− 0,005	− 0,004	− 0,004	− 0,005	− 0,006
30	− 0,006	− 0,007	− 0,008	− 0,008	− 0,008	− 0,007	− 0,007	− 0,007	− 0,006	− 0,006
40	− 0,006	− 0,006	− 0,006	− 0,006	− 0,006	− 0,007	− 0,007	− 0,007	− 0,006	− 0,006
50	− 0,006	− 0,005	− 0,005	− 0,004	− 0,003	− 0,002	− 0,001	0,000	0,001	0,002
60	0,003	0,003	0,004	0,004	0,005	0,005	0,006	0,006	0,007	0,007
70	0,007	0,007	0,007	0,007	0,007	0,008	0,008	0,008	0,008	0,008
80	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008
90	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,009	0,009	0,009

T_{90}/K	0	10	20	30	40	50	60	70	80	90
100	0,009	0.011	0.013	0,014	0,014	0,014	0,014	0,013	0,012	0,012
200	0,011	0,010	0,009	0,008	0,007	0,005	0,003	0,001		

$- t_{68})$/°C

$_{90}$/°C	0	− 10	− 20	− 30	− 40	− 50	− 60	− 70	− 80	− 90
− 100	0,013	0,013	0,014	0,014	0,014	0,013	0,012	0,010	0,008	0,008
0	0,000	0,002	0,004	0,006	0,008	0,009	0,010	0,011	0,012	0,012

$_{90}$/°C	0	10	20	30	40	50	60	70	80	90
0	0,000	− 0,002	− 0,005	− 0,007	− 0,010	− 0,013	− 0,016	− 0,018	− 0,0021	− 0,024
100	− 0,026	− 0,028	− 0,030	− 0,032	− 0,034	− 0,036	− 0,037	− 0,038	− 0,039	− 0,039
200	− 0,040	− 0,040	− 0,040	− 0,040	− 0,040	− 0,040	− 0,040	− 0,039	− 0,039	− 0,039
300	− 0,039	− 0,039	− 0,039	− 0,040	− 0,040	− 0,041	− 0,042	− 0,043	− 0,045	− 0,046
400	− 0,048	− 0,051	− 0,053	− 0,056	− 0,059	− 0,062	− 0,065	− 0,068	− 0,072	− 0,075
500	− 0,079	− 0,083	− 0,087	− 0,090	− 0,094	− 0,098	− 0,101	− 0,105	− 0,108	− 0,112
600	− 0,115	− 0,118	− 0,122	− 0,125 *	− 0,08	− 0,03	0,02	0,06	0,11	0,16
700	0,20	0,24	0,28	0,31	0,33	0,35	0,36	0,36	0,36	0,35
800	0,34	0,32	0,29	0,25	0,22	0,18	0,14	0,10	0,06	0,03
900	− 0,01	− 0,03	− 0,06	− 0,08	− 0,10	− 0,12	− 0,14	− 0,16	− 0,17	− 0,18
000	− 0,19	− 0,20	− 0,21	− 0,22	− 0,23	− 0,24	− 0,25	− 0,25	− 0,26	− 0,26

$_{90}$/°C	0	100	200	300	400	500	600	700	800	900
000		− 0,26	− 0,30	− 0,35	− 0,39	− 0,44	− 0,49	− 0,54	− 0,60	− 0,66
000	− 0,72	− 0,79	− 0,85	− 0,93	− 1,00	− 1,07	− 1,15	− 1,24	− 1,32	− 1,41
000	− 1,50	− 1,59	− 1,69	− 1,78	− 1,89	− 1,99	− 2,10	− 2,21	− 2,32	− 2,43

* A discontinuity in the first derivative of $(t_{90} - t_{68})$ occurs at a temperature of t_{90} = 630,6 °C, at which $(t_{90} - t_{68})$ = − 0,125 °C.

APPENDIX

The International Temperature Scale of 1927 (ITS-27)

The International Temperature Scale of 1927 was adopted by the seventh Conférence Générale des Poids et Mesures to overcome the practical difficulties of the direct realization of thermodynamic temperatures by gas thermometry, and as a universally acceptable replacement for the differing existing national temperature scales. The ITS-27 was formulated so as to allow measurements of temperature to be made precisely and reproducibly, with as close an approximation to thermodynamic temperatures as could be determined at that time. Between the oxygen boiling point and the gold freezing point it was based upon a number of reproducible temperatures, or fixed points, to which numerical values were assigned, and two standard interpolating instruments. Each of these interpolating instruments was calibrated at several of the fixed points, this giving the constants for the interpolating formula in the appropriate temperature range. A platinum resistance thermometer was used for the lower part and a platinum rhodium/platinum thermocouple for temperatures above 660 °C. For the region above the gold freezing point, temperatures were defined in terms of the Wien radiation law: in practice, this invariably resulted in the selection of an optical pyrometer as the realizing instrument.

The International Temperature Scale of 1948 (ITS-48)

The International Temperature Scale of 1948 was adopted by the ninth Conférence Générale. Changes from the ITS-27 were: the lower limit of the platinum resistance thermometer range was changed from − 190 °C to the defined oxygen boiling point of − 182,97 °C, and the junction of the platinum resistance thermometer range and the thermocouple range became the measured antimony freezing point (about 630 °C) in place of 660 °C; the silver freezing point was defined as being 960,8 °C instead of 960,5 °C; the gold freezing point replaced the gold melting point (1 063 °C); the Planck radiation law replaced the Wien law; the value assigned to the second radiation constant became $1{,}438 \times 10^{-2}\,\mathrm{m \cdot K}$ in place of $1{,}432 \times 10^{-2}\,\mathrm{m \cdot K}$; the permitted ranges for the constants of the interpolation formulae for the standard resistance thermometer and thermocouple were modified; the limitation on λT for optical pyrometry ($\lambda T \leqslant 3 \times 10^{-3}\,\mathrm{m \cdot K}$) was changed to the requirement that « visible » radiation be used.

The International Practical Temperature Scale of 1948 (Amended Edition of 1960) (IPTS-48)

The International Practical Temperature Scale of 1948, amended edition of 1960, was adopted by the eleventh Conférence Générale: the tenth Conférence Générale had already adopted the triple point of water as the sole point defining the kelvin, the unit of thermodynamic temperature. In addition to the introduction of the word « Practical », the modifications to the ITS-48 were: the triple point of water, defined as being 0,01 °C, replaced the melting point of ice as the calibration point in this region; the freezing point of zinc, defined as being 419,505 °C, became a preferred alternative to the sulphur boiling point (444,6 °C) as a calibration point; the permitted ranges for the constants of the interpolation formulae for the standard resistance thermometer and the thermocouple were further modified; the restriction to « visible » radiation for optical pyrometry was removed.

Inasmuch as the numerical values of temperature on the IPTS-48 were the same as on the ITS-48, the former was not a revision of the scale of 1948 but merely an amended form of it.

The International Practical Temperature Scale of 1968 (IPTS-68)

In 1968 the Comité International des Poids et Mesures promulgated the International Practical Temperature Scale of 1968, having been empowered to do so by the thirteenth Conférence Générale of 1967-1968. The IPTS-68 incorporated very extensive changes from the IPTS-48. These included numerical changes, designed to bring it more nearly in accord with thermodynamic temperatures, that were sufficiently large to be apparent to many users. Other changes were as follows: the lower limit of the scale was extended down to 13,81 K; at even lower temperatures (0,5 K to 5,2 K), the use of two helium vapour pressure scales was recommended; six new defining fixed points were introduced — the triple point of equilibrium hydrogen (13,81 K), an intermediate equilibrium hydrogen point (17,042 K), the normal boiling point of equilibrium hydrogen (20,28 K), the boiling point of neon (27,102 K), the triple point of oxygen (54,361 K), and the freezing point of tin (231,9681 °C) which became a permitted alternative to the boiling point of water; the boiling point of sulphur was deleted; the values assigned to four fixed points were changed — the boiling point of oxygen (90,188 K), the freezing point of zinc (419,58 °C), the freezing point of silver (961,93 °C), and the freezing point of gold (1 064,43 °C); the interpolating formulae for the resistance thermometer range became much more complex; the value assigned to the second radiation constant c_2 became $1{,}4388 \times 10^{-2}\,\mathrm{m \cdot K}$; the permitted ranges of the constants for the interpolation formulae for the resistance thermometer and thermocouple were again modified.

The International Practical Temperature Scale of 1968 (Amended Edition of 1975) (IPTS-68)

The International Practical Temperature Scale of 1968, amended edition of 1975, was adopted by the fifteenth Conférence Générale in 1975. As was the case for the IPTS-48 with respect to the ITS-48, the IPTS-68 (75) introduced no numerical changes. Most of the extensive textual changes were intended only to clarify and simplify its use. More substantive changes were: the oxygen point was defined as the condensation point rather than the boiling point; the triple point of argon (83,798 K) was introduced as a permitted alternative to the condensation point of oxygen; new values of the isotopic composition of naturally occurring neon were adopted; the recommendation to use values of T given by the 1958 ^{4}He and 1962 ^{3}He vapour-pressure scales was rescinded.

The 1976 Provisional 0,5 K to 30 K Temperature Scale (EPT-76)

The 1976 Provisional 0,5 K to 30 K Temperature Scale was introduced to meet two important requirements: these were to provide means of substantially reducing the errors (with respect to corresponding thermodynamic values) below 27 K that were then known to exist in the IPTS-68 and throughout the temperature ranges of the ^{4}He and ^{3}He vapour pressure scales of 1958 and 1962 respectively, and to bridge the gap between 5,2 K and 13,81 K in which there had not previously been an international scale. Other objectives in devising the EPT-76 were « that it should be thermodynamically smooth, that it should be continuous with the IPTS-68 at 27,1 K, and that is should agree with thermodynamic temperature T as closely as these two conditions allow ». In contrast with the IPTS-68, and to ensure its rapid adoption, several methods of realizing the EPT-76 were approved. These included: using a thermodynamic interpolation instrument and one or more of eleven assigned reference points; taking differences from the IPTS-68 above 13,81 K; taking differences from helium vapour pressure scales below 5 K; and taking differences from certain well-established laboratory scales. Because there was a certain « lack of internal consistency » it was admitted that « slight ambiguities between realizations » might be introduced. However the advantages gained by adopting the EPT-76 as a working scale until such time as the IPTS-68 should be revised and extended were considered to outweigh the disadvantages.