19. Thermometry in Magnetic Fields

Most thermometers change their calibration in the presence of a magnetic field. In this chapter we discuss by how much traceability to the original calibration can be affected and how accuracy can be preserved for the different types. The discussion will include types of thermometers from both Parts 1 and 2, as the problem of ensuring a traceable temperature value in the presence of a magnetic field is not restricted to industrial applications. It is very important in cryogenics and in thermophysical-property measurements at the highest possible accuracy. Some types of thermometer specifically developed for use in a magnetic field will also be briefly considered.

The general problem has two possible solutions: a) use of a thermometer insensitive, within the required accuracy, to magnetic fields up to the maximum strength likely to be encountered; b) accurate correction of the thermometer reading for the shift due to the magnetic field. The latter solution is made difficult by possible anisotropy of the magnetic-field sensitivity of the thermometer, or of the magnetic field itself, and, in addition, needs the local magnetic field strength to be known with sufficient accuracy. The first solution is almost mandatory for thermometers used in temperature regulation; otherwise, change of the magnetic field value would result in a change of the regulated temperature. In addition, for thermometers that exhibit a high magnetic-field shift, the sensitivity to temperature changes may be dramatically lower [Pavese and Cresto (1984)], resulting in a much worse regulation. Table 19.1 collects the data available on the magnetically-induced temperature errors of thermometers. It should be cross-checked with Table 1.1 which gives the quality of the thermometers with regard to general reproducibility.

All of the thermometers for use at cryogenic temperatures included in Part 1 exhibit substantial sensitivity to a magnetic field.

Although platinum resistance thermometer calibrations change considerably in magnetic fields [Brandt and Aubin (1988)], the magnetic error can be well corrected for because it is only slightly orientation dependent and varies little from thermometer to thermometer since the thermometers are well characterized by their values of W(H_20 t.p.). Below the liquid-nitrogen temperature range, however, the correction becomes too large to allow the best accuracy in fields larger than a few teslas. If lesser accuracy is acceptable the range of use of the correction may be extended to lower temperatures and higher fields, but the error then becomes dependent on the value of W(H_20 t.p.). The correction is lower for IPRTs with W(H_20 t.p.) = 1.385 and can be used to 30 K at 19 T, or to 20 K at 5 T. A correction must always be applied, even for uncertainties of the order of ± 0.1 K. It should

Table 19.1: Magnetic Field-Dependent Temperature Errors for Low Temperature Thermometers

Magnitude of relative temperature
error $|\Delta T|/T$ (%) for values of B

Type of Sensor	T(K)	Magnetic Flux Density, B									Notes	References
		1 T	2.5 T		8 T		14 T		19 T			
Carbon radio resistors											a	Sample and Rubin (1977)
Allen-Bradley (2.7, 3.9, 5.6, 10 C)	0.5		2-4		5-13		7-20					
	1.0		2-4		6-15		9-25					
	2.5		1-5		6-18		10-30					
	4.2		1-5		5-20		10-35					
Allen-Bradley (47, 100, 220 Ω)	4.2		<1		5		10				a	ibidem
	10		<1		3		5					
	20		<1		1		2					
Speer, Grade 1002 (100, 220, 470 C)	0.5		0-2		0-1		0-6				b	ibidem
	1.0		1-2		2-4		3-9					
	2.5		3-5		1-4		7-14					
	4.2		4-9		2-5		4-13					
Matsushita (68, 200, 510 C)	1.5		1-2		10-15						c	ibidem
	2.1		1		10-15							
	4.2		2-3		4-8							
KVM carbon composite resistors	2.4		3		8 (5T)						d	Astrov et al. (1977)
	4.2		1.5		5 "							
	10		0.4		1.4 "							
	20		0.1		0.4 "							
	80		<0.01		<0.01 "							
Carbon-Glass Resistors	2.2		0.1		1.5		3		4		e	Rubin and Brandt (1986)
	4.2		0.5		2		5		7			
	10		0.2		1.1		3		4			
	20		<0.01		0.02		0.03		0.13			
	45		0.07		0.5		1.3		2			
	88		0.06		0.5		1.3		2			
	190		0.04		0.3		1.0		1.7			
	310		<0.01		0.2		0.6		1.1			
Thermistors	4.2		<0.05		1		3				f	Sample and Rubin (1977)
	10		<0.05		0.3		1					
	20		<0.05		0.1		0.5					
	40		<0.05		0.1		0.5					
	60		<0.05		0.1		0.3					
Germanium Resistors	2.0		8-10		60						g	ibidem
	4.2		5-20		30-55		60-70					
	10		4-15		25-60		60-75					
	20		3-20		15-35		50-80					
	70		3-10		15-30		25-50					
Germanium Resistors TSG-2	4.2		30		120						g	Astrov et al. (1977)
	20		2.5		6							
Specially doped Ge resistors KG	4.2		<0.2.		0.5 (6T)						h	ibidem; Matacotta et al. (1984)
	10		<0.2		<0.5 "							
	20		<0.5		2-3 "							
	30		<0.5		5 "							
	80		0.15		0.5 "							
Platinum Resistors	10		100		250						i	Pavese & Cresto (1984); Neuringer et al. (1971); Rubin & Brandt (1986)
	20		2-8	20	25	100	250					
	40		0.5	<1	3	5	6	10	9			
	66		0.1	<0.5	0.8	2	2	5	4			
	87		0.04	<0.5	0.4	1	1	2	2			
	110		0.02		0.2		0.6		1			
	190		<0.01		0.06		0.2		0.3			
	300		<0.01		0.02		0.07		0.13			
			(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)		

Type of Sensor	T(K)	Magnetic Flux Density, B					Notes	References
		1 T	2.5 T	8 T	14 T	19 T		
Rhodium-Iron resistors	2.0		22				j	Pavese & Cresto (1984); Rusby (1972); Rubin & Brandt (1986)
	4.2	2	11	40(6T)				
	20	0.8	4	10(5T)				
	40		1.5	12	30	40		
	66		0.3	2.5	6	9		
	87		0.2	1.5	4	6		
	110		0.1	0.9	2.4			
	190		0.03	0.3	0.9			
	300		<0.01	0.1	0.4			
Platinum-Cobalt resistors	2	25	30				k	Shiratori et al. (1982); Pavese & Cresto (1984)
	4.2	8	3	40 (5T)				
	10	1	<0.1	12 "				
	20	0.2	1	3.5 "				
	30	0.2	0.3	1.5 "				
Cryogenic linear resistance sensor	4	20	250				l	McDonald (1973)
	10	17	100					
	20	8	50					
	30	5	30					
KELTIP resistors (Au/Mn)	4.2		4	13	20		m	Rubin & Brandt (1986)
	40		2	30	70	110		
	66		0.4	4	12	20		
	87		0.15	1.5	5	10		
	110		0.03	0.25	1			
	190		0.02	0.2	0.5			
	300		0.02	0.1	0.4			
SrTi03 capacitors	2.2		<0.02	<0.02	0.02		n	ibidem
	4.2		<0.01	<0.01	0.01			
	20		<0.05	<0.05	<0.05			
	50		<0.05	<0.05	<0.05			
	88		<0.01	<0.01	<0.01	<0.01		
	110		<0.01	<0.01	<0.01	<0.01		
	190		<0.01	<0.01	<0.01	<0.01		
Si Diodes	4.2		75				o	Sample & Rubin (1977)
	10		20	30	50			
	20		4	7	10			
	30		3	4	5			
	77		0.2	0.5	0.5			
GaAs Diodes	4.2		2-3	30-50	100-250		p	ibidem
	10		1.5-2	25-40	75-200			
	20		0.5-1	20-30	60-150			
	40		0.2-0.3	4-6	15-30			
	80		0.1-0.2	0.5-1	2-5			
Au + 0.07 % Fe/ Chromel P thermocouple	5		2	10	15		q	Sample et al. (1974)
	10		3	20	30			
	20		2	15	20			
	45		1	5	7			
	100		0.1	0.8				
Chromel P/Constantan thermocouple (Type E)	10		1	3	7		r	ibidem
	20		<1	2	4			
	45		<1	<1	2			
Cu + 0.01 % Fe/Cu thermocouple	5		2	3.5 (5T)			q,r	Astrov et al. (1977)
	10		0.8	2 "				
	20		0.6	1.5 "				
	50		0.3	0.6 "				
Vapour pressure thermometers	no intrinsic error except with 0$_2$						s	
Helium gas thermometer	no intrinsic error						s	Van Degrift et al. (1980)

Notes to Table 19.1

a) $\Delta R/R_0$ monotonic in B and T, and always positive. Higher nominal resistance units have smaller $|\Delta T|$. Good agreement between similar units.

b) $\Delta R/R_0$ both positive and negative with complicated B and T dependence. Variations between similar units.

c) $\Delta R/R_0$ approximately independent of nominal resistance value. Higher resistance units have smaller $|\Delta T|$.

d) Specifically developed for use as a thermometer.

e) Behavior similar to Allen-Bradley resistors. Negative $\Delta R/R_0$ below -20 K.

f) Very low magnetoresistance, but few types useful or available below 77 K.

g) Not recommended except at very low fields because of large, and strongly orientation dependent, $|\Delta T|$.

h) Orientation dependent only above 20 K. Complicated behaviour below 10 K makes corrections difficult.

i) Some orientation dependence. Useful at all B only for $T > 30$ K. Magnetoresistance depends on $W(H_20$ t.p.) value (a) 1.385 (b) 1.3914.

j) Little orientation dependence. Useful only at low fields.

k) Little orientation dependence. ΔR negative below about 12 K and 2.5 T. Useful only below 3T, where it is the best high-stability thermometer.

l) Linear foil-type thermometer; magnetoresistance is negative and extremely high above 1 T.

m) Errors are negative for $T \leq 140$ K.

n) Maximum in capacitance versus temperature near 70 K, so that sensitivity is very low between about 60 K and 80 K.

o) Strongly orientation dependent; values are given for junction parallel to B.

p) Orientation dependent. Smaller values of $|\Delta T|/T$ apply to diode junction parallel to B.

q) Gradients in the magnetic field crossed by the wires can cause higher errors.

r) Different % Fe gives rise to larger errors.

s) With use of non-magnetic bulb and connecting tube.

be noted that these lower temperature limits are approaching the overall low temperature limit for optimum advantage in using PRTs.

For temperatures below about 20 K, rhodium-iron resistance thermometers are in general preferred to PRTs. The sensitivity of their calibrations to magnetic fields is also much less marked than that of SPRTs below 30 K, but is comparable to it above. Anisotropy, correctability, and interchangeability of units are also comparable. The corrections become especially significant below 10 K, even for low fields (1 T). It is next to impossible to trace back to the zero-field calibration with high accuracy, but the correction must be applied even for low accuracy and low fields (1 T). At 4.2 K the change in resistance divided by the zero-field resistance is roughly proportional to the square of the magnetic flux density [Rusby (1972)]. The dependence of the calibration on temperature and magnetic flux density is shown in Fig. 19.1.

The platinum 0.5% cobalt resistance thermometer shows a much better behaviour in magnetic fields than does the rhodium-iron thermometer, while anisotropy, correctability, and interchangeability of units are comparable with those of SPRTs. The sensitivity to magnetic fields is smaller than for rhodium-iron, though it has a more complicated behaviour, as shown in Fig. 19.2; in fact, there is a change of sign of magnetoresistivity below about 14 K and 2.5 T. At 30 K the sensitivity to magnetic fields up to 6 T is less than one-third of that for PRTs. For low levels of accuracy, this thermometer can be used *without* corrections, within an uncertainty of ± 0.2 K, in the region above 8 K and below 3 T. Should the cobalt content of the alloy be reduced to about 0.3 atomic %, the low-temperature limit would become 4 K, with only a small change in the magnetic field limit (2.5 T) [Pavese and Cresto (1984)].

Germanium resistance thermometers have a high sensitivity to magnetic fields, even higher than that of PRTs above 10 K, and comparable with that of rhodium-iron below 10 K. Correctability is good, but the corrections can be made only in situ because they are strongly orientation-dependent (for best accuracy the sensing element of the thermometer should be parallel to the magnetic field). Consequently, the correction also applies only to a specific unit, with no interchangeability, even for low accuracy. Because of this, germanium thermometers are all but useless at all temperatures in the presence of a strong magnetic field. $\Delta R/R$ increases more or less proportionally with B^2 and decreases monotonically as T increases (see Fig. 19.3). Table 19.1 gives values of the error that may be expected in various magnetic fields. Research has been undertaken in the USSR [Astrov et al. (1977), Zinov'eva et al. (1979)] and, more recently, in China [Fu Chiying et al. (1986)] to try to overcome the high magnetosensitivity of germanium thermometers. At present only the USSR type is available; it is a multiply-doped germanium resistor (type

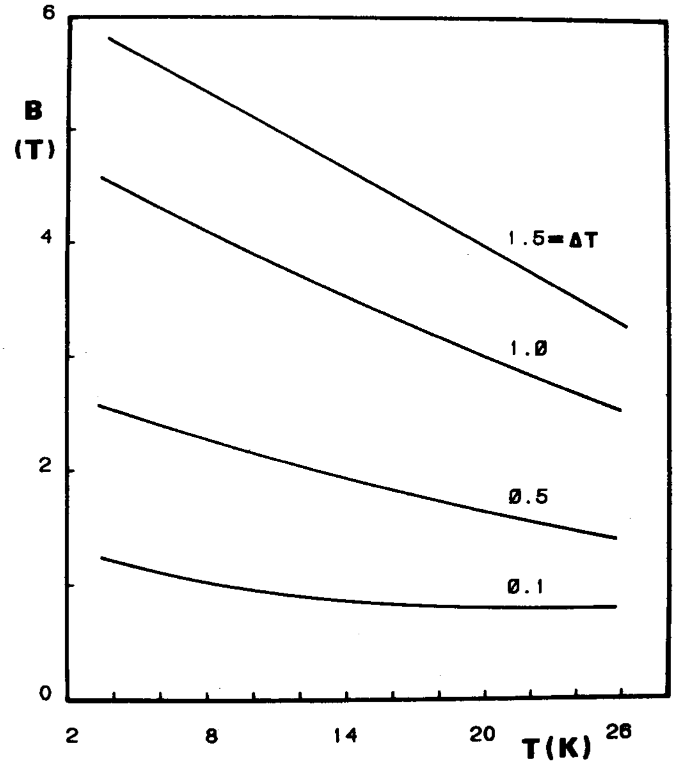

Fig. 19.1: The change in calibration (ΔT(mK)) of rhodium 0.5% iron as a function of temperature and magnetic flux density [Pavese and Cresto (1984)].

KG) which shows a much lower sensitivity to magnetic fields than any other of the above thermometers without its stability to thermal cycling being very much lower than that of regular germanium thermometers [Besley et al. (1986)]. The main problem is correctability, as the behaviour of the correction versus temperature is complicated; on the other hand, the thermometers are much less orientation-dependent than ordinary germanium thermometers below 20 K.

Among other semiconducting resistance thermometers, carbon resistors are known to have relatively small and reproducible magnetic field dependence [Sample and Rubin (1977), Sample and Neuringer (1974), Sample et al. (1974), Sanchez et al. (1977), Saito and Sa to (1975), Neuringer and Rubin (1972), Alms et al. (1979)] (see Table 19.1 for the relative errors in temperature that may be expected). For temperatures below about 50 mK typical errors in temperature incurred by neglect of the magnetoresistance are shown in Fig. 19.4.

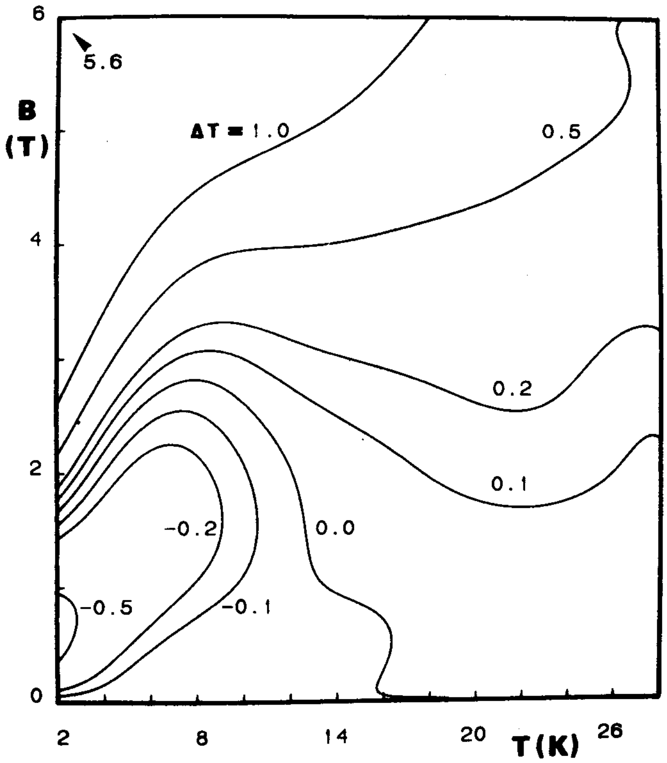

Fig. 19.2: The change in calibration (ΔT(mK)) of platinum 0.5% cobalt as a function of temperature and magentic flux density [after Pavese and Cresto (1984)].

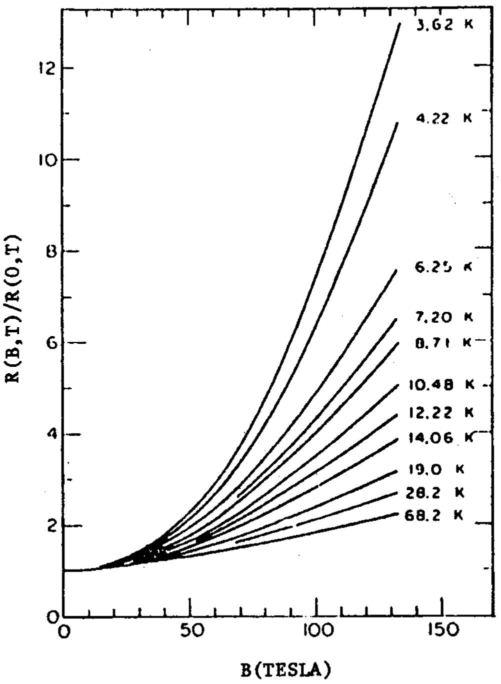

Fig. 19.3: Ratio of a CryoCal germanium thermometer resistance in a magnetic field to its resistance in the absence of a field when the thermometer current is perpendicular to the magnetic field [after Neuringer and Rubin (1972)].

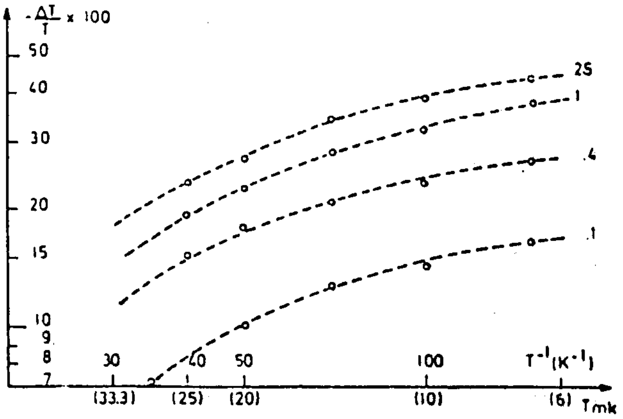

Fig. 19.4: Error in the temperature for carbon thermometers when magnetoresistance effects are neglected at the magnetic flux densities (teslas) indicated [Sanchez et al. (1977)].

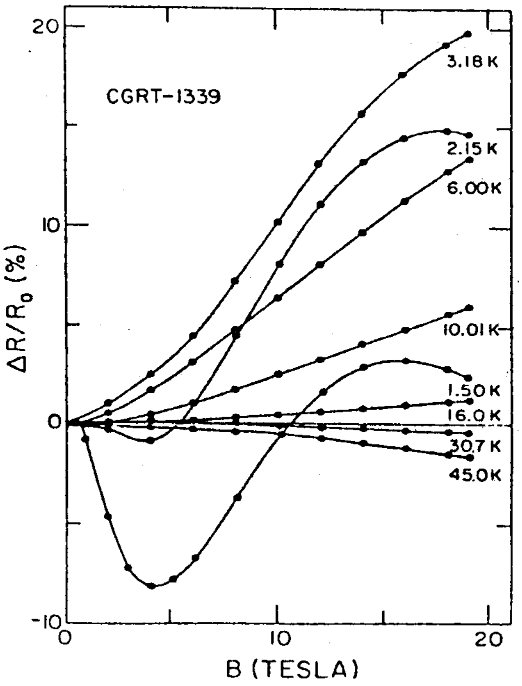

Fig. 19.5: Longitudinal magnetoresistance versus magnetic field for a typical carbon-glass thermometer [Sample et al. (1982)].

Carbon-glass thermometers (Chapter 12) were developed in an attempt to combine the low sensitivity of carbon resistance thermometers to magnetic fields with an improved stability. Carbon-glass shows good correctability (to within 10 mK [Sample et al. (1982)]) and little orientation dependence (equivalent temperature change less than 0.3% at 19 T from parallel to perpendicular position, between 4.2 K and 77 K). On the other hand, interchangeability is bad, as with germanium thermometers. The magnetoresistance of carbon-glass is much smaller (Fig. 19.5) than that of the previous types up to the highest field strengths but the same level of stability is never reached. In particular, carbon-glass thermometers have been reported to drift severely after a few years use in fields up to 12 T [Couach et at. (1982)].

Amongst the non-resistive thermometers used in cryogenics, none shows a reproducibility comparable with those of the resistance types. The magnetoresistance of diode thermometers (Chapter 14) is strongly orientation-dependent in magnetic fields. Correctability and interchangeability are poor. Some types of thermocouple have limited magnetic shift (see Table 19.1) but, apart from the intrinsic low accuracy, correction is almost impossible as the error develops along the *whole* length of the wire immersed in the magnetic field and stray emfs develop especially where field gradients are strong (there is no effect at all if the magnetic field region is isothermal). A capacitive thermometer is impervious to magnetic-field errors but the capacitance of the usual material ($SrTiO_3$) is known to be unstable on thermal cycling and dependent on charge effects and on the applied voltage. In addition, the capacitance versus temperature characteristic is not monotonic below 100 K. Some new ceramic materials may avoid these drawbacks [Chen Pufen and Li Jinwan (1986)].

At present none of these non-resistive thermometers should be considered as reliable storage for a traceable temperature scale, whether a magnetic field is involved or not. It is perhaps worth noting that two non-electric thermometers are best-suited as standards for approximating the temperature scales in the presence of a magnetic field: vapour pressure thermometers (except when using oxygen, which is paramagnetic) and gas thermometers. They are intrinsically immune to magnetic errors. They suffer the drawbacks, of course, of large size and complicated measurement requirements.