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BS 1041-3: 1989

Temperature measurement —

Part 3: Guide to selection and use of industrial resistance thermometers

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Foreword

This Part of BS 1041 has been prepared under the direction of the Industrial-process Measurement and Control Standards Committee. It is a revision of BS 1041-3:1969 which is withdrawn, revision having proved necessary as a result of continuing developments. This revision is intended to provide guidance on the selection and use of resistance thermometers, primarily in the sphere of plant instrumentation but also for scientific and technological use in many other fields.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 16, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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0 Introduction

All materials that conduct electricity exhibit some change of resistance with temperature. However, the magnitude and character of that change depends upon the material used, as does the temperature range over which it may be used. For many years practical thermometers relied upon a small number of pure metals, having positive changes of resistance with temperature. However, in the past few decades semiconductor materials have become available, enabling the production of resistance thermometer sensing resistors possessing much greater variation of resistance with temperature, and with negative or positive characteristics. Standardization of semiconductor elements has not yet been achieved but new fields of application of resistance thermometry have been opened up by their development. However, although a wide variety of metallic and semiconductor resistance thermometer sensors have been developed for special applications, particularly at very low temperatures, this code is concerned only with those which have achieved substantial industrial usage.

In the past, resistance thermometry practice usually favoured the use of null-balance bridges, generally resistive, but sometimes capacitive or inductive. Nowadays, constant current circuits are available enabling resistance thermometer sensors to be used with standard voltage measuring instruments (e.g. digital voltmeters). Also, as a result of recent advances in digital electronics and the use of microprocessors, there are now available a number of digital thermometers which indicate directly in temperature units.

1 Scope

This Part of BS 1041 gives guidance on the selection and use of industrial resistance thermometers incorporating a metallic or semiconductor sensing resistor, which changes in resistance with temperature.

NOTE The titles of the publications referred to in this standard are listed on the inside back cover.

2 Definitions

For the purpose of this Part of BS 1041, the following definitions apply.

2.1
resistance thermometer

a measuring device for ascertaining and exhibiting, in some suitable manner, the temperature of the thermometer sensing resistor. Essentially, it consists of a sensing resistor together with a measuring element and some form of interconnection

2.2
resistance thermometer sensor

a temperature-responsive device consisting of a sensing resistor within a protective sheath, internal connecting wires and external terminals to permit the connection of electrical measuring elements

NOTE 1 Mounting means or connection heads may be included.

NOTE 2 Typical constructions are shown in Figure 1.

2.3
sensing resistor

that part of the resistance thermometer sensor of which the change in resistance is used to measure temperature

2.4
measuring element

that part of the thermometer which responds to the change of resistance of the sensing resistor and enables an evaluation of the temperature of that resistor to be made

2.5
internal connecting wires

that part of the thermometer which provides electrical connection between the sensing resistor and the terminals at the head of the sensors

NOTE Compensating leads may be included.

2.6
external connecting cable

that part of the thermometer which connects the terminals at the head of the sensor to the measuring element

NOTE In some designs of thermometers which are not fitted with terminals, the internal and external connecting wires may be joined together within the head of the thermometer sensor.

2.7
metallic resistance thermometer sensor

a resistance thermometer sensor, the sensing resistor of which is a metallic conductor

2.8
semiconductor resistance thermometer sensor

a resistance thermometer sensor, the sensing resistor of which is a semiconductor

2.9
resistance ratio

the ratio of resistance at a temperature t °C to that at 0 °C (expressed as R_t/R_0)

2.10
padding resistor

a resistor which is sometimes used in conjunction with the sensing resistor to bring the resistance of the thermometer sensor within specified limits

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3 Principle of resistance thermometry

The electrical resistance of a material varies with any change in its temperature. In a resistance thermometer sensor, a metallic conductor or a semiconductor material with a large, reproducible and stable change of resistance with temperature is mounted to give mechanical and chemical protection while maintaining good thermal contact with its environment. Electrical connections are provided so that the resistance may be measured. This resistance can be related to temperature once the characteristic has been established.

4 Constructional features of metallic resistance thermometer sensors

Platinum is predominantly used for the sensing resistors of industrial metallic resistance thermometer sensors because its refinement and properties are well established, its temperature/resistance characteristic is reproducible and it can be used up to about 850 °C. Nickel is sometimes used on the grounds of economy or because of its better sensitivity, but its characteristic is less linear. Copper, which has good linearity but sensitivity poorer than nickel, is also sometimes used, but neither of these base metals is normally suitable for sensing resistors which are to be used outside the range – 100 °C to + 180 °C.

In order to maintain long-term stability it is necessary to minimize strain in the sensing resistor during fabrication and subsequent use. It is also desirable that resistance thermometer sensors should be constructed such that:

a) thermoelectric voltages which may be generated by the use of dissimilar metals cancel each other;

b) current flowing through them produces insignificant self-heating;

c) the windings are non-inductive;

d) they are suitable for use in measuring systems using direct current or alternating current at frequencies up to 500 Hz;

e) the transmission of heat to and from the sensing resistor by conduction along the sheath, internal wires and insulators is negligible;

f) the insulation resistance between the sensing resistor (including its internal connecting wires) and the protective sheath is adequate.

The design of a platinum wire-wound industrial sensing resistor necessarily involves a compromise between insensitivity to vibration and stability of characteristic, since to maximize its ability to withstand vibration the wire should be fully encapsulated and cannot therefore be entirely strain-free. (In contrast, thermometers made for use as laboratory standards of the highest accuracy are usually constructed so that the resistance wire is free to expand and contract with the minimum of constraint.) For industrial thermometers where vibration levels are such that it is essential to attach the wire firmly to the former, the wire is usually wound upon a glass or ceramic former, which is then coated with glass or ceramic cement. The coating is selected in an attempt to match the expansion properties of the platinum, but although the thermometer is extremely robust it has somewhat poorer stability than a partially-supported coil. The temperature range over which it can be used does not normally exceed 500 °C.

In the partially-supported coil construction, helical coils of platinum wire are mounted in the bores of a multi-bore alumina tube. The coils are anchored by a small amount of glaze so that while the greater part is free, a small portion of each turn is attached. An alternative method involves embedding the platinum coil in alumina powder to reduce the effects of vibration. By these techniques, thermometers with stabilities of a few hundredths of a degree can be constructed for use over the range – 200 °C to + 850 °C.

Recent years have seen the introduction of a design of metallic resistance thermometer sensor in which the sensing resistor is a film of platinum deposited onto a suitable substrate. Such sensors, which can be produced at a very modest cost, are highly insensitive to vibration and have stabilities similar to those of wire-wound glass-coated detectors over the range from about – 50 °C to + 500 °C. They are particularly suited to applications such as surface temperature measurement and air temperature monitoring. They generally show fast time response, due to the intimate contact of the film with the substrate and the lower mass that needs to be heated.

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Constructional methods similar to those described for platinum may be used with other metals, such as copper and nickel. Resistance thermometer sensing resistors of all types can be fabricated in various shapes, limited only by the need to ensure an adequate electrical resistance efficiently insulated. The surface area can be made large in relation to the volume to provide fast response or the sensing resistor can be made compact for measuring temperature at a point. Alternatively, it can be extended over a considerable distance so as to measure an average temperature.

It is sometimes permissible to immerse the sensing resistor directly in the medium of which the temperature is being measured. This method has the advantage that the sensor responds rapidly to temperature changes. Generally, however, some form of protection is necessary. This may be merely a ventilated cover for mechanical protection as in the measurement of static or low-velocity air temperatures, or a completely enclosed and sealed sheath for protection against corrosive or electrically-conductive fluids, high pressures or abrasive media.

Where total enclosure of the sensing resistor is necessary, special consideration should be given to the thermal conductance between the sheath and the sensor and precautions will be needed to minimize errors caused by conduction of heat along the sheath as well as along the internal connecting wires. The time of response and the self-heating of the sensing resistor may also be significant, especially if it is situated inside a heavy thermowell, or is being used to measure static gas temperatures.

5 Constructional features of semiconductor resistance thermometer sensors

The temperature-sensitive material is usually a sintered metal oxide and is often encapsulated in glass. As no support is required and as the resistivity is much higher than that of any metal used in resistance thermometry the sensing resistors can be extremely small. Typically a bead, 0.25 mm to 0.5 mm diameter, is thinly glazed, and supported by its leads. To provide further chemical and mechanical protection and electrical insulation it may be sealed in the tip of the glass probe.

Sensing resistors in rod or disc form are commonly available, thin discs being particularly suitable for surface temperature measurement. However, generally, semiconductor sensors are not appropriate for use in averaging temperature measurement.

6 Characteristics of resistance thermometers

6.1 General

Characteristics which are common to both metallic and semiconductor resistance thermometer sensors include the following.

a) An external power supply is always required to energize the resistance thermometer sensor. Operation may be by direct current or by alternating current at frequencies usually not in excess of 500 Hz.

b) The energy dissipated in the sensing resistor by the current that passes through it causes a rise of temperature of the resistor above its surroundings. The magnitude of the temperature rise depends upon the design and construction of the sensing resistor, its mounting and the medium in which it is used, as well as upon the measuring current. For example, an unmounted resistor which has a self-heating effect of < 0.01 °C/(m·W) when immersed in a stirred water bath, may show an effect between 20 and 40 times greater when used in unstirred air. In practice, the energy dissipated is limited so as to prevent significant errors in temperature measurement, while still maintaining a relatively high output signal.

c) Thermal response time is limited by the need to protect and insulate the temperature-sensitive material. Variations in construction lead to widely differing response times. A response time of 0.5 *s* or less can be achieved with some sealed sensors.

d) It is possible to make circuits intrinsically safe.

e) The accuracy of the measuring element can be checked by substituting precision temperature-stable resistors for the sensing resistor.

f) Measuring circuits can be used in which no compensation is necessary for changes in ambient temperature.

6.2 Metallic resistance thermometer sensors

Metallic resistance thermometer sensing resistors capable of providing accurate, reliable and reproducible temperature measurement in the range from about – 260 °C to + 850 °C (or higher) are available, but it should be emphasized that only with more specialized resistance thermometers can temperatures below – 200 °C or above 600 °C be measured. Metallic sensing resistors possess the following special characteristics.

a) The temperature coefficient of resistance is always positive.

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b) Resistance thermometer sensing resistors manufactured to conform to standard characteristics are electrically interchangeable within defined tolerances (see BS 1904).

c) The mathematical expression relating resistance ratio and temperature of platinum, given in BS 1904, may be employed in bridge networks and computer calculations.

d) The stability of a metallic resistance thermometer sensing resistor makes it suitable for narrow temperature spans when a sufficiently sensitive measuring element is available.

e) Calibration checks are required only where the greatest possible accuracy is necessary, or when overheating or other misuse is suspected.

f) Any number of sensors can be switched to the same measuring element, although switch resistance may influence the accuracy attained.

6.3 Semiconductor resistance thermometer sensors

Semiconductor resistance thermometer sensing resistors are normally capable of reproducible temperature measurement over a limited part of the range – 100 °C to + 300 °C. However, with specialized materials and constructions, temperatures outside this range can be measured. Semiconductor temperature sensing resistors, in general, possess the following characteristics.

a) Semiconductor resistance thermometer sensors have sensitivities very much higher than those of metallic thermometer sensors.

b) Semiconductor resistance thermometer sensing resistors are usually of much higher resistance than metallic resistors, so they are less affected by interconnection resistances.

c) Materials with either positive or negative temperature coefficients of resistance are available.

d) Semiconductor sensing resistors can be made very cheaply when errors within about 1 °C are acceptable on the replacement of a sensor. When closer interchangeability is required the sensors may be adjusted, or specially selected by the manufacturer, or compensated by a suitable network.

e) Approximate linearity of resistance change of a circuit, over a range of ± 20 °C about a nominal temperature, can be achieved by a simple shunt. Similarly, linearity of voltage output can be obtained by the use of a series resistor. Linearity over wider ranges can be achieved by more sophisticated electronic means.

f) The stability of a suitably processed and protected semiconductor sensing resistor, subjected to a limited range of temperatures, can be comparable with that of a standard metallic sensor. Glass-protected types are the most stable and are suitable for the higher temperatures of use.

g) Overheating or other misuse can cause a significant change of characteristic. The effect of damage is not always obvious and it is advisable to check the sensor accuracy at regular intervals, or when misuse is suspected.

h) Any number of sensors can be switched to the same measuring element. Accuracy is then limited by sensor interchangeability.

7 Selection of resistance thermometer sensors

There is an extremely wide range of resistance thermometer sensors available and selection of the most suitable for a particular application needs care. Where significant levels of vibration, thermal shock or nuclear radiation are likely to be encountered in service, the manufacturer should be consulted because some designs of thermometer sensors are likely to be affected less than others. It is particularly important that the manufacturer be consulted where thermometers are to be exposed to neutron irradiation, because as well as stability considerations, the elements of the sensor may become radioactive, creating long term handling problems. Some of the relevant parameters are as follows.

Plastics begin to deteriorate when the accumulated exposure to gamma radiation reaches 10^6 Gy (10^8 rads) although with some plastics it is possible to exceed 10^7 Gy (10^9 rads) when the exposure is accumulated in a short time.

A wide range of materials have a significant cross section for neutron capture and in some cases long term radiation sources can be created by exposure to thermal neutrons for a short time. Longer exposures result in transmutation of the materials so that the electrical resistance will change.

Materials in general show smaller effects from exposure to fast neutrons. However, accumulations of damage due to atom displacement and transmutation, which fast neutrons cause, can produce hardening and other effects in metallic materials and fragmentation of some ceramics.

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In addition to finding a suitable type of sensor for the particular environmental conditions, it is necessary to consider methods of indication, compatibility with existing systems, and overall economy as factors in sensor selection. However, for general purpose measurement of temperature at a point, platinum resistance thermometer sensors to BS 1904 with the preferred sizes given in BS 2765 will usually be found to be satisfactory and should be used whenever possible.

If these specifications are not acceptable, it is advisable to consider other established types of resistance thermometer sensors, as special designs are expensive and can entail delay when replacements are required.

A semiconductor sensing resistor is most likely to be chosen where small size, high output, low cost or special characteristics are significant factors.

Semiconductor sensing resistors comprise three main types.

a) Those having a negative temperature coefficient of resistance of exponential form, usually made from metal oxides. These sensing resistors are usually called “NTC thermistors” and are the type most commonly used for temperature measurement.

b) Those having a positive temperature coefficient which is relatively linear over the customary range of use; the commonest type is the silicon resistor. These sensing resistors are usually called “PTC thermistors”.

c) Those having a positive temperature coefficient with a marked discontinuity at a characteristic temperature at which the resistance rises very steeply. This characteristic point depends upon the semi-conductor material composition and can be varied in manufacture. The material is usually a metallic titanate. These sensors are mainly used as switching devices for over-temperature protection of transformers, motors, heaters, etc.

Other semiconductors using silicon, germanium and gallium arsenide are also used in temperature measurement. However, with the exception of germanium, which is used in resistance thermometry well below 0 °C, these materials are usually used in the form of diodes over very limited temperature ranges.

Figure 2 shows the resistance/temperature characteristics of typical semiconductor sensing resistors compared with platinum.

The temperature limitations of the more usual sensing resistors are given in Table 1. Other materials are available for special application, e.g. tungsten or molybdenum metallic sensors for high temperature use, rhodium-iron and germanium sensors for low temperatures, and special types of semiconductor sensors for use up to 1 000 °C, but these should be used only after careful consideration of the problems involved.

Table 1 — Operating temperature of resistance thermometer sensing resistors

Sensing resistor	Normal minimum operating temperature	Normal maximum operating temperature	Special maximum operating temperature
	°C	°C	°C
Metallic sensing resistors			
Copper	– 100	+ 100	+ 150
Nickel	– 60	+ 180	+ 350
Platinum	– 200	+ 600	+ 850
Semiconductor sensing resistors			
Mixed metal oxides	– 100	+ 200	+ 600
Silicon	– 160	+ 160	+ 200

NOTE 1 Satisfactory measurement at temperatures above the normal maximum is possible only when special constructions and carefully controlled environments for the sensing resistors are used.

NOTE 2 Platinum resistance thermometer sensing resistors of special construction can be used to measure temperatures down to – 259 °C (14 K). Below – 200 °C, sensors have to be individually calibrated.

NOTE 3 Copper resistance thermometer sensing resistors of special construction can be used to measure temperatures down to – 200 °C.

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The approximate relationship of resistance ratio to temperature for platinum, nickel and copper is given in Table 2.

Table 2 — Approximate relationship between resistance ratio and temperature for metallic sensing resistors

Temperature	**Resistance ratio R_t/R_o**		
	Platinum[a]	**Nickel**	**Copper**
°C			
– 200	0.18	—	—
– 100	0.60	—	0.57
– 60	0.76	0.70	0.74
– 50	0.80	0.74	0.79
0	1.00	1.00	1.00
50	1.19	1.29	1.21
100	1.38	1.62	1.43
150	1.57	1.99	1.65
180	1.68	2.23	—
200	1.76	—	—
250	1.94	—	—
300	2.12	—	—
350	2.30	—	—
400	2.47	—	—
500	2.81	—	—
600	3.14	—	—
700	3.45	—	—
800	3.76	—	—
850	3.90	—	—

NOTE Some thermometer sensors use padding resistors to bring the resistance of the sensor within specified limits. Generally, they are used in series with the sensing resistor, but in some types of nickel thermometers both series and shunt padding resistors are used to enable the thermometer sensor to match an exponential resistance/temperature curve.

[a] See BS 1904.

8 Procedure for installation

It is assumed in the siting of the thermometer sensor and the choice of thermometer pocket that any advice given by the suppliers of the resistance thermometer sensor has been considered. The following additional advice is applicable to most installations.

a) Cables containing single-strand cores have the disadvantage that breakage of the strand results in disconnection of the circuit, while multi-strand conductors give rise to the possibility of erroneous measurements in bridge circuits due to unsuspected changes in conductor resistance caused by strand breakage.

b) Cables should be routed, and their total resistance should be limited, so as to minimize changes in conductor resistance due to ambient temperature changes.

c) Cables should be positioned to minimize any electromagnetic pick-up from adjacent current-carrying conductors. In particular, parallel runs should be avoided. It is usually advisable to enclose the conductors in a conducting screen which may take the form of conduit or continuous braiding. Twisting of the wires together is also effective.

d) Insecure electrical connections are a source of variable resistance. Where joints between cables are essential, they should be in a junction box for ready inspection. Conditions causing deterioration of joints are vibration, corrosion and thermal cycling.

e) No earth connection should normally be allowed on either the sensing resistor or any part of the circuit. A test of insulation resistance to earth is usually desirable; this should be repeated whenever exposure to damp or corrosion is suspected. It is occasionally necessary to prevent the build up of static electricity in the system, since this can cause insulation breakdown. A resistive earth connection from a suitable point in the measuring circuit is then desirable.

f) When a 2-wire bridge circuit is used, the measuring element is arranged for a constant terminal input resistance at a fixed temperature. A ballast resistor, adjustable by the user, brings the measured external resistance of the sensor and connections up to this value.

g) When 3-wire or 4-wire bridge circuits are used, each wire should have the same resistance. The total resistance should be limited to the value recommended for the measuring instrument selected.

It is often convenient to connect two or more thermometer sensors in sequence to a single measuring element. It is necessary to use a switch of constant low resistance and to ensure that the various interconnection resistances are all within the tolerances appropriate to the measuring circuit being used.

h) Conductor materials, and the location of electrical connections between different conductor materials should be chosen so as to minimize errors caused by thermoelectric effects.

Systems using a.c. excitation are not prone to error from this source.

i) It may be necessary to take into account the capacitance between conductors in an a.c. system.

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9 Measuring circuits

9.1 General

Measurements are made by passing current through a sensing resistor and measuring the potential across it. If the current is known, the potential is a measurement of the resistance and hence the temperature. If the current is not known exactly the potential may be compared with the potential across a known resistor; this is the basis of the bridge systems discussed below. Bridge circuits may be either the null-balance (balanced-bridge) type or the direct-deflection (fixed-bridge) type. Whichever of these methods is employed, the requirement is to determine the resistance of the sensing resistor independently of the resistance of the connections.

9.2 Bridge systems

9.2.1 *General.* All bridge resistors, the temperature sensing resistor excepted, are arranged to have a negligible change of resistance with temperature, and in a.c. bridges are non-inductive.

When a bridge circuit is used, it is customary to connect the resistance thermometer sensor to the measuring bridge by copper conductors, which may have an appreciable change of resistance with temperature. Assuming that the correct installation procedure has been followed, errors due to changes in conductor temperature are kept within acceptable limits, partly by making the conductor resistance small in relation to the sensing resistor and partly by the circuits discussed below.

All circuits require a source of low voltage electrical supply which is commonly a smoothed and stabilized d.c. power source. In some designs, an alternating supply is used, which may have a frequency of up to 500 Hz.

9.2.2 *Balanced-bridge instruments.* The bridge circuit is maintained in a balanced condition by manual or automatic adjustment of resistance in one or more arms of the bridge. In Figure 3 to Figure 11, “balance” means an absence of potential between “a” and “c” and hence zero current through the balance detector, which may be a galvanometer or an electronic amplifier.

The adjustable resistance usually takes the form of a slidewire which is linked mechanically or electrically to an associated temperature scale. Figure 3 illustrates the simplest form of this circuit. The sensing resistor is contained within the arm “cd”. The condition of balance occurs when $R_{ab}/R_{bc} = R_{da}/R_{cd}$ so that the value of R_{da} is a measure of R_{cd} when R_{ab}/R_{bc} is known. It is usual practice to make $R_{ab} = R_{bc}$ so that $R_{cd} = R_{da}$ at balance.

The balanced condition of the bridge is not affected by normal variations in the voltage supplied to it, but it should be noted that the current in the balance detector when the bridge is not balanced is proportional to the applied voltage. This affects the out-of-balance voltage which may occur before a correction to the resistance R_{da} is required, i.e. it affects the discrimination of the measuring system.

9.2.3 *Compensation for conductor resistance.* Simple circuits illustrating the method of compensating for conductor resistance are shown in Figure 4 to Figure 6. Compensation is only completely effective in balanced-bridge circuits.

In industrial applications of these electrical circuits, the resistance thermometer sensor can be remote from the rest of the bridge and connected to it by copper conductors. The resistance thermometer sensor together with the conductors constitutes R_{cd}.

Figure 4 represents a circuit designed for a fixed maximum value of conductor resistance, with an adjustable resistor inserted in “cd” to make up this maximum value. The resistance of the copper conductors changes with variation in the ambient temperature and when the conductors are long or of inadequate cross section, this change in resistance may be so large as to cause a significant error in the temperature reading. (For example, the temperature coefficient of resistivity of copper is such that a copper cable of resistance 1 Ω will change by 4 mΩ, per °C change in ambient temperature; this is equivalent to 0.02 °C change in resistance reading of a 100 Ω platinum sensing resistor, if two such leads are used to connect it to the measuring circuit.)

The error may sometimes be kept within acceptable system limits by choice of conductor size, but “2-wire” installations are usually restricted to a maximum of 1 Ω to 2 Ω per conductor resistance (corresponding to about 100 m of cable). Other forms of bridge are used for cable runs in excess of this and are satisfactory for cable runs of 10 Ω to 15 Ω per conductor (typically 1 km).

Figure 6 indicates how the effect of the resistance of the conductor and its variation with temperature can be substantially eliminated by inserting an equal length of identical conductor in “da” (generally using multi-core cable). This is commonly described as a “4-wire compensating-cable system”.

Figure 5 shows how a similar result may be obtained by connecting one conductor of the power supply to the connecting head of the resistance thermometer sensor. This is commonly described as a “3-wire system”.

In the circuits represented by Figure 5 and Figure 6 it is necessary for R_{ab} to be equal to R_{bc} to obtain complete compensation.

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In addition to the errors introduced by the resistance of the conductors, the sliding contact incorporated in the arm "da" in Figure 3 to Figure 6 is capable of introducing errors, since resistance at the contact is added into the bridge arm. Various circuit arrangements are employed in practice (see Figure 7 to Figure 11) to avoid such errors, by arranging that contact resistance is introduced into the current supply or the balance detector circuit, where it cannot affect the accuracy of the bridge balance.

In the circuit of Figure 8, the resistance of the conductors in the bridge arms should be equal but, even so, the balance position is completely independent of interconnection resistance at only one position of the contact, where $R_{ab} = R_{bc}$. By a suitable choice of values, however, adequate accuracy can be obtained over the full range of contact movement.

A compensated circuit, using one slidewire only, is provided by the use of a 4-wire system (see Figure 9). When $R_{ab} = R_{bc}$, the position of balance is completely independent of conductor resistance, provided that the resistances of each conductor pair are equal.

All the bridges systems described can be made self-balancing by using a servo-mechanism controlled from the balance detector.

9.2.4 *Inductive-ratio bridge.* This is an a.c. bridge method incorporating precision-wound transformers for ratio arms. It is capable of the highest accuracy and can be made robust and transportable; it has a negligible temperature coefficient and can be made very stable.

9.2.5 *Fixed-bridge instruments.* In a fixed-bridge instrument only the sensing resistor is allowed to vary, the other bridge resistance being chosen so that the bridge is in balance for one value of R_{cd}.

At temperatures represented by other values of R_{cd}, the out-of-balance voltage developed across a-c is a measure of the temperature, provided that the bridge supply voltage is stabilized.

2-wire, 3-wire or 4-wire circuit arrangements (see Figure 4 to Figure 6) may be used, R_{ad} being a fixed resistor.

If a 2-wire system is used, the method of correction for conductor resistance is the same as that used for a balanced bridge.

If a 3-wire or 4-wire system is used, compensation is only complete at the point when the bridge is balanced. The error in the latter can be reduced by raising the resistance values of R_{ab} and R_{bc} so as to minimize changes in bridge current as the thermometer sensor resistance changes with temperature.

Although the detector may be a simple galvanometer with direct deflectional indication of temperature, in practice an electronic amplifier is normally used to provide a high input impedance and sufficient power to drive a more robust deflectional instrument. Alternatively, the bridge out-of-balance voltage can be measured using a digital voltmeter or a potentiometric indicating and recording instrument.

9.2.6 *Differential temperature measurement.* For differential temperatures a second resistance thermometer sensor is introduced into "da", two 2-wire cables being used (see Figure 10); this arrangement is suitable for conditions in which both cables are of similar resistance. Where the two cables are of different length or resistance and the highest accuracy is required, improved compensation is effected by the use of two 4-wire cables (see Figure 11). Bridge arms "cd" and "da" each contain a pair of wires from both cables and at the balance point $R_{cd} = R_{da}$.

9.3 Potential systems

If the sensing resistor is energized from an accurately-known and constant current source, the potential difference developed across it can be directly related to resistance, and thus to temperature.

A four-terminal network is used in the manner shown in Figure 12.

The principles of a potential system are as follows.

a) During measurement negligible current flows in the potential circuit. This requires that the input impedance of the potential measuring device be considerably greater than the sensing resistor, in order to minimize circuit loading errors during measurement. (For example, a 0.1 % error will result from an input impedance 1 000 times the sensor resistance.)

b) A temperature-measurement signal in the form of a voltage is available.

c) A number of sensors can be connected in series with the same current source, enabling voltages from each to be scanned at any speed acceptable to the measuring instrument.

d) Accurate measurements of resistance can be made if the current is accurately known. Alternatively, accurate comparisons of resistance can be made, since the current is constant even though, possibly, unknown.

e) Measurements are independent of conductor resistance and selector switch contact resistance.

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Potential systems can be used for accurate high-speed work when a number of measurements have to be made repeatedly, as in scanning and data-handling. Such systems are readily kept accurate by frequent checking of the voltage across a stable check resistor carrying the same current as the resistance thermometer sensors. The sensors can be connected in series with the same current source, the voltage across each in turn being measured. Alternatively, the current source can be switched to each sensing resistor in turn.

Small errors in current, attributable to such causes as ripple, poor resolution of the current setting or poor regulation, appear directly as an error in read-out. Due regard should be paid to the effects of change in load resistance, ambient temperature and drift with time when selecting a constant current device. In particular, design limits on the maximum load resistance of the current source may restrict the number of resistance thermometer sensors that can be connected in series.

10 Measuring instruments

10.1 General

Clause **9** describes the circuit principles most commonly used in resistance thermometry. The various instruments available which embody these circuits are outlined in **10.2** to **10.6**, but full descriptions of the instruments are not given.

NOTE Consideration of the accuracy of any instrument or system has been specifically excluded.

10.2 Instruments that include fixed-bridge circuits

10.2.1 *General.* The out-of-balance potential of a fixed-bridge changes progressively with changes in sensing resistor temperature and offers a changing signal to a detector.

10.2.2 *Galvanometer instrument.* A detector which was commonly used in the past, and which is still sometimes used, is the moving-coil galvanometer. It may be arranged to indicate temperature directly on a graduated scale.

The galvanometer may be fitted with one or more limit detectors which operate at pre-set deflections. Photoelectric or inductive principles are commonly employed. Operation of the detector may be used for “on-off” control and for alarms.

10.2.3 *D.C. amplifier or other signal-converter.* The fixed-bridge out-of-balance voltage is amplified without significant disturbance of the bridge power, to provide an analogue output of sufficient power to feed into local or remote indicators, recorders or controllers.

Alternatively, an analogue-to-digital converter is used in conjunction with a linearizing circuit or microprocessor, to provide a digital display in temperature units.

An amplifier designed with a very low power requirement is used in conjunction with a fixed-bridge network to produce a signal-converter for installation close to the resistance thermometer sensor. As well as minimizing sensor connecting cable resistance, the converter provides a large analogue signal with high electromagnetic interference immunity for connection to remote control or data-handling equipment. Two conductors are used to connect the converter to its remote power supply and to carry both supply and measurement currents. The transmitter current is usually 4 mA d.c. to 20 mA d.c., the amplifier and fixed-bridge being adjusted so that 4 mA corresponds to the minimum measuring temperature.

10.2.4 *Self-balancing recorder or indicator.* A potentiometric recorder is used to measure the out-of-balance voltage across the fixed-bridge. The constant-voltage bridge supply and fixed-bridge resistors are usually contained within the instrument circuit.

10.3 Instruments that include null-balance bridge circuits

10.3.1 *General.* A null-balance bridge requires adjustment of the resistance or impedance value in one, two or three arms of the bridge in order to achieve a balance; a detector serves to determine that balance has been reached.

The position of the adjusting mechanism is then a measure of temperature. The instrument may take one of the forms given in **10.3.2** or **10.3.3**.

10.3.2 *Manually-adjusted bridge.* This may use a galvanometer or, more usually, an amplifier and analogue panel meter.

10.3.3 *Automatic self-balancing bridge.* This normally employs an amplifier as the detector, which reacts to any out-of-balance condition and actuates a servo-mechanism to balance the bridge. The mechanism may form part of an indicator, recorder or controller.

10.4 Instruments that include potential systems

The instrument is connected directly across the resistance thermometer sensor, which is energized by a stable current source. It is important that the impedance of the measuring element is high enough to ensure that the current through it is negligible compared with the total current through the temperature sensing resistor. The measuring element may take one of the following forms.

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a) Manually-operated potentiometer.

b) Self-balancing potentiometric indicator, recorder or controller.

c) Voltage amplifier or other signal-converter. This provides an analogue output of sufficient power to feed into separate indicators or recorders.

d) Digital voltmeter. This provides a direct reading of the voltage across the resistance thermometer sensor. It may also be used to feed a digital signal into a remote display unit, a computer or other data-handling systems.

10.5 Multi-point instruments

A multi-point instrument is one in which a single measuring element is used for determining the temperatures of each of a number of different resistance thermometer sensors.

Connection to each of the sensors is made by means of a selector switch (which may be mechanical or electronic), and the connection is maintained for sufficient time to permit the sensing and measuring elements to respond fully. The switch is usually driven so that it selects thermometer sensors in a regular sequence, the response time of the combined sensing and measuring elements imposing a practical upper limit on the frequency of selection.

The sensor selector switch is inserted directly into the measuring circuit; with some circuits, particular care in design is essential to minimize possible errors arising from switch contact resistance and switch thermal e.m.f.s. The errors are most likely to be significant in systems designed for rapid selection.

Solid state switching is essential for some fast scanning systems, and can lead to accuracies comparable to those obtainable with the best type of mechanical switching.

Multi-pen recorders are frequently used to overcome the problems of discontinuous measurement and possible input selector switch problems inherent in multi-point instruments. Each measured input may be complete with its own amplifier, measuring circuit, servo-mechanism and recording pen, permitting a different temperature range for each record.

Modern designs of instruments may have an individual pen and step-motor servo for each input, selection of inputs and repositioning of the recording pen being microprocessor-controlled.

10.6 Multi-range instruments

A multi-range instrument is one provided with a means of selection which permits its use on any one of two or more temperature ranges, the span of the measuring element being caused to correspond with each range thus selected.

The accuracy of the complete instrument system is often limited by the accuracy of the measuring instrument, stated as a percentage of span. Optimum accuracy is then obtained by choosing the narrowest temperature range which is appropriate to the sensitivity of the measuring instrument.

In some instruments the range selection is made by means of a switch; in others (particularly digital-display thermometers) it is sometimes necessary to interchange printed circuit cards. Where a range selector switch is fitted, this may give rise to errors due to contact resistance or to thermal e.m.f.s at the switch contacts.

11 Digital data-processing and logging systems

11.1 General

Data-logging is the automatic measurement and recording in digital form of a number of input signals. The information may be presented in various forms, e.g. typewritten in direct temperature units, coded on magnetic tape or disc, or punched tape or cards, for subsequent processing.

A typical system comprises a multiplexer (scanner), an analogue-to-digital converter and an output drive unit. To this basic system may be added modules to provide amplification of the input signal before measurement, linearization of the resistance/temperature characteristics of the sensing resistor, alarm initiation, etc.

11.2 Conversion systems

The resistance change of the resistance thermometer sensor can be converted to a corresponding d.c. voltage required by an analogue-to-digital converter for data-logging equipment by the following methods.

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11.2.1 *Potentiometric.* An accurately-known constant-current source is switched to each thermometer sensor in turn, together with the potential measuring connections to the converter. Four interconnections are required for each sensor. In some circuits direct output recording in temperature units requires zero voltage input when the temperature is at scale zero. This condition may be satisfied by connecting an accurate reference voltage (usually adjustable), corresponding to the voltage developed across the sensor at 0 °C, in opposition to the incoming signal before presentation to the analogue-to-digital converter. Alternatively, in some modern digital equipment, the 0 °C resistance of the thermometers may be keyed into the voltmeter, which then calculates the temperature directly.

11.2.2 *Fixed-bridge.* A number of fixed-bridges, each connected to a separate resistance thermometer sensor, are supplied from an accurate constant-voltage d.c. source. The bridge out-of-balance voltages are connected to the multiplexer.

The voltage supply is usually common to all bridges and, consequently, 2-pole out-of-balance voltage selection is imperative. As open-circuit bridge potentials are being measured the input impedance of the measuring instrument should be high enough to prevent circuit-loading errors.

Compensation for the resistance of the connecting wires and cable by 3-wire interconnections is commonly used, although designs using a modified Kelvin double bridge circuit are available (Figure 13). These require 4-wire connections to each thermometer and further reduce conductor resistance errors.

11.2.3 *Fixed-bridge with voltage amplifier.* An amplifier may be used with each fixed-bridge to provide a higher voltage or current (0 V to 5 V or 4 mA to 20 mA). Industrial practice is to use a 2-wire converter (4 mA to 20 mA), as described in **10.2.3**, for each resistance thermometer input. The increased output permits modification by shunting and potential-dividing and may more readily be made compatible with a system having facilities for measuring a variety of physical quantities, all converted to a common output signal (4 mA to 20 mA) for logging or processing.

The higher voltages available ease the duty of the multiplexer and are preferred for use with semiconductor switching. The location of the converter close to the resistance thermometer sensor minimizes interconnecting resistance problems and the high signal level electrical interference immunity, together with high resistance capability (typically 1 000 Ω) is eminently suitable for industrial use. Such systems can be designed to meet intrinsic safety requirements.

12 Linearization

12.1 General

Most sensing resistors use materials which have non-linear resistance/temperature characteristics. For many applications it is necessary or convenient to have a pointer deflection, digital indication or output signal which varies linearly with temperature changes.

12.2 Sensing resistor linearization

12.2.1 *Metallic sensors.* Many measuring elements are themselves approximately linear, and overall linearity may be achieved by the use of sensing resistors with linear characteristics. Copper can be considered to have linear characteristics over the temperature range from 0 °C to 100 °C, but to relate resistance to temperature outside this range, a second-order term needs to be introduced. The second-order terms in the characteristics of platinum and nickel have opposite signs; a composite sensing register of these two metals can be made approximately linear over the range of 0 °C to 100 °C.

12.2.2 *Semiconductor senses.* In systems using negative temperature coefficient thermistors, optimum linearity is obtained when the thermistor is energized from a source resistance having a value given by the equation:

$$R_s = R_T \frac{B - 2\,T_m}{B + 2\,T_m}$$

where

R_s is the source resistance;

R_T is the thermistor resistance at temperature T_m;

B is the material constant of the thermistor (in kelvins);

T_m is the temperature at the mid-point of the linear range (in kelvins).

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The resistance may be connected across the thermistor in constant-current systems, or in series in constant-voltage systems. The value of R_s may have to be adjusted to allow for the resistance of the measuring element.

12.3 Measuring element linearization

An instrument with a null-balance bridge, or a potential system, can provide a linear temperature output with special circuits or, in a few instances, by cam-corrected slidewires.

In a fixed-bridge circuit there is a non-linear relationship between the out-of-balance voltage and the change in value of the resistance thermometer sensor. The extent of this non-linearity depends not only on the non-linear characteristics of the sensing resistor but also on the load power which is drawn from the bridge by the indicator, i.e. it is inversely related to the indicator input resistance. Non-linearity due to this effect may be considerable for a galvanometric indicator but may be negligible for a potentiometric indicator or a d.c. amplifier with a high input impedance.

It is easier to make a linear fixed-bridge instrument with a nickel resistance thermometer sensor than with a platinum resistance thermometer sensor. The simple bridge network and a nickel sensor have opposing departures from linearity, which can be made to cancel one another. The departure from linearity of a platinum sensor and a bridge are additive, but correction may be made by using active circuits or non-linear components.

When the bridge out-of-balance voltage is fed to a computer or to an instrument containing a microprocessor, the conversion to temperature can be made by mathematical manipulation. The non-linear response of the sensing resistor may be corrected by polynomial-fitting to a standard curve, the thermometer coefficients being stored in the computer or in a read-only-memory in the micro-processor. Alternatively, segmented curve-fitting procedures may be used involving the storage of resistance/temperature tables in the computer or in a read-only-memory. In both cases it is possible to store coefficients or tables which relate to an individually-calibrated thermometer sensor.

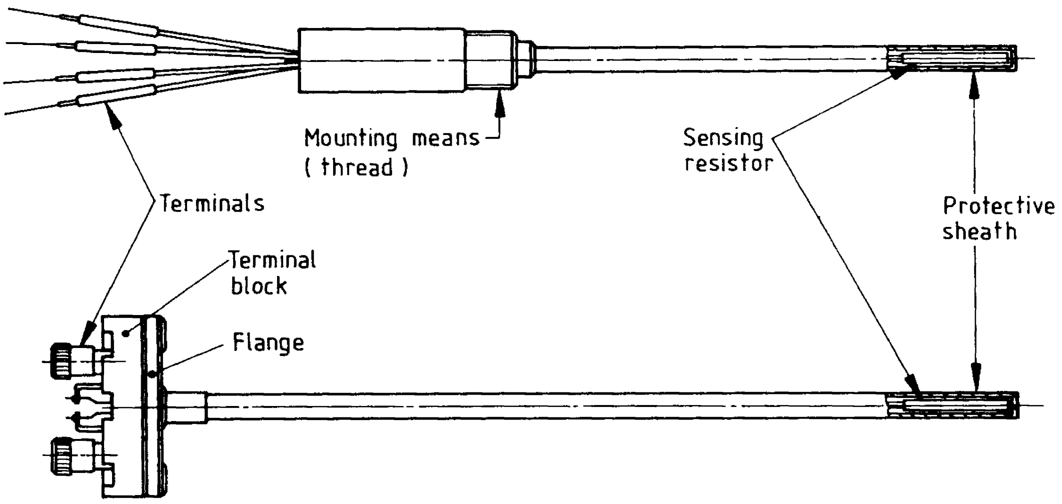

Figure 1 — Typical construction of resistance thermometer sensor

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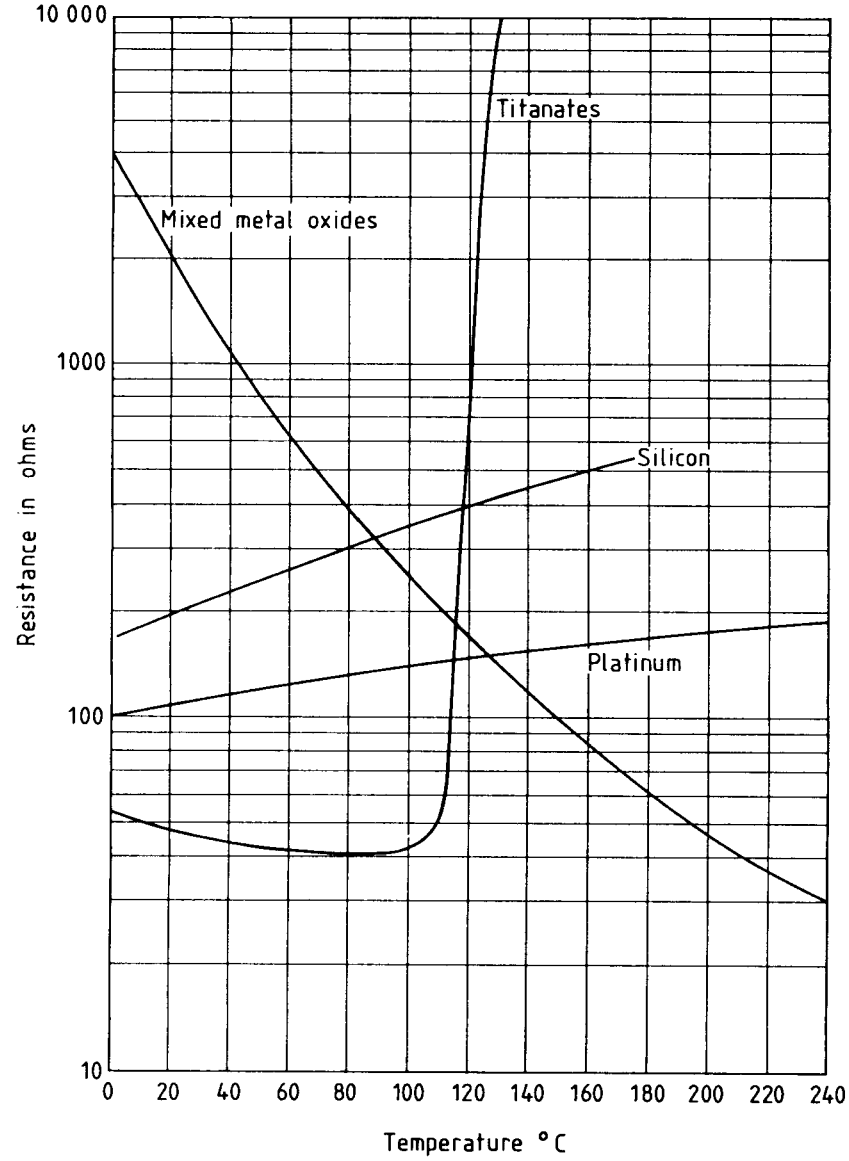

NOTE Platinum shown for reference.

Figure 2 — Resistance/temperature relationships for typical semiconductor resistance thermometer elements

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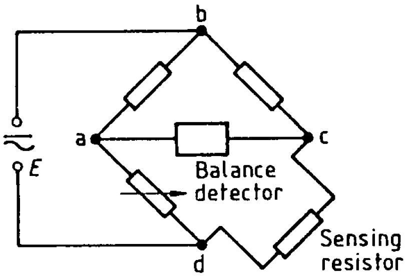

Figure 3 — Basic bridge circuit

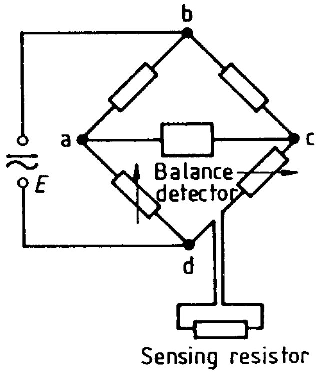

Figure 4 — Circuit for 2-wire system

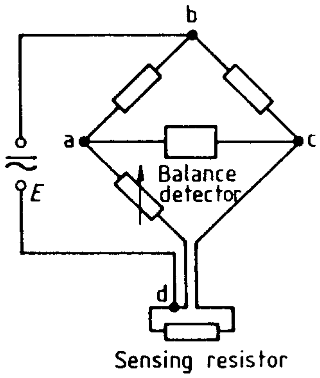

Figure 5 — Circuit for 3-wire system

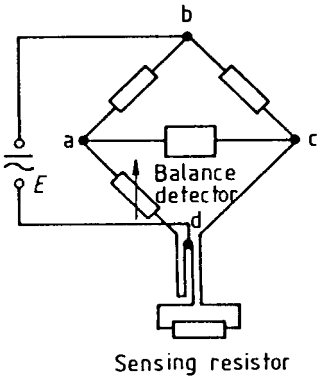

Figure 6 — Circuit for 4-wire compensated system

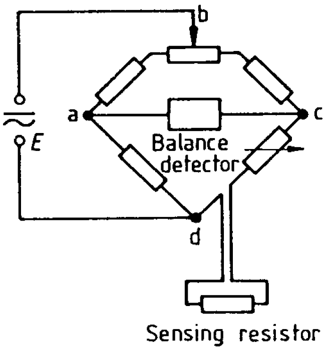

Figure 7 — Bridge (2-wire system)

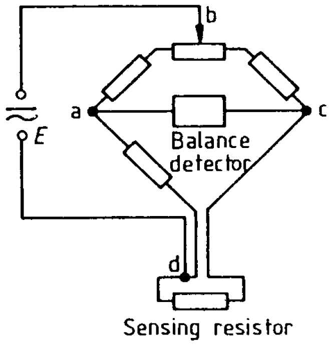

Figure 8 — Bridge (simple 3-wire system)

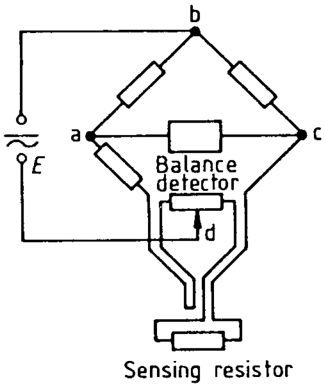

Figure 9 — Bridge (4-wire compensated system)

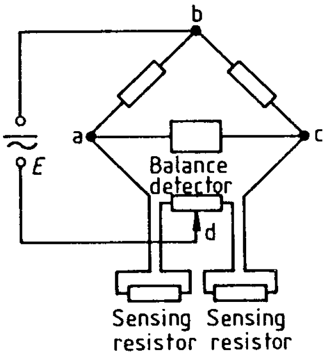

Figure 10 — Differential system

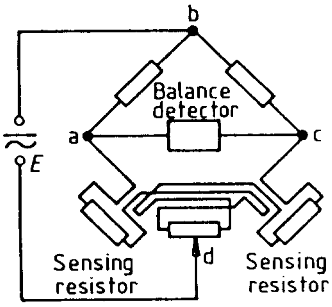

Figure 11 — Differential system with full conductor resistance compensation

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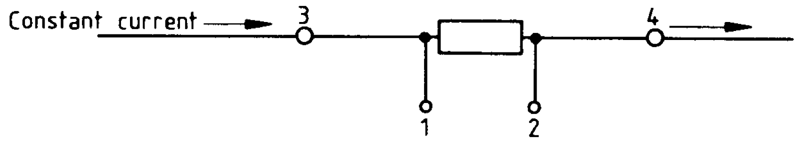

Figure 12 — Four-terminal sensing resistor

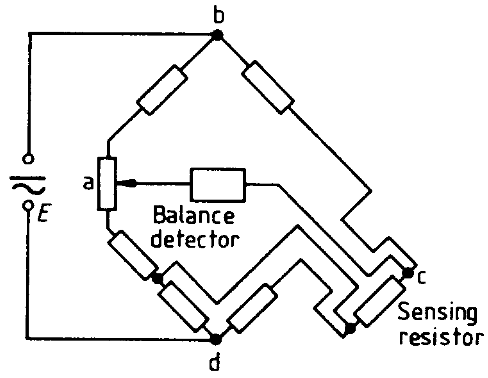

Figure 13 — Kelvin double bridge (modified)

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Publications referred to

BS 1904, *Specification for industrial platinum resistance thermometer sensors.*
BS 2765, *Specification for dimensions of temperature detecting elements and corresponding pockets.*

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