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Incorporating Amendment Nos. 1, 2 and 3

Methods for

Determining thermal insulating properties with definitions of thermal insulating terms

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Co-operating organizations

The Refrigeration, Heating and Air Conditioning Industry Standards Committee, under whose supervision this British Standard was prepared, consists of representatives from the following Government departments and scientific and industrial organizations:

Association of Consulting Engineers
Association of Manufacturers of Domestic Electrical Appliances
Boiler and Radiator Manufacturers' Association
British Mechanical Engineering Confederation
British Oil and Gas Firing Equipment
Manufacturers' Association
British Refrigeration and Air Conditioning Association*
Department of the Environment*
Department of Health and Social Security*
Electricity Council, The Central Electricity
Generating Board and the Area Boards in England and Wales
Engineering Equipment Users' Association*

Gas Council*

Heating and Ventilating Contractors' Association
Heating and Ventilating Research Association
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Royal Institute of British Architects*
Society of British Gas Industries
Water-tube Boilermakers' Association

The Government departments and scientific and industrial organizations marked with an asterisk in the above list, together with the following, were directly represented on the committee entrusted with the preparation of this British Standard.

Asbestos Cement Manufacturers' Association
British Chemical Plant Manufacturers' Association
Combustion Engineering Association
Council of British Manufacturers of Petroleum Equipment
Department of the Environment, Building Research Station
Electrical Research Association
Fibre Building Board Development Organization Ltd.
Eurisol-UK Association of Manufacturers of Mineral Fibre Insulation
Gypsum Plasterboard Development Association
Royal Institute of British Architects
Structural Insulation Association
Thermal Insulation Contractors' Association

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Contents

		Page
Co-operating organizations		Inside front cover
Foreword		iii
Introduction		1
1	General	3
1.1	Scope	3
1.2	Definitions	3
2	General principles of measurement	3
2.1	*Text deleted*	
2.2	*Text deleted*	
2.3	*Text deleted*	
3	Testing conditions and test reports	3
3.1	*Text deleted*	
3.2	*Text deleted*	
3.3	*Text deleted*	
3.4	*Text deleted*	
4	Methods for determining thermal properties	3
4.1	General	3
4.2	Thermal conductivity	3
4.3	Thermal transmittance and thermal conductance (above approximately 0.7 W/[m^2 K)]	8
4.4	Emissivity	8
4.5	Heat capacity per unit mass (temperatures up to approximately 1 000 °C)	8
5	References	9
Appendix A Additional methods of measuring thermal conductivity		10
Appendix B Heat flow meter method of measuring thermal conductivity with two test specimens		10
Appendix C Heat flow meter method of measuring thermal conductivity with a single test specimen		12
Appendix D Transient state method of thermal conductivity measurement		13
Appendix E Determination of thermal conductivity by the use of a thermal probe		16
Appendix F Units and conversion factors		18
Appendix G Materials of medium conductivity in slab form. Test equipment		28
Figure 1 — Diagram illustrating definition 2		21
Figure 2 — Spherical vessel for low temperature conductivity tests		22
Figure 3 — Heat flow meter apparatus		23
Figure 4 — Heat flow meter with single specimen		24
Figure 5 — Typical two specimen arrangement for transient flow measurement of thermal properties		25
Figure 6 — Differential thermocouples for measurement of average temperature differences		26
Figure 7 — Diagram of probe with thermocouple reference junction		27
Figure 8 — Diagram of plain (unguarded) hot plate apparatus		29

	Page
Table 1 — Summary of symbols and dimensions of quantities	2
Table 4 — Quantity of heat (conversion factors)	18
Table 5 — Thermal transmission (conversion factors)	18
Table 6 — Thermal conductivity (conversion factors)	18
Table 7 — Thermal conductance, thermal transmittance, surface coefficient, convection coefficient and radiation coefficient (conversion factors)	19
Table 8 — Heat capacity per unit volume (conversion factors)	19
Table 9 — Thermal diffusivity (conversion factors)	20
Publications referred to	Inside back cover

Foreword

BS 874 was first issued in 1939 and revised in 1956 and in 1965.

In the present revision a few changes have been made in the text of the 1965 issue.

The standard has been metricated using SI units [For further information on SI units reference should be made to BS 3763 *"The International System of units (SI)"]*. British units and their conversion factors are shown for reference purposes only (see Appendix F).

Additional references have been added in respect of recent work on this subject.

Particular attention is drawn to the appendices describing additional methods of measuring thermal conductivity. The scope and purpose of these additional methods is explained in Appendix A.

The properties of materials, including thermal conductivity, may change during their working life and provision is not made in this standard for the general requirements of thermal insulating materials. Reference should be made to other British Standards according to the type and use of the product.

British Standards dealing with the general requirements of thermal insulating materials are as follows:

BS 1334, *The use of thermal insulating materials for central heating and hot and cold water supply installations.*

BS 1588, *The use of thermal insulating materials in the temperature range 95 °C to 230 °C.*

BS 1902, *Methods of testing refractory materials.*

BS 1902-1A, *Sampling and physical tests.*

BS 2972, *Methods of test for thermal insulating materials*[1)].

BS 3533, *Glossary of terms relating to thermal insulation.*

BS 3708, *The use of thermal insulating materials between 230 °C and 650 °C.*

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 30, 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.

[1)] In process of revision

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Introduction

In expressing the results of tests, or in calculations relative to the passage of heat through materials, a number of technical terms are in use of which a selection is defined below. Of these, terms ending in "ivity" have been used to designate properties normally independent of size or shape, sometimes called specific properties, examples being "conductivity" and "resistivity". Each quantity defined may be expressed in a variety of units, consequently no units have been explicitly stated in the definitions. A summary of the chief systems in common use is given in Appendix F.

In some of the definitions, reference is made to "hot and cold faces". In all such cases it is assumed that the system through which heat is flowing has two identifiable isothermal surfaces (not necessarily plane). It should be realized that in some instances, such as furnace work, the "cold" face of the material may in fact be at a fairly high temperature, whilst in refrigeration work, on the other hand, the "hot" face may be below freezing point.

The simplest system is a uniform material, i.e. a material such that if a sample is enclosed between flat parallel hot and cold faces at given temperatures, the steady rate of heat conduction under given constant temperature conditions is proportional to the area of these faces and inversely proportional to the distance between them. Thus concrete faced with plaster is not a uniform material, since two samples having the same dimensions, but with different proportions of plaster thickness to concrete thickness, will conduct heat at different rates under the same temperature conditions.

In practice, heat flow through much more complicated systems has to be considered. All such systems are referred to below as "structures", and this term may therefore signify objects as diverse as an insulating material made of alternate layers of metal foil and air, an aircraft cabin, a corrugated roof, the wall of a furnace, or a complete building. It is, however, still assumed in the definitions that a hot face and a cold face may be identified.

Summary of symbols and dimensions for quantities defined

The symbols M, L and T at the heads of the third to fifth columns in Table 1 are those for the fundamental dimensions of mass, length and time. The symbol θ in the sixth column refers to temperature and Q in the seventh column refers to quantity of heat. The numbers in the third to seventh columns are the power indices of the dimensions appropriate to the various quantities defined. Thus the dimensions of thermal conductivity k are $QL^{-1}\ T^{-1}\ \theta^{-1}$.

The quantities defined may, of course, be expressed in terms of mass, length, time and temperature only, in which case the appropriate indices may be found by ascribing to quantity of heat Q the dimensions $ML^2\ T^{-2}$

Table 1 — Summary of symbols and dimensions of quantities

Symbol	Quantity	Dimensions in terms of				
		Mass M	Length L	Time T	Temperature θ	Heat Q
		Index				
q	Thermal transmission			− 1		1
k	Thermal conductivity		− 1	− 1	− 1	1
C	Thermal conductance		− 2	− 1	− 1	1
R	Thermal resistance		2	1	1	− 1
f	Surface coefficient		− 2	− 1	− 1	1
U	Thermal transmittance		− 2	− 1	− 1	1
S	Shape factor		1			
c	Heat capacity per unit mass	− 1			− 1	1
h	Heat capacity per unit volume		− 3		− 1	1
α	Thermal diffusivity		2	− 1		
r	Reflectivity					
E	Emissivity					
σ	Stefan's constant		− 2	− 1	− 4	1
f_r	Radiation coefficient		− 2	− 1	− 1	1
f_c	Convection coefficient		− 2	− 1	− 1	1
ρ	Bulk density	1	− 3			

Some of the quantities, after verbal definition, are accompanied by a defining equation, in which the following symbols and subscripts have been adopted.

Q = quantity of heat
L = thickness of slab with plane parallel faces measured in the direction of heat flow
A = area of hot or cold face
θ = temperature
T = absolute temperature

Subscripts

s = surface
m = medium (air or fluid)
r = radiation
c = convection
1 = hot side
2 = cold side

1 General

1.1 Scope

This British Standard describes methods for determining thermal insulating properties of materials and includes definitions of thermal insulating terms.

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

1.2 Definitions

This clause has been superseded by BS 874-1, which is published as a separate document.

2 General principles of measurement

This clause has been superseded by BS 874-1, which is published as a separate document.

3 Testing conditions and test reports

This clause has been superseded by BS 874-1, which is published as a separate document.

4 Methods for determining thermal properties

4.1 General

This clause has been superseded by BS 874-1, which is published as a separate document.

4.2 Thermal conductivity

4.2.1 *For materials of moderate or low conductivity*

The method given in this clause has been superseded by BS 874-2.1:1986, which is published as a separate document.

4.2.2 *For materials of medium conductivity in slab form*

4.2.2.1 *General*

Hot face temperature: Up to 100 °C

Thermal conductivity: Greater than 0.15 W/(m K) and less than 2.0 W/(m K).

Details of suitable unguarded hot plate test equipment are described in Appendix G.

The test procedure shall apply to all materials. Additional specific requirements which shall be observed for masonry materials such as pre-cast concrete are listed under **4.2.2.3**.

4.2.2.2 *All materials.* Two similar specimens of material shall be tested. Their bulk density shall not differ by more than ± 5 % from the mean density. They shall be nominally 300 mm square; and actual lengths and widths shall each be measured in at least three widely different positions and the average dimensions determined. Thicknesses of the specimens shall be preferably between 40 mm and 50 mm. For the higher conductivity materials in this range specimen thickness up to 75 mm may be used. Actual thicknesses shall be measured to the nearest 0.2 mm in at least six widely different positions and the average thickness determined. The surfaces of the specimens shall be plane and parallel. The difference in thickness across the full width shall not exceed 2 % of the mean thickness. The deviation from flatness shall not exceed 0.2 mm over the full width as judged by straightedge and feeler gauge.

When the area of the test material is insufficient to provide test specimens in one piece (e.g. most bricks and blocks), the test specimens may be constructed from several pieces. Their thickness shall be the same as the final test specimens. The densities of the pieces used in both specimens shall not differ by more than ± 5 % from the mean density. The surfaces between the pieces shall be machined true and joined with a minimum thickness of a suitable adhesive. The width of the joints shall not exceed 1 mm and the total length shall not exceed 1 500 mm for each specimen. Contacts or joints across the heat flow in the specimen are not permitted.

Conditioning of materials shall be in accordance with **3.2**.

The specimens shall be placed one on each side of the electrically heated hot plate, and the whole assembly held between the two cold plates which shall be maintained at a constant temperature by liquid flow. The hot and cold face temperatures of the specimens shall be in accordance with **3.1**.

Suitable sheet, for example silicone rubber, shall be inserted between the specimens and the plates to improve the thermal contact, and to insulate the thermocouples electrically. To ensure proper thermal contact, the apparatus shall be loaded with an additional pressure of not less than 0.003 MN/m^2. This is equivalent to a mass of 30 kg acting over plates of side 300 mm.

The temperatures of each of the hot and cold faces of the specimens shall be measured by a minimum of four fine wire thermocouples. Intimate contact of the thermocouples with the surfaces of the specimens is essential, and they shall be in contact for at least 25 mm from the junction. For materials of thermal conductivity higher than 0.5 W/(m K), the thermocouples shall be cemented into grooves in the surfaces of the specimens. Details and positioning of the thermocouples shall be in accordance with Appendix G.

The whole apparatus shall be enclosed in thermal insulating material, not less than 100 mm thick, to minimize heat losses and the effects of change in the ambient temperature outside the insulation. Suitable insulating materials are detailed in Appendix G.

The ambient temperature outside the insulation shall be within the range of the hot and cold face temperatures and shall not fluctuate by more than ± 3 °C.

The thermal conductivity shall be derived from test measurements obtained under steady state conditions: as much as one and a half days may be required after first switching on the electrical input to an unguarded hot plate apparatus. When the readings indicate that conditions are steady, and this is confirmed by two subsequent measurements at not less than 1 h interval, final readings are started. Average temperatures shall be calculated for both the hot and the cold faces, and they shall be valid only when at least three consecutive conductivity values have a maximum spread of 2 %. The temperature difference between the highest and lowest readings in a set of readings on any individual hot face or cold face shall be not greater than 1 °C.

For unguarded hot plate equipment, a correction shall be applied for the heat loss from the sides of the apparatus: this shall be determined by a test under similar conditions of thickness and temperature on a reference material of known thermal conductivity, as determined by the guarded hot plate method (see **4.2.1**). Appendix G gives an example of a suitable reference material.

The thermal conductivity value reported shall be the mean of the three corrected equilibrium values.

4.2.2.3 *Masonry materials.* The following additional requirements shall be observed for masonry materials:

a) The specimen thickness shall be at least three times the maximum nominal aggregate size and preferably between 40 mm and 50 mm.

b) For dry densities less than 1 800 kg/m^3, the specimen thickness shall be not greater than one-fifth of the length.

c) For dry densities of 1 800 kg/m^3 and above, the specimen thickness shall be not greater than one-quarter of the length.

d) Specimens shall be at least 28 days old prior to testing, and the date of manufacture of the material from which the specimens were prepared shall be reported to the testing authority.

e) Materials shall be conditioned to constant mass by exposure to the air of a well ventilated room. In case of dispute the material shall be conditioned to a constant mass in an atmosphere of 65 ± 5 % relative humidity and at 20 ± 2 °C. Conditioning shall be from an initial wet condition. Accelerated drying of the specimens prior to test shall render the test invalid.

f) The hot face temperature shall be 27 ± 3 °C, and the cold face temperature shall be 10 ± 3 °C, with the further provision that the temperature difference between hot and cold faces shall be not less than 15 °C.

g) The specimens shall be weighed immediately before and after testing and this shall be followed by the determination of the oven dry density of the specimens.

The moisture content of the specimens at the time of the test shall be calculated as described in **3.3** except that the dry density shall be determined by:

1) drying for at least 16 h in a ventilated oven having a temperature controlled at 105 °C to 110 °C;

2) cooling the specimens in a desiccator and weighing them, and

3) repeating 1) and 2) until the mass lost in one cycle does not exceed 0.1 gram per millimetre of thickness of the specimen.

The test shall be invalid if:

1) there is a variation greater than 0.2 % by volume between the moisture contents before and after testing;

2) the average of the two moisture contents determined is less than 1 % by volume (except for materials of which the equilibrium moisture content is less than 1 %) or greater than 5 % by volume (except for materials of which the equilibrium moisture content exceeds 5 %).

4.2.3 ***For materials of medium conductivity in thin sheet form***

Hot face temperature: up to approximately 100 °C

Thermal conductivity: 0.15 to 2 W/(m K)

Some materials are only available in thin sheet form and for the following method (see Refs. 6, 7, 8 and 18) the test specimen is in the form of a pair of disks 75 mm in diameter and from 3 mm to 15 mm in thickness. Care should be taken to ensure that the faces of the disks are plane and parallel; the deviation from flatness should not exceed 0.05 mm. The disks are placed one on each side of an electrically heated hot plate of the same size, and the whole is clamped between two cold plates of the same size, maintained at a constant temperature by liquid flow. A film of liquid, such as glycerol or oil, is used between the test disks and the plates to improve the thermal contact; absorbent specimens are previously coated with a very thin film of impervious material, e.g. shellac. The temperatures are determined by means of at least two thermocouples attached to each plate. The whole apparatus is enclosed in thermal insulation, from 70 mm to 100 mm thick, to minimize heat losses and the effect of changes in ambient temperature. If the apparatus is operated at temperatures above 40 °C an electrically heated guard tube about 120 mm in diameter is fitted around the apparatus to reduce heat losses.

When conditions have become steady the electrical energy dissipated in the hot plate is measured. The correction for the temperature drop across the liquid films between the disks and the plates is obtained by measurements on metal or fused silica disks of known conductivity, or by measurements on a thick and a thin disk of the test material.

The correction for the heat loss from the sides of the apparatus is obtained by measurements on disks of material of known conductivity, such as ebonite or solid plastics. These disks are to be similar in size to the test disks.

The thermal conductivity is then calculated from the corrected heat flow and from the area and thickness of the disks, together with the corrected hot and cold face temperatures.

4.2.4 ***For materials at high temperatures***

Hot face temperature: from 100 °C to 600 °C

Thermal conductivity: up to 0.2 W/(m K)

Two similar specimens of the material to be tested are used, each about 50 mm in thickness and 450 mm square. They are placed one on either side of a hot plate, approximately 300 mm square, which is surrounded by a co-planar guard plate 450 mm square externally, with a central square hole 3 mm larger than the hot plate. Two cold plates, each 450 mm square and cooled by water flow, are placed on the outer faces of the specimens. Fine wire thermocouples (e.g. 0.2 mm) are laid in contact with the hot faces and cold faces of the specimens and they are electrically insulated from the hot and cold metal plates by being covered with thin sheets of asbestos paper. The hot plates and the guard plate have independent electrical windings. The edges of the apparatus are covered with thermal insulation at least 70 mm thick (see Refs. 9 and 10).

To carry out a test, the electrical energies are adjusted so that the temperature of the guard plate is equal to that of the hot plate when conditions have become steady. The electrical energy dissipated in the hot plate is measured and the conductivity calculated from a knowledge of this quantity, regarded as flowing through a square of area halfway between that of the hot plate and that of the central hole in the guard plate, together with the observed hot face and cold face temperatures and the thickness of the specimens.

4.2.5 ***For materials at very high temperatures***

Hot face temperature: 400 °C to 1 000 °C

Thermal conductivity: up to 1.5 W/(m K)

A test specimen 450 mm square and of uniform thickness from 50 mm to 80 mm is used. The materials tested in the apparatus may be of various types and are suitably supported horizontally in the apparatus (see Ref. 11).

1) Rigid slabs such as refractory concrete or slabs built up of bricks bonded with cement are normally held in an angle-iron frame about 600 mm square, which is fitted with screws which support the edges of the slab. Thermocouples are cemented to the bottom of shallow grooves in the surfaces of the central 230 mm square test area of the slab. Care should be taken to ensure that the faces of the slab are as flat as practicable, the deviation of the flatness over the upper (cold face) central test area should not exceed 0.2 mm.

2) Semi-rigid slabs and similar materials, such as fibrous mats or plastic compositions, are placed in the apparatus on a flat plate, e.g., of heat-resistant alloy measuring 450 mm × 450 mm by about 3 mm thick. This plate has cuts about 100 mm long in the corners and edges to reduce warping. Where the compressibility of the material makes it necessary, the thickness of the test specimen is maintained by supporting the cold plate on small distance pieces inserted in holes in the test specimen. A correction is applied for the heat flow through the distance pieces.

3) Loose fill materials, such as powders or granules, are packed as uniformly as practicable into a frame about 450 mm square resting on a plate as above. Where necessary, the thickness of the test specimen is maintained as in 2) above or by means of a grid of thin mica sheets. A correction is applied for the heat flow through the distance pieces.

The slab or plate is heated from below by electrical resistors and the quantity of heat flowing through the central area of the specimen is determined by means of a water flow calorimeter plate about 230 mm square supported on the upper face of the specimen.

The calorimeter is supplied with constant temperature water at a steady flow rate from a constant-head tank. The temperature rise of water flowing through the calorimeter is determined by a multiple-junction differential thermocouple or other suitable thermometer. (The calorimeter assembly may be calibrated by an electrical energy input method during a separate calibration test.) A water-cooled co-planar guard ring plate, about 110 mm wide, is fitted around the calorimeter plate to ensure uniform heat flow through the central area of the specimen on which measurements are made. A gap not more than 3 mm wide is maintained between the guard ring plate and the calorimeter plate in order to minimize thermal contact between these plates. The temperatures of the hot and cold surfaces of the central area are measured by means of thermocouples.

The edges of the test specimen are covered with thermal insulating material at least 70 mm thick to minimize heat losses. The exposed surfaces of the calorimeter plate and the differential thermocouple unit are insulated with at least 70 mm of low conductivity thermal insulating material.

When the conditions are steady a series of observations is made of the temperatures, the water-flow rate and the water temperature rise through the calorimeter and the heat flow is calculated from these observations. For each hot face temperature condition, observations are made using at least two different water-flow rates. The thermal conductivity of the central section of the specimen is calculated from the heat flow through the central section, regarded as flowing through a square of area halfway between that of the calorimeter and that of the central hole in the guard plate, together with the observed hot and cold face temperatures and thickness of the central section.

Thermal conductivities at high cold face temperatures are determined by measuring the temperature by means of thermocouples fixed parallel to the faces at known positions inside the test specimen.

4.2.6 ***For high temperature insulating and refractory materials***

Hot face temperature:over 800 °C

Thermal conductivity:up to about 4 W/(m K)

This method is similar to that described in **4.2.5**; a detailed description is given in BS 1902.

4.2.7 ***For loose fill materials, in air or vacuum, at low temperatures***

Cold face temperature: about 80 K (– 193 °C)
Thermal conductivity: within the range 0.015 W/(m K) to 0.10 W/(m K)

4.2.7.1 *General.* To evaluate insulants for use in containers for liquefied gases it is sufficient to determine the mean thermal conductivity over the temperature range between ambient and the boiling point of the liquid. This mean thermal conductivity of powder or fibrous loose fill insulants is measured in the apparatus shown in Figure 2. The insulant forms a spherical shell around a container filled with liquid oxygen or liquid nitrogen and the rate of evaporation of the liquid is observed.

4.2.7.2 *Apparatus.* The liquid is contained in a spherical metal vessel about 150 mm in diameter, supported in a concentric copper sphere about 300 mm in diameter. Any insulating supports can be employed, but a convenient arrangement uses three plastics-impregnated fibre tubes 10 mm in diameter and 5 mm bore. The inner vessel is fitted with two metal tubes, one as an inlet for liquid, the other an outlet for gas, and these are connected by rubber tubing to corresponding tubes passing through the outer vessel. The latter is made in three sections as indicated in the drawing. One section is the lower hemisphere which is fitted with a cylindrical skirt on which the whole apparatus is supported. The second section comprises most of the upper hemisphere, these two sections being bolted together by means of a circumferential flange on each. The third section of the outer vessel is the lid, which is 150 mm in diameter and closes the aperture through which the insulant is inserted into the annular shell. The lid carries a connection through which the insulating space may be evacuated, if required, and is bolted to a flange attached to the upper hemisphere. The joints between these three components are sealed with "O" rings. Provision is made for fixing a thermometer bulb or other temperature measuring device, thermopile etc. in contact with the outer vessel to measure its temperature.

Containers of other shapes, e.g. cylindrical, may be employed if suitably constructed.

4.2.7.3 *Procedure.* The insulating space is filled with the insulant under test to the appropriate bulk density. For powders this may be achieved by vibrating the vessel during filling. For fibrous insulants a previously weighed amount is compressed as uniformly as possible into the space. The lid is then placed in position and if required the insulating space is evacuated; this is essential if the test is to be carried out with liquid nitrogen. If the test is to be carried out at atmospheric pressure a breathing tube filled with a desiccant such as silica gel or activated alumina is connected in place of the vacuum pump to prevent atmospheric moisture condensing on the insulant. The inner vessel is then filled with liquid oxygen or liquid nitrogen, as required, and is kept filled until the evaporation rate has become constant, indicating that the temperature distribution through the insulant has reached equilibrium. The evaporation rate is then measured by passing the gas through a water-saturator and then through a water-sealed, positive-displacement gas meter.

4.2.7.4 *Calculation.* If the rate of evaporation is V litres per second referred to at s.t.p.,[2)] the heat influx Q in watts is calculated from one of the equations:

$Q = 305\ V$ for liquid oxygen, or

$Q = 250\ V$ for liquid nitrogen.

The heat inleak through the tubes and supports Q' is determined either from a series of experiments with an insulant of known conductivity or by calculation. The net heat transfer through the insulant is $Q - Q'$ and the thermal conductivity is calculated from the equation

$$Q - Q' = kS(T_1 - T_2)$$

where

k = the mean thermal conductivity, W/(m K), over the range T_1 to T_2

T_1 = temperature of the outer vessel, K

T_2 = temperature of the inner vessel, K (90 K for liquid oxygen at normal atmospheric pressure and 77 K for nitrogen at the same pressure)

S = shape factor, m; for this vessel $S = \dfrac{4\ \pi\ r_1 r_2}{r_1 - r_2}$

where r_1 and r_2 are the radii of the outer and inner spheres respectively in metres

[2)] s.t.p. is defined as 0 °C, 1 standard atmosphere (101.325 kPa).

4.2.8 For metals and dense ceramics

Temperature: up to 1 000 °C

Thermal conductivity: above about 7 W/(m K)

A specimen of the material in the form of a cylindrical bar, from 10 mm to 25 mm diameter and about 200 mm long, is screwed or otherwise joined to a similar size bar of known thermal conductivity (Refs. 1 and 17).

Bars of large diameter are required for materials of low conductivity. An electrical heater is fitted to one end of the composite bar arid a cooling unit to the other end. Thermocouples are attached to the composite bar at various measured positions. This unit is supported in a vertical position and is surrounded by a guard tube, also fitted with thermocouples, which is electrically heated at the top and centre and cooled at the bottom. The whole apparatus is filled and enclosed with powder material for thermal insulation to reduce heat losses (see Ref. 12). For tests at temperatures above say 400 °C, the apparatus is assembled in a water-cooled metal chamber which can be evacuated to prevent oxidation of the bars and also to minimize heat losses through the insulation (see Ref. 12).

To carry out a test the top of the composite bar is heated to a constant temperature and the bottom of the bar is maintained at a lower constant temperature. The temperatures along the guard tube are adjusted so that they are similar to the corresponding positions on the composite bar. When conditions are steady, observations are made of the thermocouples attached to the bar and also of the water-flow differential thermocouple cooling units if this is fitted to the bar.

The conductivity of the test bar is then calculated from the area of the test bar, the temperature gradient per unit length along this bar and the heat flow derived from the temperature gradient along the bar of known conductivity. A correction is applied to this heat flow to allow for small heat losses from the composite bar to the guard tube if the temperatures are not closely similar. When the heat flow is also measured by a water flow calorimeter, the percentage difference between the two heat flows must be less than the permitted tolerance of the determination.

For measurements at low temperatures, below 0 °C, a direct electrical heat input method is used, since it is possible to minimize the heat losses from the heater and the test bar and to apply corrections for these losses (see Ref. 19).

4.3 Thermal transmittance and thermal conductance [above approximately 0.7 W/(m^2 K)]

The methods given in this clause have been superseded by BS 874-3.1, which is published as a separate document.

4.4 Emissivity

A sheet of material measuring nominally 300 mm square is required for this test. The central portion of this sheet (about 300 mm × 150 mm) is pulled or otherwise held in good thermal contact along its whole length round half the outer surface of a vertical brass or copper cylinder about 100 mm in diameter and 300 mm long. The lower half of the portion of the sheet which is in contact with the cylinder is coated with a dead black paint of known emissivity. The temperature of the surface is maintained steady at a uniform temperature of about 60 °C by internal heating. For this purpose the cylinder may be closed at the bottom and filled with water or low viscosity oil which is stirred and temperature controlled. The radiation from the uncoated area of the sheet in contact with the cylinder is compared with that from the blackened surface by means of a thermopile.

It is essential to screen the apparatus from draughts and any sources of thermal radiation.

The result shall be reported as the ratio of the radiation emitted from the metal foil, E_1, to that emitted from the blackened surface, E_0, i.e. emissivity = E_1/E_0

4.5 Heat capacity per unit mass (temperatures up to approximately 1 000 °C)

Various types of equipment are used to determine the heat capacity of a known mass of material at various temperatures. The electrical energy input method (see Ref. 13) is convenient for the temperature range from about 15 °C to 100 °C. The "drop calorimeter" method (see Refs. 14 and 15) can be used over a wide range of temperatures, say – 80 °C to 1 000 °C. The corrections to be applied to the experimental observations may be obtained by an electrical energy input method or by measurements on a sample of material of known thermal capacity such as pure aluminium oxide.

5 References

Test methods referred to above are described in more detail in the following papers.

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(19) WHITE G. Measurement of solid conductors at low temperature. *Thermal conductivity* (R.P. Tye, Editor), vol. 1., Academic Press (London & New York), 1969, 69–109.

Appendix A Additional methods of measuring thermal conductivity

The determination of the thermal conductivity of materials by the steady-state methods, described in Sections **2** and **4**, requires careful design and operation of the equipment to obtain accurate values, for example, within ± 3 % for the guarded hot-plate method (see Ref. 12). Moreover, relatively long test periods are necessary, ranging from about a day for tests on thin disk samples by method **4.2.3** to several days for some of the other methods. These periods of time are required for the assembly of the apparatus and to enable adjustments to be made to guard plate temperatures etc. and also to ensure that constant temperatures and heat flow conditions have been attained.

For the routine testing of materials, say for quality control, it is advantageous to use more rapid methods of measurement; also short-time tests are necessary for damp or wet materials in order to minimize the migration of water due to temperature gradients during the test. By the use of transient-state methods or a heat flow meter in a steady-state method, as described below, the overall time required for a test may be less than an hour up to several hours; they have the further advantage that the equipment and its operation are usually simpler than those for the standard methods. These test methods are therefore suitable for comparative tests on large numbers of similar materials or on wet materials, where the standard methods (see Sections **2** and **4**) would be impracticable or too time consuming. According to the method used a wide range of materials can be tested, including insulating or building materials either in the normally conditioned state (see Section **3**) or in the wet state, having conductivities up to 1.5 W/mK and measurements can be made at temperatures ranging from about – 200 °C to 100 °C.

These short-time test equipments normally require frequent calibration by means of reference specimens of known thermal conductivity and it is usually desirable that the dimensions and conductivity of the test specimens should be similar to those of the reference specimens used for the calibrations. The accuracy of the conductivity value obtained for a test material will depend upon the limits within which the conductivity of the reference material is known and also upon the reproducibility of the test conditions during the calibration and test measurements. Hence, these are regarded as secondary methods giving conductivity values within 5 % or 10 % but the reproducibility of measurements may be better than 3 %.

Detailed descriptions of four test methods are given in Appendix B, Appendix C, Appendix D and Appendix E; the sizes quoted are given for guidance only but they have been found convenient. In order to avoid large errors in the measurement of conductivity it is essential to observe the requirements stated in the various methods, for example, the flatness and temperature control of the cold plates and the hot plates, the flatness of the test specimens and accurate measurement of their thicknesses, the need to attain uniform constant temperature conditions in the specimens before starting test measurements, constancy of the electrical heat inputs, frequent calibration of the equipment with reference specimens etc.

Appendix B Heat flow meter method of measuring thermal conductivity with two test specimens

B.1 General

This Appendix and the following Appendix C include two arrangements of apparatus for measuring thermal conductivity by means of a heat flow meter. The arrangement shown in Figure 3, using a pair of test specimens is described in this Appendix. The arrangement shown in Figure 4, using a single specimen, is described in Appendix C.

B.2 Scope of method

This method is suitable for materials of thermal conductivity not greater than 0.15 W/(m K).

The typical hot face temperatures are between 0 °C and 100 °C with temperature differences across the specimens ranging from 15 °C to 50 °C. Lower and higher temperatures may be used if appropriate precautions are taken.

The long term reproducibility of measurements obtained with the apparatus described in this Appendix should be better than 3 %.

B.3 Principle of method

This is a steady state method in which the heat flowing through the specimens is measured by means of a heat flow meter, i.e. a thermopile calibrated to relate its output e.m.f. to the rate of heat flow per unit area. It is therefore necessary to calibrate the apparatus periodically with materials of known thermal conductivity.

B.4 Apparatus

B.4.1 *General.* The assembly of apparatus and test specimens shall comprise a cold plate, one of the test specimens, a heat flow meter, the second test specimen and a hot plate, assembled either horizontally or vertically in that order (see Figure 3).

B.4.2 *Heat flow meter*. This shall consist of a round or square thermopile not less than 100 cm^2 in area mounted in a round or square support about 3 mm thick having flat parallel faces of linear dimensions not less than those of the hot and cold plates.

The material of this support shall be homogeneous, isotropic, non-hygroscopic and thermally stable.

It is recommended that the calibration constant of the heat flow meter shall be such that the e.m.f. generated under all test conditions shall be at least 500 μV.

The thermal conductance of the heat flow meter shall be such that the temperature difference between its faces shall not exceed 2 % of that between the hot and cold plates.

B.4.3 *Hot and cold plates.* These shall be constructed of a high thermal conductivity metal. They shall be flat to within 0.5 mm per metre. The linear dimensions of the plates shall be not less than twice those of the sensitive section (thermopile) of the heat flow meter.

One or more thermocouples shall be embedded in the surfaces of each plate.

The temperature of both plates shall be controllable so that the average temperatures of the plate surfaces in contact with the specimens do not fluctuate by more than ± 0.1 °C during the test period and individual thermocouple readings should not differ by more than 0.4 °C during the test period.

B.4.4 *Instrumentation.* A potentiometer or other measuring device, having a sensitivity of ± 1 μV or better shall be used for measurements of all thermocouples or heat flow meters.

The thermocouples shall be made from calibrated thermocouple wire of about 0.2 mm diameter and of materials such as nickel chromium alloys having a low thermal conductivity.

Means shall be provided to measure the thickness of the test specimens in position for the test to the nearest 0.1 mm.

B.4.5 *Constant temperature enclosure.* The assembly shall be contained in an enclosure maintained to within ± 0.5 °C of the mean of the hot and cold face temperatures. Alternatively, heat losses may be restricted by adequate edge insulation.

Provision shall be made to maintain the air in this enclosure at a relative humidity such that condensation cannot occur on the cold plate during the test.

B.5 Test specimens

Both specimens shall have faces that are flat to within 0.5 mm/m and parallel to within 0.5 mm. Their linear dimensions shall be not less than those of the hot and cold plates. Typical dimensions are 200 mm × 200 mm or larger.

The combined thickness of the pair of specimens shall be between 20 mm and 50 mm.

Any difference in thickness between the specimens shall not exceed 1 mm.

B.6 Procedure

Arrange the pair of specimens between the hot and cold plates, one on either side of the heat flow meter (see Figure 3).

Bring the hot and cold plates together to ensure close contact between them, the test specimens and the heat flow meter. (This can be checked by trying to move by hand, without exerting much force, each of the pair of test specimens. Such movement should not be possible.)

Measure the thickness of each of the pair of test specimens.

The apparatus shall be controlled so that the difference between the temperature of the hot and cold plates is not less than 15 °C.

Record the hot and cold plate temperatures until three successive readings agree within the limit given in **B.4.3** and, at the same time, record the e.m.f. of the heat flow meter.

B.7 Calculation of results

For the mean test temperature calculate the thermal conductivity of the test specimen from the formula:

$$k = \frac{ZLV}{\Delta\theta}$$

where

k = the thermal conductivity of the specimen at temperature θ [W/(m K)]

Z = the calibration constant for the apparatus at temperature θ [W/(m^2 μV)] (see **B.8**)

L = combined thickness of the two specimens, (m)

θ_1 = hot face temperature (°C)

θ_2 = cold face temperature (°C)

$\Delta\theta = \theta_1 - \theta_2$ (°C)

θ = the mean temperature, $\frac{1}{2}(\theta_1 + \theta_2)$ (°C)

V = the e.m.f. generated by the heat flowmeter at temperature θ (μV)

B.8 Calibration

B.8.1 *Reference test specimens.* This test method requires that the heat flow meter be calibrated with a pair of reference test specimens, the thermal conductivity of which has been determined simultaneously by the appropriate method of **4.2**. Such reference specimens must have stable physical characteristics and be accompanied by a curve relating thermal conductivity to mean temperature of test over the appropriate range. The thickness and thermal conductivity of the reference specimens should be similar to the thickness and thermal conductivity of the specimens to be tested. Care should be taken to maintain the characteristics of the reference specimens, e.g. to avoid alterations of density due to compression.

B.8.2 *Calibration procedure and calculation.* The method is identical to that detailed in **B.6**.

Under steady state conditions the calibration constant of the apparatus is given by $Z = \frac{k\Delta\theta}{LV}$

NOTE The calibration constant is temperature dependent and care must be taken to ensure that the mean calibration temperature is the same as the mean test temperature.

Appendix C Heat flow meter method of measuring thermal conductivity with a single test specimen

C.1 General

This is the second of two arrangements of apparatus for measuring thermal conductivity by means of a heat flow meter. It uses a single test specimen and is shown in Figure 4. The arrangement using two specimens is described in Appendix B and is shown in Figure 3.

C.2 Scope of method

The scope of this method is that detailed in **B.2**.

C.3 Principle of method

The principle is that detailed in **B.3**.

C.4 Apparatus

C.4.1 *General.* The assembly of apparatus and test specimen shall comprise a cold plate, a heat flow meter, the test specimen and a hot plate, assembled either horizontally or vertically in that order (see Figure 4).

C.4.2 *Heat flow meter.* This shall be constructed as described in **B.4.2**. Suitable means shall be employed to determine the average temperature of the test specimen side of the heat flow meter.

C.4.3 *Hot and cold plates.* These shall be constructed as described in **B.4.3**.

C.4.4 *Instrumentation and constant temperature enclosure.* These shall be provided as indicated in **B.4.4** and **B.4.5**.

C.5 Test specimen

Only a single specimen is needed having a thickness between 20 mm and 50 mm. In other respects the specimen shall comply with the requirements of **B.5**.

C.6 Procedure

The procedure is as detailed in **B.6** except that the single test specimen is positioned between the heat flow meter and the hot plate (see Figure 4).

C.7 Calculation of results

For the mean test temperature calculate the thermal conductivity of the test specimen from the formula:

$$k = \frac{ZLV^1}{\Delta\theta}$$

where V^1 = the e.m.f. generated by the heat flow meter at temperature θ_2.

C.8 Calibration

C.8.1 *Reference test specimens.* These shall be a matched pair of specimens as described in **B.8.1**.

C.8.2 *Calibration procedure and calculation.* The two test specimens shall be used in successive determinations in the calibration procedure which is as detailed in **C.6**.

The calibration constant is given by the formula:

$$Z = \frac{k}{2}\left(\frac{\Delta\theta_x}{L_x V_x^1} + \frac{\Delta\theta_y}{L_y V_y^1}\right)$$

The symbols are as before except that subscripts x and y indicate values obtained from the first and the second determination respectively.

Appendix D Transient state method of thermal conductivity measurement

D.1 Scope of method

For materials in the wet or dry state in slab form of thermal conductivity not greater than 0.5 W/(m K) and a test temperature 0 °C to approximately 40 °C.

D.2 Principle of method

The method is suitable for use on wet or dry materials.

After achieving initial steady conditions, the time needed to carry out the conductivity determination will be from about 10 minutes to two hours dependent upon the dimensions and thermal properties of the specimen.

The method was developed at the Building Research Station for use on insulating and building materials in slab form[3)].

D.3 Apparatus

D.3.1 *General.* The assembly consists essentially of a cold plate, a specimen, a heater, another specimen and finally a second cold plate, mounted in that order (see Figure 5).

D.3.2 *Cold plates.* These should be not less than 300 mm square and flat. Means must be provided for controlling their temperature at any point within the desired operating range of the equipment to an accuracy of ± 0.15 °C. This will normally be achieved by using heat sinks such as metal or concrete slabs or by using plates with liquid circulation.

D.3.3 *Heater.* The heater shall consist of a uniform sheet of electrically conducting material fitted with suitable electrical connections to a stabilized source of electrical power incorporating means of measuring accurately the power dissipated in the heater. The active area of the heater shall be nominally the same size as the cold plate and its thermal capacity must be kept as small as possible.

A suitable heater material is graphite coated paper, although it is thought that thin metal foil (up to 0.02 mm thick) might also be utilized for this purpose. The uniformity of the electrical resistance of the material used should be checked.

[3)] See BALL E.F. A simple transient flow method of measuring thermal conductivity and diffusivity. *Proc. Inst. Refrig.* Feb, 1967.

D.3.4 *Thermocouples.* The average temperature-difference across the specimens is measured near their centres using fine-wire (up to 0.2 mm diameter) thermocouples, differentially connected. To improve sensitivity of temperature measurement four thermocouples should be used on each specimen, all eight thermocouples being connected in series (see Figure 6). When very damp specimens have to be measured, the thermocouples should be electrically insulated from the specimens. One way of doing this is to interpose thin rubber sheets (up to 0.2 mm thick), each having nominally the same area as the cold plate, between the junctions and the specimen surface; a correction for the effect of these rubber sheets is given in **D.6**.

D.4 Specimens

Specimens shall be in the form of two similar slabs nominally the same size as the cold plate and between 5 mm and 50 mm thick. To minimize edge heat losses, the thickness should be as small as possible, compatible with the overriding requirements that the specimens must be homogeneous and representative of the original sample. The thicker specimens are used for materials of high conductivity. The faces of rigid specimens should be flat and parallel.

D.5 Procedure

Assemble the apparatus and the specimens (see **D.3.1**) and enclose in a box or cabinet so as to be free from draughts, solar radiation and sudden changes of temperature.

If the value of the thermal conductivity is required at a base temperature different from room temperature, heat or cool the box to the chosen base temperature. Allow the conditions to become steady at the required base temperature as indicated by the differential thermocouple output.

Steady conditions are defined as not more than 0.1 °C drift in temperature difference per hour (as measured at, say, 10 minute intervals) and not more than 0.1 °C residual temperature difference across the specimen.

When conditions are steady, energize the heater and record the increase of temperature difference across the specimens, measuring time from the instant that power is applied to the heater. Ample precision of measurement can be achieved by applying sufficient power to give a temperature rise of 1 °C or 2 °C.

D.6 Calculation of result

D.6.1 From the temperature/time record select at least five suitable pairs of values of time (t) and time ($2t$). The thermal conductivity values obtained from one set of observations should not differ from each other by more than 10 %. The average of the thermal conductivity values is taken to be the thermal conductivity of the material.

For each pair of values calculate:

$$X = \frac{\Delta\theta_2}{\Delta\theta_1} \qquad (1)$$

where

$\Delta\theta_1$ = the temperature difference (°C) at time t

$\Delta\theta_2$ = the temperature difference (°C) at time $2t$

Using the values given in **D.6.2**, determine the value of Y corresponding to each value of X calculated from equation (1); the value of k corresponding to each value of t may then be found from:

$$k = \frac{qLY}{2A\Delta\theta_1} \qquad (2)$$

where

k = the thermal conductivity [W/(m K)]

q = the electrical power input to the heater (W)

L = the average thickness of the specimens (m)

A = the area of one face of the specimen (m^2)

Where four rubber sheets are used (see **D.3.4**) the value obtained from equation (2) becomes k_m in equation (3) below.

$$\frac{1}{k} = \frac{1}{k_m} - \frac{2d}{k_r L} \quad (3)$$

where

k = the true conductivity of the specimens
k_m = the measured conductivity
k_r = the conductivity of the rubber
d = the thickness of each rubber sheet
L = the average thickness of the specimens

This correction is only exact in the steady state but it may be used for the method described, since the errors involved will be less than those arising from other causes.

D.6.2 Values of X and Y for calculations are as follows:

X	Y	X	Y
1.01	0.991	1.21	0.774
1.02	0.981	1.22	0.763
1.03	0.970	1.23	0.751
1.04	0.960	1.24	0.739
1.05	0.949	1.25	0.727
1.06	0.939	1.26	0.714
1.07	0.928	1.27	0.702
1.08	0.918	1.28	0.688
1.09	0.907	1.29	0.673
1.10	0.897	1.30	0.658
1.11	0.886	1.31	0.643
1.12	0.876	1.32	0.628
1.13	0.865	1.33	0.613
1.14	0.854	1.34	0.597
1.15	0.842	1.35	0.578
1.16	0.831	1.36	0.558
1.17	0.819	1.37	0.536
1.18	0.808	1.38	0.508
1.19	0.797	1.39	0.472
1.20	0.785	1.40	0.411

Appendix E Determination of thermal conductivity by the use of a thermal probe

E.1 Scope of method

This method is suitable for testing materials with thermal conductivity not greater than 1.5 W/(m K) and is intended for use under circumstances in which a standard method would be impracticable or too time consuming, for example:

for in situ determinations,

for use with moist or wet materials,

for rapid determinations at temperatures between about – 200 °C and 100 °C,

for quality control testing.

This is a secondary method and requires that the apparatus be calibrated against a known reference sample at regular intervals.

E.2 Principle of method

E.2.1 The method measures the rate of rise of temperature resulting from the transient heat flow generated by a line heat source. It is characterized by the simplicity of the apparatus and speed of operation.

E.3 Apparatus

E.3.1 The apparatus in its simplest form is shown diagramatically in Figure 7.

E.3.2 *Probe.* An insulated heater wire and a thermocouple are inserted into a 100 mm or longer length of stainless steel tubing of approximately 1.5 mm outside diameter. Solid copper connectors are joined to the ends of the heater wire where they will be protected by the probe handle. Connections to the thermocouple wire are of size adequate to withstand the normal handling of the probe. These connections are protected by the probe handle which may be a plastics or metal tube sealed against ingress of moisture, dirt etc., or cast thermosetting resin e.g. epoxide resin.

E.3.3 *Thermocouple circuit.* The leads are joined in a circuit which incorporates a reference junction and a means of measuring the thermal e.m.f. as shown in either A or B in Figure 7.

E.3.4 *Heater circuit.* Solid copper wires are used to join a constant current source (e.g. battery or accumulator), switch, variable resistance and milliammeter to the probe heater in the simple series circuit shown in Figure 7.

E.3.5 *Measuring equipment.* Thermocouple e.m.f. is measured by a galvanometer, thermoelectric potentiometer or recording potentiometer (sensitivity ± 5 μV or better).

E.3.6 *Timer.* A stop clock or similar timing device is required.

E.4 Test specimen

E.4.1 *Dimensions.* The test specimen should ideally be large enough to permit the full length of the probe to be inserted and provide 50 mm of cover all round the probe. It is, however, possible to achieve realistic results with specimens which are not deep enough to cover the full length of the probe provided that the thermocouple is adequately covered and the remainder of the probe needle is insulated with a material having a thermal conductivity similar to that of the material under test. A cube of 100 mm side is ideal for use with a probe with a 75 mm needle as it permits tests to be made in three mutually perpendicular planes.

E.4.2 *Number of tests.* A minimum of three tests shall be carried out. For some materials it will be necessary to make measurements in three mutually perpendicular directions. More than one specimen may be required for these tests.

E.5 Procedure

E.5.1 *Calibration of the probe.* It has been shown that ideally:

$$\theta_1\theta_2 = \frac{Q}{4\,\pi\,K}\ \ln\frac{t_2}{t_1} \qquad (1)$$

where

θ_1 = temperature of probe at time t_1
θ_2 = temperature of probe at time t_2
k = thermal conductivity
Q = heat input to the probe per unit time
ln = natural logarithm

In practice, variations in construction necessitate the calibration of individual probes. Calibration should be carried out in the manner described in **E.5.2**, using a material of known thermal conductivity similar in value to that of the material to be tested. The heater current must be constant over the time interval t_1 to t_2 whence equation (1) may be written

$$k = \frac{Z}{x_2 - x_1} \qquad (2)$$

from which $Z = k(x_2 - x_1)$ (3)

where

Z = the instrument constant for the probe determined by calibration
x_1, x_2 = the thermocouple e.m.fs. or galvanometer deflections corresponding times t_1 and t_2.

In practice it is not necessary to convert these readings to temperatures since the instrument constant Z incorporates all undetermined constants.

E.5.2 *Testing the sample.* The test specimen should be allowed to come into equilibrium with the temperature of the test room when the following sequence of operations is carried out.

E.5.2.1 Insert the probe into the test specimen. Where it is necessary to make a hole it is essential that it is of such a size that the probe is in good thermal contact with the specimen.

E.5.2.2 Wait for the probe to attain a steady temperature. This may take some minutes since the insertion of the probe into the sample generates heat which must be allowed to dissipate.

E.5.2.3 When the thermocouple e.m.f. has become constant, switch on the probe heater current and start the stop clock simultaneously. It is essential that the probe current is the same as that used in the determination of the instrument constant Z. The thermocouple e.m.f. is noted at 10 second intervals for three minutes or at two points at a pre-determined interval (e.g. 50 seconds and 150 seconds). This time scale is satisfactory for materials having conductivity less than 0.05 W/(m K). Longer time scales (say, 10 minutes) will be required for materials of higher conductivity.

E.6 Expression of results

The results of the test may be plotted on semi-logarithmic paper, galvanometer reading (mm) or thermal e.m.f. (μV) against log time (seconds). The two points to be used to calculate k from equation (2) must lie on the straight line portion of the graph. The ratio t_2/t_1 must be the same as that for which the probe was calibrated. Alternatively, the galvanometer or potentiometer readings at two pre-determined intervals (e.g. 50 seconds and 150 seconds) may be used without drawing a graph. These two intervals must lie on the straight line portion of a calibration graph for similar materials.

The thermal conductivity is then calculated from equation (2).

E.7 References

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Appendix F Units and conversion factors

The quantities arising in heat transmission calculations are now expressed in metric (SI) units which are based on the watt (or joule per second), metre, kilogram and kelvin.

Various other units or combinations of units have also been used, the commonest of these are listed below, together with the relations between them. Certain of these, which are printed in bold type, are exact, the remainder are correct to 4 significant figures. More precise figures may be found in BS 350, "*Conversion factors and tables*".

F.1 Quantity of heat

See Table 4. The unit is the joule (J).

Table 4 — Quantity of heat

	J	kcal	Btu
1 joule (J)	**1**	2.388×10^{-4}	9.478×10^{-4}
1 Kilocalorie (kcal)	**4186.8**	**1**	3.968
1 British thermal unit (Btu)	1 055	0.2520	**1**

NOTE 1 1 therm = 100 000 British thermal units = 105.5 megajoules.
NOTE 2 The kilocalorie is based on the "international table calorie".

F.2 Thermal transmission

See Table 5. The unit is the watt (W).

Table 5 — Thermal transmission

	W	cal/s	kcal/h	Btu/h
1W	**1**	0.2388	0.8598	3.412
1 cal/s	**4.1868**	**1**	**3.6**	14.29
1 kcal/h	**1.163**	0.277 8	**1**	3.968
1 Btu/h	0.2931	7.000×10^{-2}	0.2520	**1**

F.3 Thermal conductivity

See Table 6. The unit is watt per square metre for one metre thickness and one kelvin difference in temperature [W/(m K)].

Table 6 — Thermal conductivity

	$\frac{W}{m\,K}$	$\frac{J\,cm}{cm^2\,s\,°C}$	$\frac{cal\,cm}{cm^2\,s\,°C}$	$\frac{kcal\,m}{m^2\,h\,°C}$	$\frac{Btu\,ft}{ft^2\,h\,°F}$	$\frac{Btu\,in}{ft^2\,h\,°F}$
$1\ \frac{W}{m\,K}$	**1**	**0.01**	2.388×10^{-3}	0.859 8	0.577 8	6.933
$1\ \frac{J\,cm}{cm^2\,s\,°C}$	**100**	**1**	0.238 8	85.98	57.78	693.3
$1\ \frac{cal\,cm}{cm^2\,s\,°C}$	**418.68**	**4.186 8**	**1**	**360**	241.9	2 903
$1\ \frac{kcal\,m}{m^2\,h\,°C}$	**1.163**	$\mathbf{1.163 \times 10^{-2}}$	2.778×10^{-3}	**1**	0.672 0	8.064
$1\ \frac{Btu\,ft}{ft^2\,h\,°F}$	1.731	1.731×10^{-2}	4.134×10^{-3}	1.488	**1**	**12**
$1\ \frac{Btu\,in}{ft^2\,h\,°F}$	0.1442	1.442×10^{-3}	3.445×10^{-4}	0.1240	8.333×10^{-2}	**1**

NOTE Rationalized forms of some of the expressions given above are also used respectively as follows:
$\frac{W}{cm\,°C}$, $\frac{cal}{cm\,s\,°C}$, $\frac{kcal}{m\,h\,°C}$, $\frac{Btu}{ft\,h\,°F}$

F.4 Thermal resistivity

The unit is metre kelvin per watt (m K/W); thermal resistivity is the reciprocal of thermal conductivity.

F.5 Thermal conductance, thermal transmittance, surface coefficient, convection coefficient and radiation coefficient

See Table 7. The unit is watt per square metre for one kelvin difference in temperature (W/[m^2 K)].

Table 7 — Thermal conductance, thermal transmittance, surface coefficient, convection coefficient and radiation coefficient

	$\frac{W}{m^2\ K}$	$\frac{J}{cm^2\ s\ °C}$	$\frac{cal}{cm^2\ °C}$	$\frac{kcal}{m^2\ h\ °C}$	$\frac{Btu}{ft^2\ h\ °F}$
1 $\frac{W}{m^2\ K}$	**1**	**10^{-4}**	2.388×10^{-5}	0.859 8	0.176 1
1 $\frac{J}{cm^2\ s\ °C}$	**10 000**	**1**	0.238 8	8.598	1 761
1 $\frac{cal}{cm^2\ s\ °C}$	**41 868**	**4.186 8**	**1**	**36 000**	7 373
1 $\frac{kcal}{m^2\ h\ °C}$	**1.163**	**1.163×10^{-4}**	2.778×10^{-5}	**1**	0.204 8
1 $\frac{Btu}{ft^2\ h\ °F}$	5.678	5.678×10^{-4}	1.356×10^{-4}	4.882	**1**

F.6 Thermal resistance, total thermal resistance and surface resistance

Thermal resistance, total thermal resistance and surface resistance are respectively the reciprocals of thermal conductance, thermal transmittance and surface coefficient. The unit is square metre kelvin per watt (m^2 K/W).

Conversion factors are obtainable from Table 7.

F.7 Shape factor

The unit is the metre (m). The conversion of the shape factor of a body from alternative units of length is carried out in accordance with the usual mathematical principles, but it is essential to avoid "mixed" units (see Note to **F.10**).

F.8 Heat capacity per unit mass

The unit is joule per kilogram for one kelvin [J/(kg K)].

4186.8 J/(kg K) = 4.1868 J/(g K) = 1 cal/(g K)= 1 kcal/(kg K) = 1 Btu/lb °F.

F.9 Heat capacity per unit volume

See Table 8. The unit is joule per cubic metre for one kelvin [J/(m^3 K)].

Table 8 — Heat capacity per unit volume

	J/(m^3 K)	kJ/(m^3 °C)	J/(cm^3 °C)	cal/(cm^3 °C)	kcal/(m^3 °C)	Btu/(ft^3 °F)
1 J/(m^3 K)	**1**	**10^{-3}**	**10^{-6}**	2.388×10^{-7}	2.388×10^{-3}	1.491×10^{-5}
1 kJ/(m^3 °C)	**1 000**	**1**	**10^{-3}**	2.388×10^{-4}	0.238 8	1.491×10^{-2}
1 J/(m^3 °C)	**10^6**	**1 000**	**1**	0.238 8	238.8	14.91
1 cal/(cm^3 °C)	**$4.186\ 8 \times 10^6$**	**4 186.8**	**4.186 8**	1	**1 000**	62.43
1 kcal/(m^3 °C)	**4 186.8**	**4.186 8**	**$4.186\ 8 \times 10^{-3}$**	10^{-3}	**1**	6.243×10^{-2}
1 Btu/(ft^3 °F)	67 070	67.07	6.707×10^{-2}	1.602×10^{-2}	16.02	**1**

F.10 Thermal diffusivity

See Table 9. Thermal diffusivity is thermal conductivity divided by thermal capacity per unit volume. It is therefore expressed, for example in terms of

$$\frac{\mathrm{W/(m\ K)}}{\mathrm{J/(m^3\ K)}} \text{ or } \frac{\mathrm{J\ m/(m^2\ s\ K)}}{\mathrm{J/(m^3\ K)}} = \frac{\mathrm{m^2}}{\mathrm{s}}$$

Table 9 — Thermal diffusivity

	m^2/s	cm^2/s	m^2/h	ft^2/h	in^2/h
1 m^2/s	**1**	**10 000**	**3 600**	38 750	5.58×10^6
1 cm^2/s	$\mathbf{10^{-4}}$	**1**	**0.36**	3.875	558.0
1 m^2/h	2.778×10^{-4}	2.778	**1**	10.76	1 550
1 ft^2/h	2.581×10^{-5}	0.258 1	9.290×10^{-2}	**1**	**144**
1 in^2/h	1.792×10^{-7}	1.792×10^{-3}	6.542×10^{-4}	6.944×10^{-3}	**1**

NOTE In calculations involving diffusivity, the units employed need to be consistent. For instance, conductivity should be expressed in the units Btu ft/(ft^2 h °F) and not Btu in/(ft^3 h °F).

F.11 Radiation constant

Since the emissivity is independent of units, it is only necessary to know Stefan's constant, in various units.

Stefan's constant $= 5.670 \times 10^{-8}\ \frac{\mathrm{W}}{\mathrm{m^2\ K^4}}$ 0r $\frac{\mathrm{J}}{\mathrm{m^2\ s\ K^4}}$

$= 1.354 \times 10^{-12}\ \frac{\mathrm{cal}}{\mathrm{cm^2\ s\ K^4}}$

$= 4.755 \times 10^{-13}\ \frac{\mathrm{Btu}}{\mathrm{ft^2\ h\ °R^4}}$

$= 1.712 \times 10^{-9}\ \frac{\mathrm{Btu}}{\mathrm{ft^2\ h\ °R^4}}$

K (kelvin) is the thermodynamic temperature using the Celsius scale.

°R (degree Rankine) is the thermodynamic temperature using the Fahrenheit scale.

NOTE In contrast to the preceding relations between units, which are man-made and capable of being fixed by definition, Stefan's constant is an experimentally determined figure liable to revision in the light of more accurate determinations.

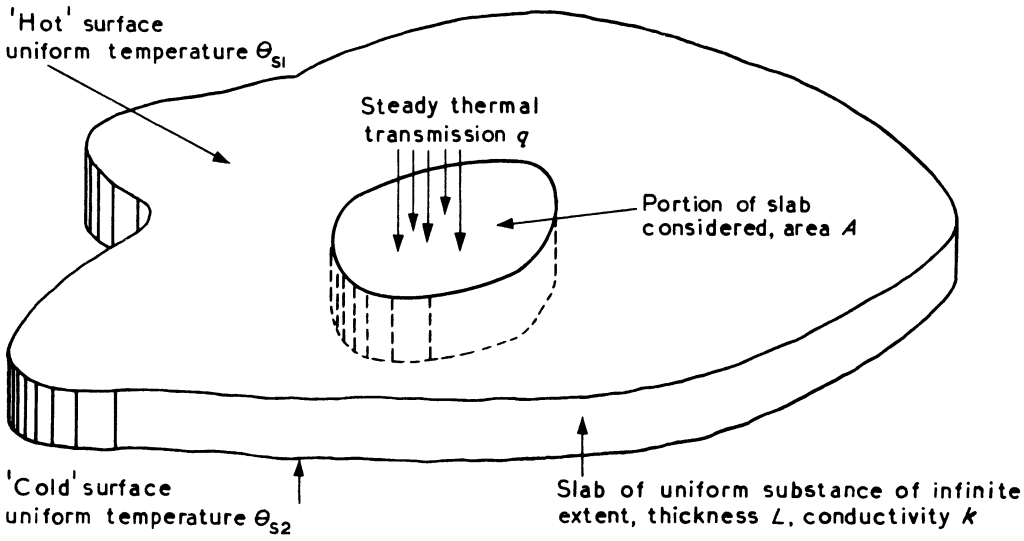


Figure 1 — Diagram illustrating definition 2. Under these conditions $q = \frac{kA}{L}(\theta_{s1} - \theta_{s2})$

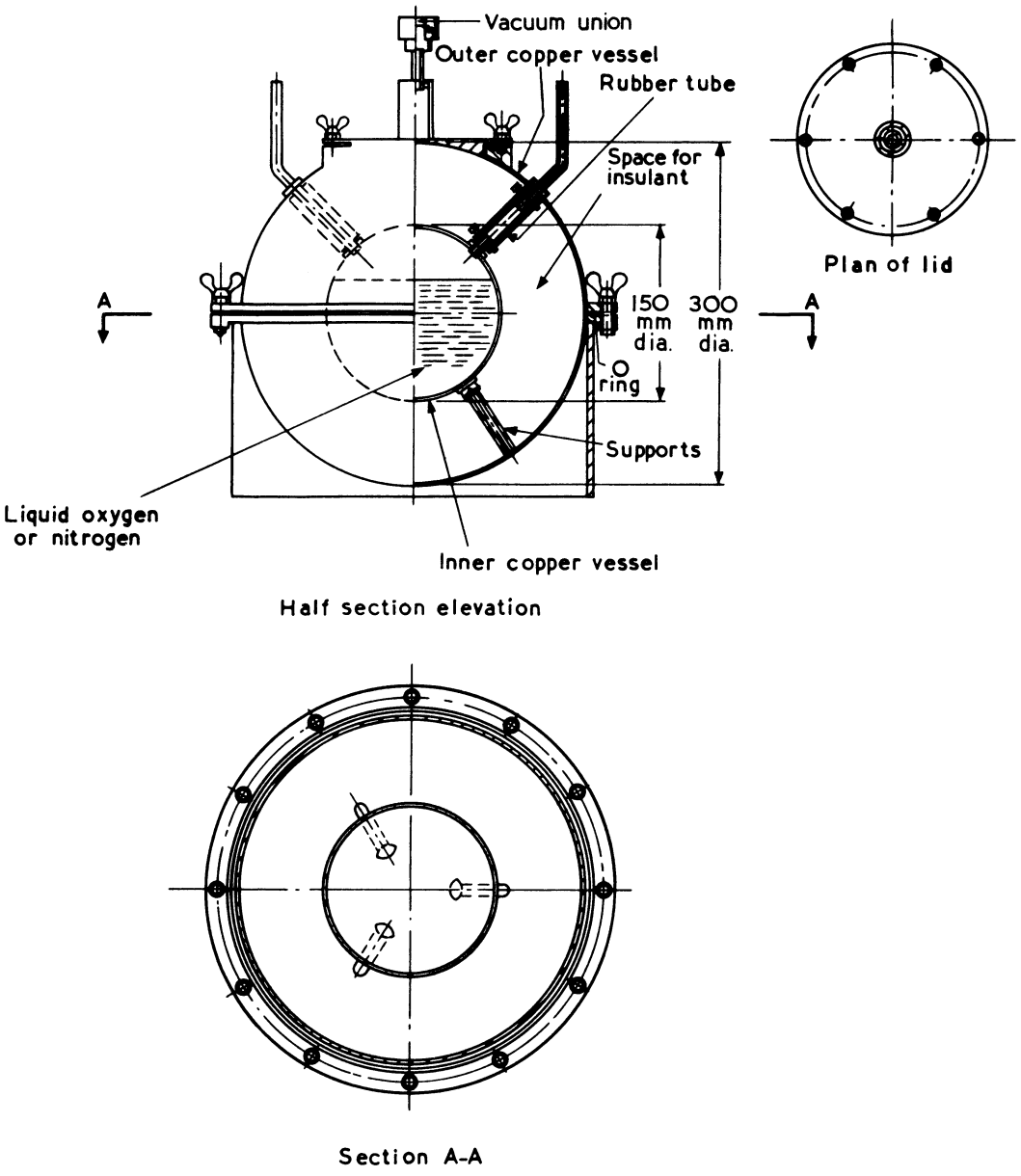


Figure 2 — Spherical vessel for low temperature conductivity tests

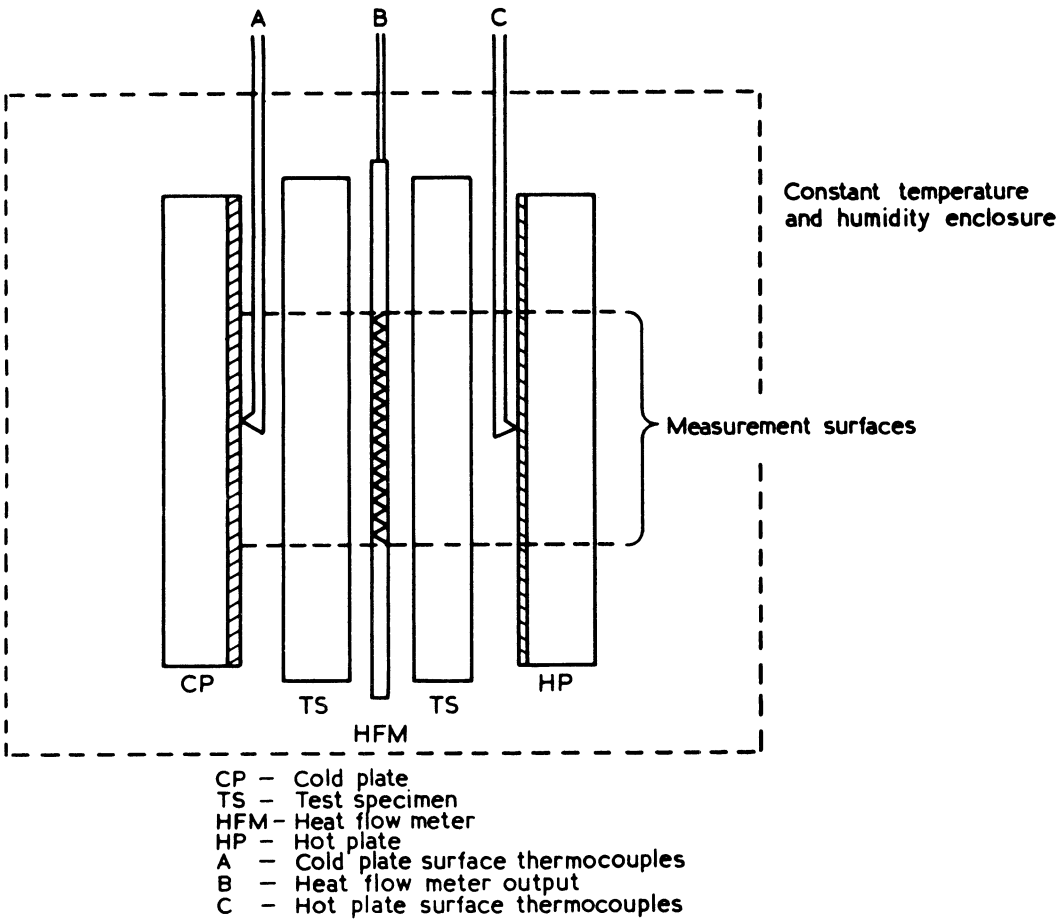
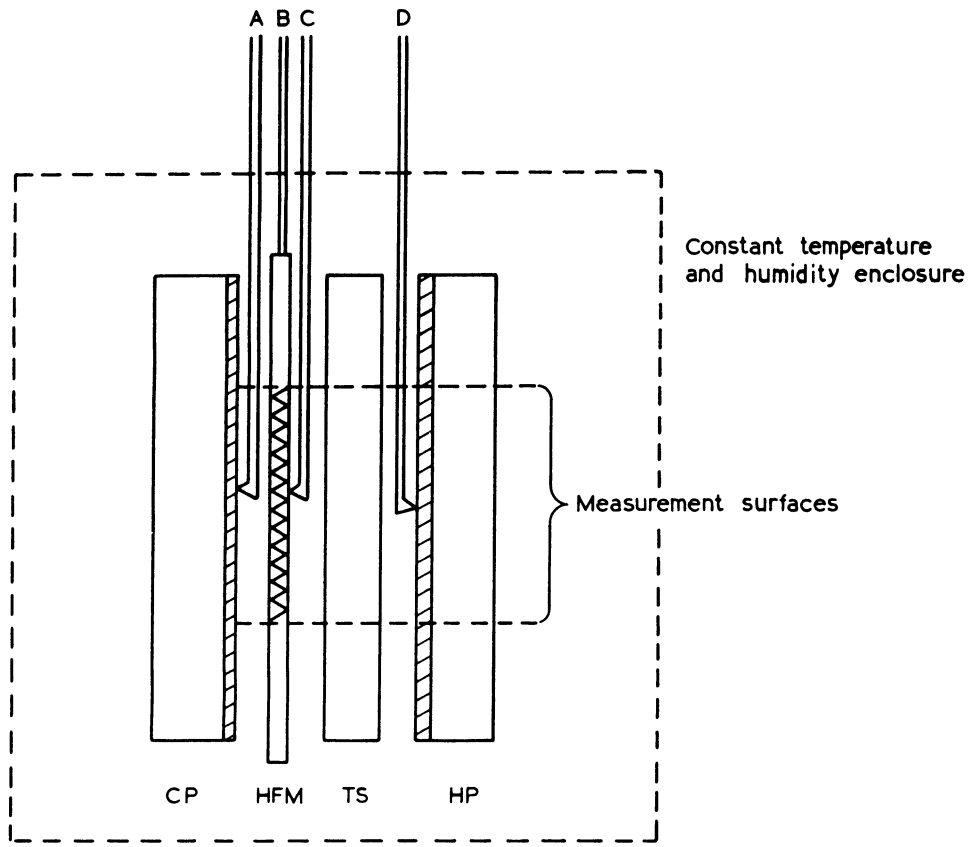


Figure 3 — Heat flow meter apparatus



CP — Cold plate
HFM — Heat flow meter
TS — Test specimen
HP — Hot plate
A — Cold plate surface thermocouples
B — Heat flow meter output
C — Heat flow meter surface thermocouple
D — Hot plate surface thermocouple

Figure 4 — Heat flow meter with single test specimen

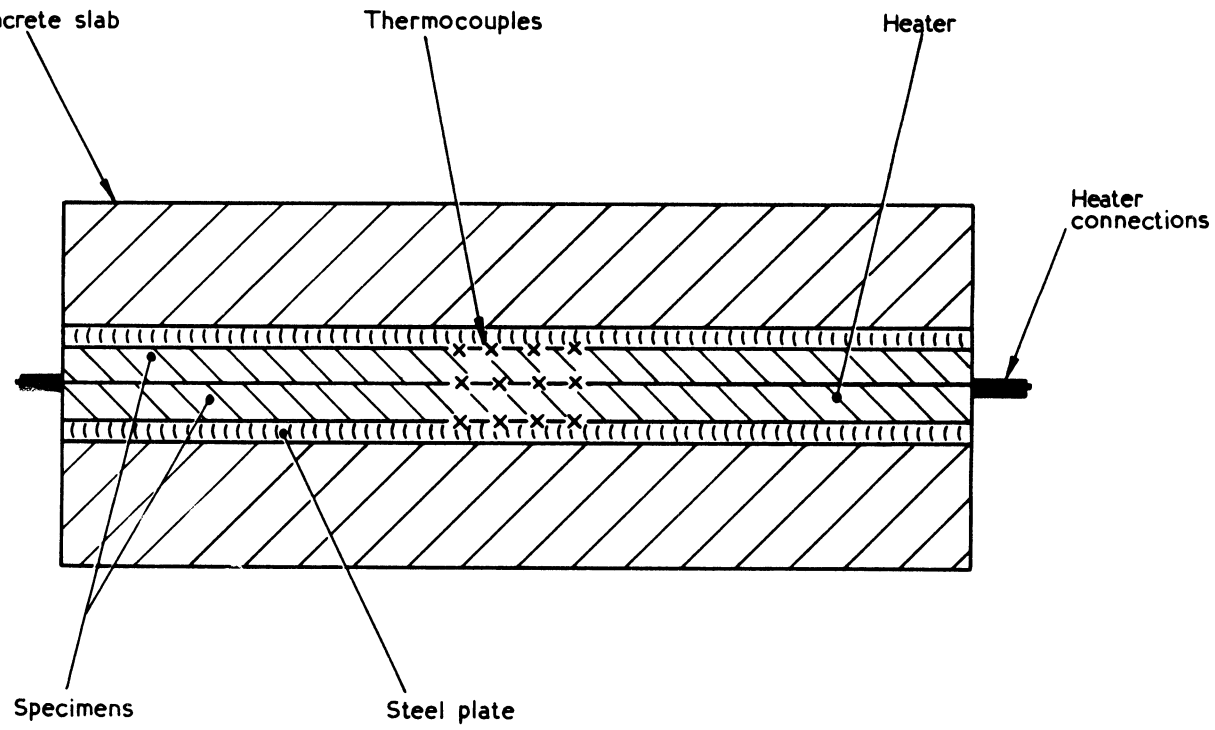


Figure 5 — Typical two specimen arrangement for transient-flow measurement of thermal properties

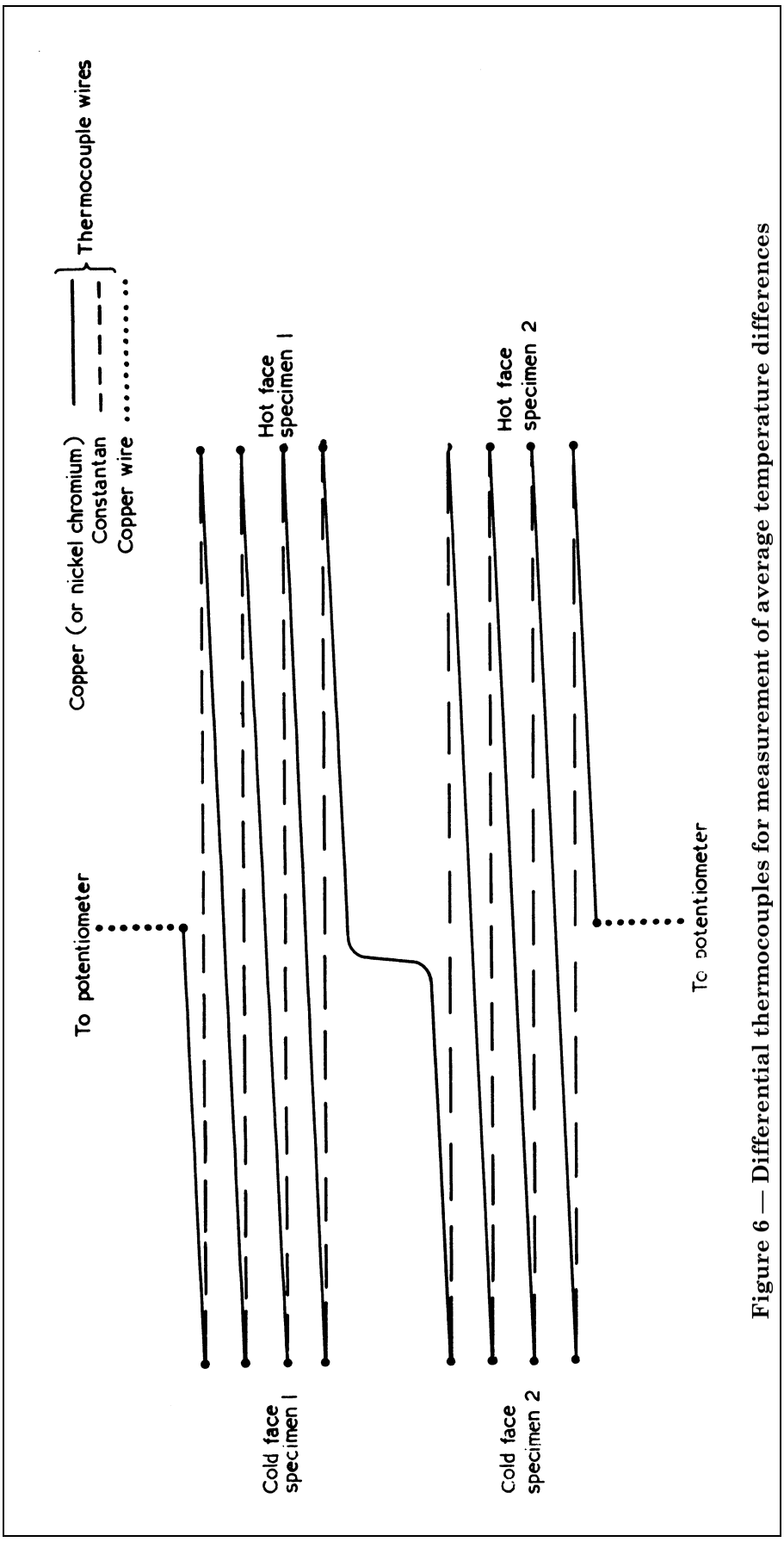


Figure 6 — Differential thermocouples for measurement of average temperature differences

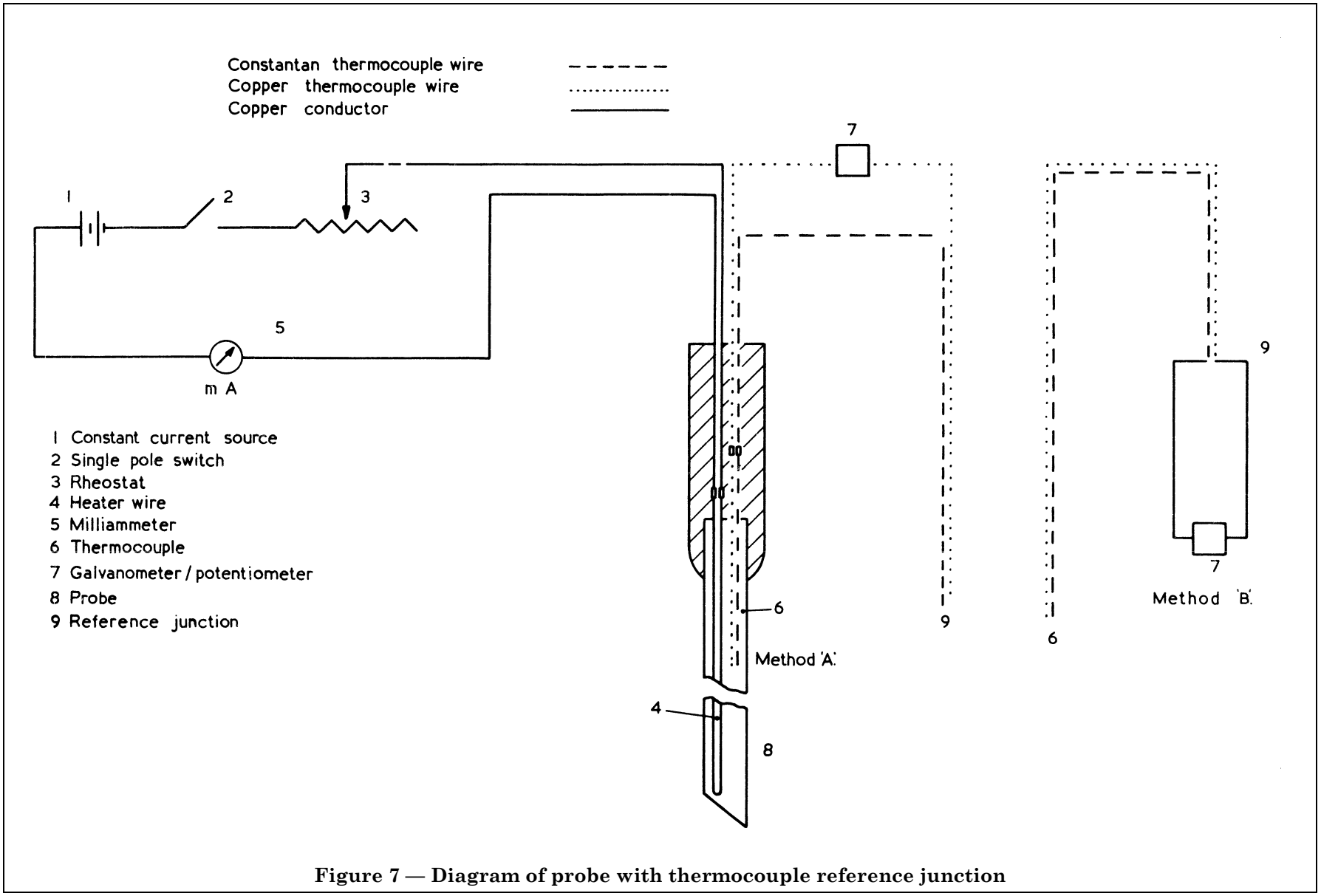


Figure 7 — Diagram of probe with thermocouple reference junction

Appendix G Materials of medium conductivity in slab form. Test equipment (see **4.2.2**.)

Test equipment for the determination of the thermal conductivity of slab specimens within the range 0.15 W/(m K) to 2 W/(m K) should comply with the following requirements if the necessary precision is to be obtained.

a) *Cold plates.* The deviation in flatness of the cold face surface shall not exceed 0.2 mm. The temperatures of the cold plates shall be maintained constant to within 1 % of the temperature difference across the specimens, e.g. ± 0.15 °C.

b) *Hot plate.* The deviation in flatness of the faces of the hot plate shall not exceed 0.2 mm.

c) *Thermal contact sheets.* Thermal contact sheets are normally made of silicone rubber sheet about 2 mm to 3 mm in thickness. Care should be taken to ensure that the faces of the sheets, specimens, hot plate and cold plates are clean and free from grit.

d) *Temperature measurements.* The constant temperature difference between the faces of the specimens shall be not less than 15 °C and the error in the measurement of this difference shall not exceed ± 1 %. [See **2.1.2**, paragraph 4 and **3.1** 1)]. Usually the thermocouples need to be calibrated to attain this precision and the cold junctions maintained at a constant uniform temperature.

The junctions of the four (or more) thermocouples shall be distributed over each face of the test specimens in the approximate positions shown in Figure 8.

The thermocouples shall be in intimate thermal contact with the surfaces of the specimens (**4.2.2**), for example by attaching them with thin adhesive tape. However, for the higher conductivity specimens, above about 0.5 W/(m K), the couples shall be cemented into shallow grooves in the surfaces of the specimens and the surface finished flat.

e) *Electrical input measurement.* The electrical energy dissipated in the hot plate shall be maintained constant over a period of several days to ± 1 % or better and the error in its measurement shall not exceed ± 0.25 %.

f) *Thermal insulation of apparatus.* Care shall be taken to apply the insulation in a uniform manner so that the side loss correction is reproduced. Suitable materials are "loose-fills" such as cork granules, mineral wool, etc. If the cold plates are maintained at temperatures below the dew point of the ambient air the apparatus and insulation shall be enclosed and sealed to prevent condensation occurring.

g) *Side loss corrections.* These corrections are obtained by the use of suitable reference specimens such as bonded glass fibre slabs (density about 100 kg/m^3). A graph can be drawn relating side loss to the difference between hot plate and ambient air temperature for various thicknesses of specimens, to cover the range of probable test conditions for which the apparatus may be used. The corrections shall be redetermined if the type of insulation or the method of applying the insulation is changed.

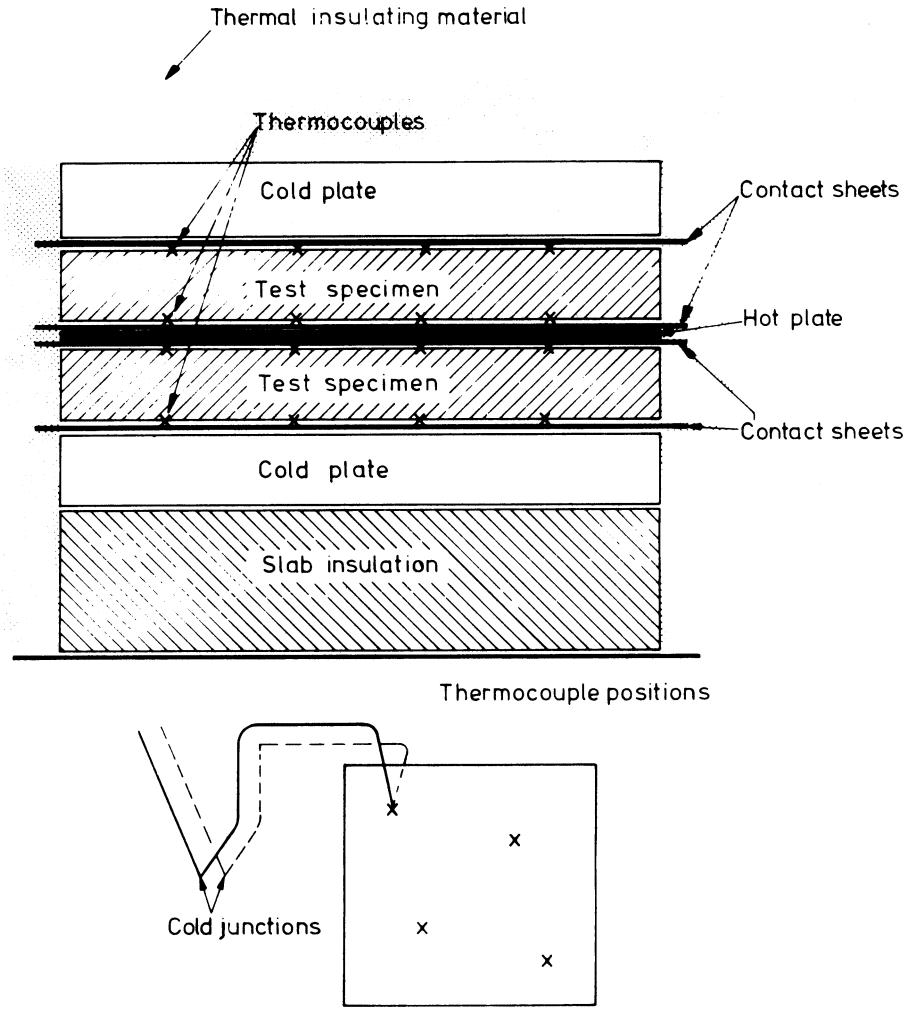


Figure 8 — Diagram of plain (unguarded) hot plate apparatus

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Publications referred to

This standard makes reference to the following British Standards:
BS 874, *Methods for determining thermal insulating properties.*
BS 874-1, *Introduction, definitions and principles of measurement.*
BS 874-2, *Tests for thermal conductivity and related properties.*
BS 874-2.1, *Guarded hot-plate method.*
BS 874-3, *Tests for thermal transmittance and conductance.*
BS 874-3.1, *Guarded hot-box method.*
BS 1902, *Methods of testing refractory materials.*
BS 2972, *Methods of test for thermal insulating materials.*
BS 3533, *Glossary of terms relating to thermal insulation.*

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