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Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus

Isolation thermique — Détermination de la résistance thermique et des propriétés connexes en régime stationnaire — Méthode de la plaque chaude gardée

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Contents

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Annexes

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 8302 was prepared by Technical Committee ISO/TC 163, *Thermal insulation*.

Annex A forms an integral part of this International Standard. Annexes B, C and D are for information only.

Introduction

0.1 Document subdivision

This International Standard is divided into three sections, representing the most comprehensive assemblage of information required to use the guarded hot plate apparatus, i.e.

Section 1: General considerations

Section 2: Apparatus and error evaluation

Section 3: Test procedures

While the user of the method specified in this International Standard for test purposes may need to concentrate only on section 3, he must also be familiar with the other two sections in order to obtain accurate results. He must be particularly knowledgeable about the general requirements. Section 2 is directed towards the designer of the apparatus, but he also, in order to provide good apparatus, must be concerned with the other sections of this method. Thus, the method will serve its purpose well.

0.2 Heat transfer and measured properties

A large proportion of thermal testing is undertaken on light density porous materials. In such cases, the actual heat transfer within them can involve a complex combination of different contributions of

— radiation;

— conduction both in the solid and gas phase; and

— convection (in some operating conditions);

plus their interactions together with mass transfer, especially in moist materials. For such materials, the heat transfer property, very often wrongly called "thermal conductivity", calculated from a defined formula and the results of measurements of heat flow-rate, temperature difference and dimensions, for a specimen may be not an intrinsic property of the material itself. This property, in accordance with ISO 9288, should therefore be called "transfer factor" as it may depend on the test conditions (the transfer factor is often referred to elsewhere as apparent or effective thermal conductivity). Transfer factor may have a significant dependence on the thickness of the specimen and/or on the temperature difference for the same mean test temperature.

Heat transfer by radiation is the first source of dependence of transfer factor on specimen thickness. As a consequence, not only material properties influence results, but also the radiative characteristics of the surfaces adjoining those of the specimen. Heat transfer by radiation also contributes to the dependence of transfer factor on temperature differences. This dependence can be experimentally detected for each type of material and for each mean test temperature when the temperature difference exceeds defined limits. Thermal resistance is therefore the property that better describes the thermal behaviour of the specimen, provided it is accompanied by information on the radiative characteristics of the adjoining surfaces. If there is the possibility of the onset of convection within the specimen (e.g. in light mineral wool for low temperatures), the apparatus orientation, the thickness and the temperature difference can influence both the transfer factor and the thermal resistance. In such cases, as a minimum it is required to fully specify the geometry and the boundary conditions of the specimen tested, even though information supplied in section 3 on test procedures does not cover these test conditions in detail. In addition, it will take considerable knowledge to evaluate the measurement, as such, especially when applying the measured values in practice.

The influence of moisture within a specimen on the heat transfer during a measurement is also a very complex matter. Therefore, dried specimens only shall be tested according to standard procedures. Measurements on moist materials need additional precautions not covered in detail in this International Standard.

The knowledge of the physical principles mentioned is also extremely important when a heat transfer property, determined by this test method, is used to predict the thermal behaviour of a specific material in a practical application even though other factors such as workmanship can influence this behaviour.

0.3 Background required

The design and subsequent correct operation of a guarded hot plate to obtain correct results and the interpretation of experimental results is a complex subject requiring great care. It is recommended that the designer, operator and the user of measured data of the guarded hot plate should have a thorough background of knowledge of heat transfer mechanism in the materials, products and systems being evaluated, coupled with experience of electrical and temperature measurements, particularly at low signal levels. Good laboratory practice in accordance with general test procedures should also be maintained.

The in-depth knowledge in each area mentioned may be different for the designer, operator and data user.

0.4 Design, size and national standards

Many different designs of guarded hot plate apparatus exist worldwide which conform to present national standards. Continuing research and development is in progress to improve the apparatus and measurement techniques. Thus, it is not practical to mandate a specific design or size of apparatus, especially as total requirements may vary quite widely.

0.5 Guidelines supplied

Considerable latitude both in the temperature range and in the geometry of the apparatus is given to the designer of new equipment since various forms have been found to give comparable results. It is recommended that designers of new apparatus read the comprehensive literature cited in annex D carefully. After completion of new apparatus, it is recommended that it be verified by undertaking tests on one or more of the various reference materials of different thermal resistance levels available.

This International Standard outlines just the mandatory requirements necessary to design and operate a guarded hot plate in order to provide correct results.

Limit values for the apparatus performance and testing conditions stated in this International Standard are given in annex A.

This International Standard also includes recommended procedures and practices plus suggested specimen dimensions which together should enhance general measurement levels and assist in improving inter-laboratory comparisons and collaborative measurement programmes.

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Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus

Section 1: General

1.1 Scope

This International Standard lays down a test method which defines the use of the guarded hot plate method to measure the steady-state heat transfer through flat slab specimens and the calculation of its heat transfer properties.

This is an absolute or primary method of measurement of heat transfer properties, since only measurements of length, temperature and electrical power are required.

Reports conforming to this standard test method shall never refer to specimens with thermal resistance lower than 0,1 $m^2 \cdot K/W$ provided that thickness limits given in 1.7.4 are not exceeded.

The limit for thermal resistance may be as low as 0,02 $m^2 \cdot K/W$ but the accuracy stated in 1.5.3 may not be achieved over the full range.

If the specimens satisfy only the requirements outlined in 1.8.1 , the resultant properties shall be described as the thermal conductance and thermal resistance or transfer factor of the specimen.

If the specimens satisfy the requirements of 1.8.2, the resultant property may be described as the mean measurable thermal conductivity of the specimen being evaluated.

If the specimens satisfy the requirements of 1.8.3, the resultant property may be described as the thermal conductivity or transmissivity of the material being evaluated.

1.2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7345:1987, *Thermal insulation — Physical quantities and definitions.*

ISO 9229:—[1], *Thermal insulation — Materials, products and systems — Vocabulary.*

ISO 9251:1987, *Thermal insulation — Heat transfer conditions and properties of materials — Vocabulary.*

ISO 9288:1989, *Thermal insulation — Heat transfer by radiation — Physical quantities and definitions.*

ISO 9346:1987, *Thermal insulation — Mass transfer — Physical quantities and definitions.*

1.3 Definitions

For the purposes of this International Standard, the following definitions apply.

The following quantities are defined in ISO 7345 or in ISO 9251:

1) To be published.

Quantity	Symbol	Units
Heat flow-rate	Φ	W
Density of heat flow-rate	q	W/m^2
Thermal resistance[1]	R	$m^2 \cdot K/W$
Thermal conductance	Λ	$W/(m^2 \cdot K)$
Thermal conductivity[2]	λ	$W/(m \cdot K)$
Thermal resistivity	r	$m \cdot K/W$
Porosity	ξ	
Local porosity	ξ_p	

1) In some cases it may be necessary to consider also the temperature difference divided by the heat flow-rate; no special symbol is assigned to this quantity, sometimes also called resistance.

2) In the most general case $\vec{q}$ and grad T do not have the same orientation ($\overset{\rightrightarrows}{\lambda}$ is not defined through a single constant λ but through a matrix of constants); moreover conductivity changes while changing position within the body, while changing the temperature and changes with time.

The following definitions related to material properties are given in ISO 9251:

- porous medium
- homogeneous medium
- homogeneous porous medium
- heterogeneous medium
- isotropic medium
- anisotropic medium
- stable medium

Other terms not defined in ISO 7345 or ISO 9251:

1.3.1 thermally homogeneous medium: Is one in which thermal conductivity $[\overset{\rightrightarrows}{\lambda}]$ is not a function of the position within the medium but may be a function of direction, time and temperature.

1.3.2 thermally isotropic medium: Is one in which thermal conductivity $[\overset{\rightrightarrows}{\lambda}]$ is not a function of direction but may be a function of the position with the medium, of time and of the temperature ($[\overset{\rightrightarrows}{\lambda}]$ is defined through a single value λ in each point).

1.3.3 thermally stable medium: Is one in which thermal conductivity λ or $[\overset{\rightrightarrows}{\lambda}]$ is not a function of time, but may be a function of the co-ordinates, of the temperature and, when applicable, of the direction.

1.3.4 mean thermal conductivity of a specimen: Is the property defined in steady-state conditions in a body that has the form of a slab bounded by two parallel, flat isothermal faces and by adiabatic edges perpendicular to the faces, that is made of a material thermally homogeneous, isotropic (or anisotropic with a symmetry axis perpendicular to the faces), stable only within the precision of a measurement and the time required to execute it, and with thermal conductivity λ or $[\overset{\rightrightarrows}{\lambda}]$ constant or a linear function of temperature.

1.3.5 transfer factor of a specimen: Is defined by

$$\mathscr{T} = \frac{qd}{\Delta T} = \frac{d}{R} \text{ W(m·K)}$$

It depends on experimental conditions and characterizes a **specimen** in relation with the combined conduction and radiation heat transfer. It is often referred to elsewhere as measured, equivalent, apparent or effective thermal conductivity of a **specimen**.

1.3.6 thermal transmissivity of a material: Is defined by

$$\lambda_t = \frac{\Delta d}{\Delta R} \text{ W/(m·K)}$$

when $\Delta d/\Delta R$ is independent of the thickness d. It is independent of experimental conditions and characterizes an insulating **material** in relation with combined conduction and radiation. Thermal transmissivity can be seen as the limit reached by the transfer factor in thick layers where combined conduction and radiation heat transfer takes place. It is often referred to elsewhere as equivalent, apparent or effective thermal conductivity of a **material**.

1.3.7 steady-state heat transfer property: Generic term to identify one of the following properties: thermal resistance, transfer factor, thermal conductivity, thermal resistivity, thermal transmissivity, thermal conductance, mean thermal conductivity.

1.3.8 room temperature: Generic term to identify a mean test temperature of a measurement such that a man in a room would regard it comfortable if it were the temperature of that room.

1.3.9 ambient temperature: Generic term to identify the temperature in the vicinity of the edge of the specimen or in the vicinity of the whole apparatus. This temperature is the temperature within the cabinet where the apparatus is enclosed or that of the laboratory for non-enclosed apparatus.

1.3.10 operator: Person responsible for carrying out the test and for the presentation through a report of the measured results.

1.3.11 data user: Person involved in the application and interpretation of measured results to judge material or system performance.

1.3.12 designer: Person who develops the constructional details of an apparatus in order to meet predefined performance limits for the apparatus in assigned test conditions and who identifies test procedures to verify the predicted apparatus accuracy.

1.4 Symbols and units

Symbol	Dimension	Unit
A	Metering area measured on a selected isothermal surface	m^2
A_g	Area of the gap	m^2
A_m	Area of the metering section	m^2
b	Guard width, starting from the gap centre-line	m
c	Imbalance coefficient	m
c_p	Specific heat capacity of the plate	J/(kg·K)
c_s	Specific heat capacity of the specimen	J/(kg·K)
d	Average thickness of a specimen	m
$d_1, d_2, ..., d_5$	Thicknesses of specimens designated $s_1, s_2, ..., s_5$	m
d_p	Metal plate thickness	m
e	Edge number	—
E_A	Error in the metering area value	—
E_d	Error in the thickness value	—
E_e	Error due to edge heat losses	—
E_E	Error in the electrical power value	—
E_g	Error due to imbalance	—
E_s	Error due to non-symmetrical conditions	—
E_T	Error in the temperature difference	—
E_Φ	Error in the heat flow-rate	—
g	Gap width	m
h_t	Density of heat flow-rate per unit temperature difference	$W/(m^2 \cdot K)$
$2l$	Side length of the metering section from gap centre to gap centre	m
m_c	Relative mass change after conditioning	—
m_d	Relative mass change due to a conditioning after drying	—
m_r	Relative mass change after drying	—
m_w	Relative mass change after test	—
M_1	Mass as received	kg
M_2	Mass after drying	kg
M_3	Mass after conditioning	kg
M_4	Mass after test	kg
M_5	Mass before test	kg
P	Perimeter	m
q	Density of heat flow-rate	W/m^2
q_e	Edge density of heat flow-rate	W/m^2
r	Thermal resistivity	m·K/W
R	Thermal resistance	$m^2 \cdot K/W$
R_e	Thermal resistance of edge insulation	$m^2 \cdot K/W$
t	Time	s
$\mathcal{T}$	Transfer factor	W/(m·K)
T_1	Temperature of the warm surface of the specimen	K
T_2	Temperature of the cold surface of the specimen	K
T_a	Ambient temperature (temperature in the vicinity of the specimen)	K

Symbol	Dimension	Unit
T_e	Temperature on the edge of the specimen	K
T_m	Mean temperature (usually $(T_1 + T_2)/2$)	K
V	Volume	m^3
y	Heating unit thickness	m
Z_1	Error parameter for the edge configuration	—
Z_2	Error parameter for the surrounding temperature	—
Z_3	Error parameter for imbalance	—
Δd	Increment of thickness	m
ΔR	Increment of thermal resistance	m^2·K/W
ΔT	Temperature difference (usually $T_1 - T_2$)	K
ΔT_g	Temperature difference through the gap	K
Δt	Time interval	s
$\Delta \mathscr{T}$	Increment of transfer factor	W/(m·K)
ε	Emissivity	W/(m·K)
λ	Thermal conductivity	W/(m·K)
λ_g	Thermal conductivity of a material facing the gap	W/(m·K)
λ_t	Thermal transmissivity	W/(m·K)
Λ	Thermal conductance	W/(m^2·K)
ξ	Porosity	—
ξ_p	Local porosity	—
Φ	Heat flow-rate	W
Φ_e	Heat flow-rate due to edge heat losses	W
Φ_{el}	Heat flow-rate on the edge	W
Φ_g	Heat flow-rate due to imbalance	W
Φ_T	Heat flow-rate in a test	W
Φ_w	Heat flow-rate through the wires	W
Φ_o	Gap heat flow-rate per unit temperature imbalance	W/K
δ_d	Density of the dry specimen	kg/m^3
ρ_p	Density of the plate	kg/m^3
ρ_s	Density of the specimen after conditioning	kg/m^3
σ_n	Stefan-Boltzmann constant	5,67 W/(m^2·K^4)

1.5 Significance

1.5.1 Factors influencing heat transfer properties

The heat transfer properties of a specimen of material may

— vary due to variability of composition of the material or samples of it;

— be affected by moisture or other factors;

— change with time;

— change with mean temperature; and

— depend upon the thermal history.

It must be recognized, therefore, that the selection of a typical value of heat transfer properties representative of a material in a particular application shall be based on a consideration of these factors and will not necessarily apply without modification to all service conditions.

As an example, this method provides that the heat transfer properties should be obtained on dried specimens, although in service such conditions may not be realized.

Even more basic is dependence of the heat transfer properties on variables such as mean temperature and the temperature difference. These dependencies should be measured or the tests made under conditions typical of use.

1.5.2 Sampling

Heat transfer properties need an adequate amount of test information to be considered representative of a material. A heat transfer property of a material can be determined by a single measurement only if the sample is typical of the material and the specimen(s) is (are) typical of the sample. The procedure for selecting the sample should normally be specified in the material specification. The selection of the specimen from the sample may be partly specified in the material specification. As sampling is beyond the scope of this test method, when the problem is not covered by a material specification, appropriate documents shall be considered.

1.5.3 Accuracy and reproducibility

The evaluation of the accuracy of the method is complex and is a function of the apparatus design, of the related instrumentation and of the type of specimen under test. However, apparatus constructed and operated in accordance with this method is capable of measuring heat transfer properties accurate to within ± 2 % when the mean temperature of the test is near the room temperature.

With adequate precautions in the design of the apparatus, and after extensive checking and cross-referencing of measurements with other similar apparatus, an accuracy of about ± 5 % should be obtainable anywhere in the full operating range of an apparatus. Such accuracy is normally easier to attain using separate apparatus for the extremes in the range. The reproducibility of subsequent measurements made by the apparatus on a specimen maintained within the apparatus without changes in test conditions is normally much better than 1 %. When measurements are made on the same reference specimen removed and then mounted again after long time intervals, the reproducibility of measurements is normally better than ± 1 %. This larger figure is due to minor changes in test conditions, such as the pressure of the plates on the specimen (that affect contact resistances), the relative humidity of the air around the specimen (that affects its moisture contents), etc.

These levels of reproducibility are required to identify errors in the method and is desirable in quality control applications.

1.6 Principle

1.6.1 Apparatus principle

The guarded hot plate apparatus is intended to establish within specimen(s), in the form of uniform slab(s) having flat parallel faces, a unidirectional uniform density of heat flow-rate at steady-state conditions as the one that would exist in an infinite slab bounded by two flat parallel isothermal surfaces.

1.6.2 Apparatus types

From this basic principle were derived two types of guarded hot plate apparatus:

a) with two specimens (and a central heating unit);

b) with a single specimen.

1.6.2.1 Two-specimen apparatus

In the two specimen apparatus [see figure 1a)], a central round or square flat plate assembly consisting of a heater and metal surface plates and called the heating unit is sandwiched between two nearly identical specimens. The heat flow-rate is transferred through the specimens to separate round or square isothermal flat assemblies called the cooling units.

1.6.2.2 Single-specimen apparatus

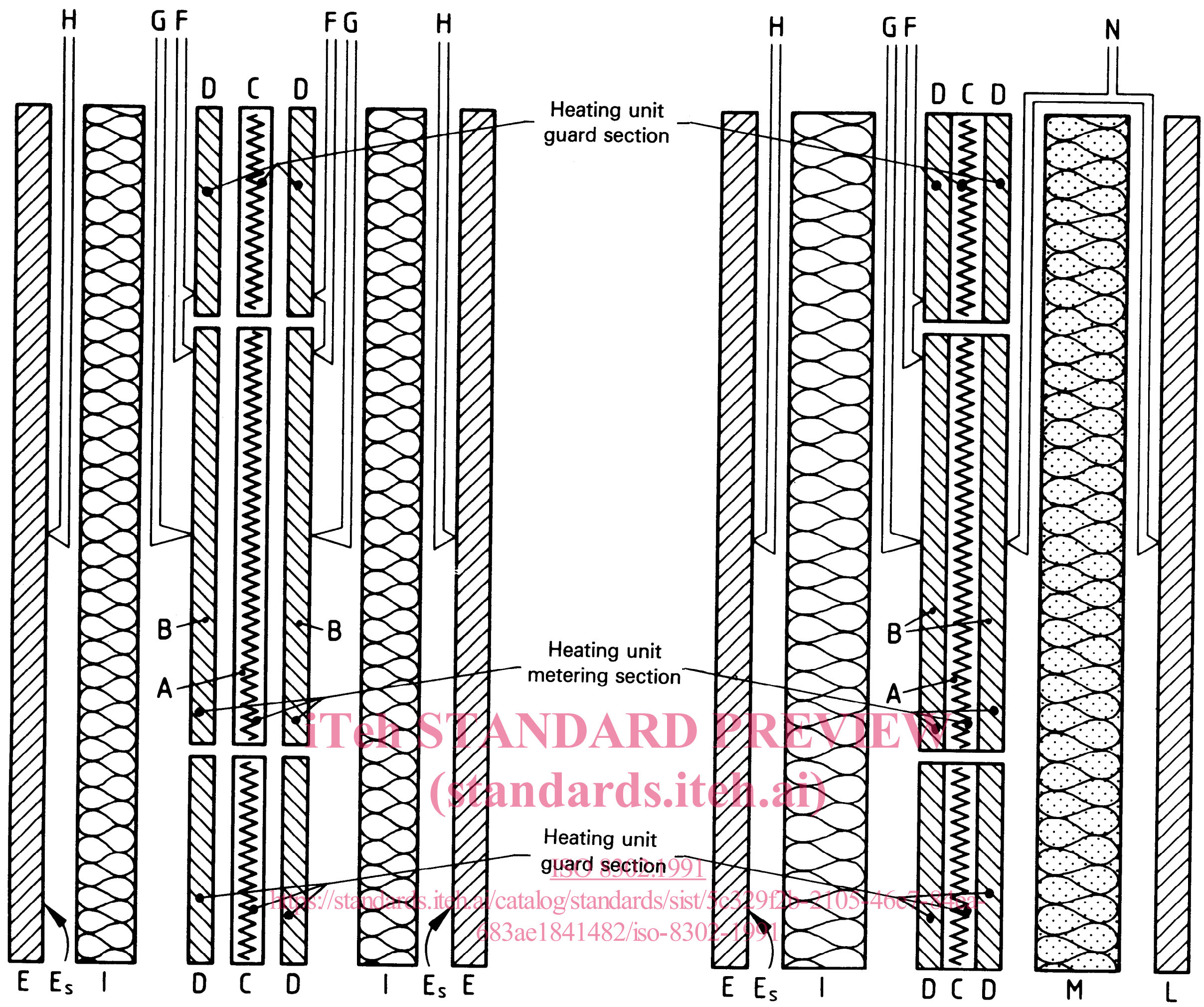
In the single specimen apparatus [see figure 1b)], the second specimen is replaced by a combination of a piece of insulation and a guard plate. A zero temperature-difference is then established across this combination. Providing all other applicable requirements of this International Standard are fulfilled, accurate measurements and reporting according to this method may be accomplished with this type of apparatus, but particular reference to the modification of the normal hot plate apparatus with two specimens should be made in the report.

1.6.3 Heating and cooling units

The heating unit consists of a separate metering section, where the unidirectional uniform and constant density of heat flow-rate can be established, surrounded by a guard section separated by a narrow gap. The cooling units may consist of a continuous flat plate assembly but it is preferable to have them in a similar form to the heating unit.

1.6.4 Edge insulation and auxiliary guarded sections

Additional edge insulation and/or auxiliary guard sections are required, especially when operating above or below room temperature.



a) Two-specimen apparatus

b) Single-specimen apparatus

Key

- A Metering section heater
- B Metering section surface plates
- C Guard section heater
- D Guard section surface plates
- E Cooling unit
- E_s Cooling unit surface plate
- F Differential thermocouples
- G Heating unit surface thermocouples
- H Cooling unit surface thermocouples
- I Test specimen
- L Guard plate
- M Guard plate insulation
- N Guard plate differential thermocouples

Figure 1 — General features of two-specimen and single-specimen guarded hot plate apparatus

1.6.5 Definition of the guarded hot plate apparatus

The term "guarded hot plate" applies to the entire assembled apparatus, that, hence, is called "guarded hot plate apparatus". The general features of the apparatus with specimens installed are shown in figure 1.

1.6.6 Measuring the density of heat flow-rate

With the establishment of steady-state in the metering section, the density of heat flow-rate, q, is determined from measurement of the heat-flow-rate, Φ, and the metering area, A, that Φ crosses.

1.6.7 Measuring the temperature difference

The temperature difference across the specimen, ΔT, is measured by temperature sensors fixed at the surfaces of the metal plates and/or those of the specimens where appropriate.

1.6.8 Measuring the thermal resistance or transfer factor

The thermal resistance, R, is calculated from a knowledge of q, A and ΔT if the appropriate conditions given in 1.8.1 are realized. If the thickness, d, of the specimen is measured, the transfer factor, $\mathcal{T}$, may be computed.

1.6.9 Computing thermal conductivity

The mean thermal conductivity, λ of the specimen may also be computed if the appropriate conditions given in 1.8.2 are realized and the thickness, d, of the specimen is measured.

1.6.10 Apparatus limits

The application of the method is limited by the capability of the apparatus to maintain the unidirectional uniform and constant density of heat flow-rate in the specimen coupled with the ability to measure power, temperature and dimensions to the limit of accuracy required.

1.6.11 Specimen limits

The application of the method is also limited by the form of the specimen(s) and the degree to which they are identical in thickness and uniformity of structure (in the case of two-specimen apparatus) and whether their surfaces are flat or parallel.

1.7 Limitations due to apparatus

1.7.1 Limitations due to contact resistances

When testing a specimen of high thermal conductance and rigid (i.e. specimens of a material too hard and unyielding to be appreciably altered in shape by the pressure of the heating and cooling units), even small non-uniformities of the surface of both specimen and the apparatus (surfaces not perfectly flat) will allow contact resistances not uniformly distributed between the specimens and the plates of the heating and of the cooling units.

These will cause non-uniform heat flow-rate distribution and thermal field distortions within the specimens; moreover, they will make accurate surface temperature measurements difficult to undertake. For specimens having thermal resistances less than 0,1 $m^2 \cdot K/W$, special techniques for measuring surface temperatures will be required. Metal surfaces should be machined or cut flat and parallel and stress-relieved.

1.7.2 Upper limits for the thermal resistance

The upper limit of thermal resistance that can be measured is limited by the stability of the power supplied to the heating unit, the ability of the instrumentation to measure power level and the extent of the heat losses or gains due to temperature imbalance errors (analysed later) between the central metering and guard sections of the specimens and of the heating unit.

1.7.3 Limits to temperature difference

Provided that uniformity and stability of the temperature of the surfaces of the heating and cooling unit plates, the noise, resolution and accuracy of the instrumentation and the restrictions on temperature measurements can be maintained within the limits outlined in sections 2 and 3, temperature differences as low as 5 K, when measured differentially, can be used in the measurements, provided the requirements described in 2.1.4.1.2 to 2.1.4.1.4 are met. Lower temperature differences shall be reported as non-compliance with this International Standard.

If temperature measurements of each plate are made by means of thermocouples with independent reference junctions, the accuracy of the calibration of each thermocouple may be the limiting factor in the accuracy of measured temperature differences. In this case, it is recommended that temperature differences of at least 10 K to 20 K are used in order to minimize temperature-difference measurement errors.

Higher temperature differences are limited only by the capability of the apparatus to deliver enough