



# Standard Test Method for Determination of the Thermal Conductivity of Anode Carbons by the Guarded Heat Flow Meter Technique<sup>1</sup>

This standard is issued under the fixed designation D 6744; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers a steady-state technique for the determination of the thermal conductivity of carbon materials in thicknesses of less than 25 mm. The test method is useful for homogeneous materials having a thermal conductivity in the approximate range  $1 < \lambda < 30 \text{ W}/(\text{m}\cdot\text{K})$ , (thermal resistance in the range from 10 to  $400 \times 10^{-4} \text{ m}^2 \cdot \text{K}/\text{W}$ ) over the approximate temperature range from 150 to 600 K. It can be used outside these ranges with reduced accuracy for thicker specimens and for thermal conductivity values up to  $60 \text{ W}/(\text{m}\cdot\text{K})$ .

NOTE 1—It is not recommended to test graphite cathode materials using this test method. Graphites usually have a very low thermal resistance, and the interfaces between the sample to be tested and the instrument become more significant than the sample itself.

1.2 This test method is similar in concept to Test Methods E 1530 and C 518. Significant attention has been paid to ensure that the thermal resistance of contacting surfaces is minimized and reproducible.

1.3 The values stated in SI units are regarded as standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

### 2.1 ASTM Standards:

C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus<sup>2</sup>

E 1530 Test Method for Evaluating the Resistance to Thermal Transmission of Thin Specimens of Materials by the Guarded Heat Flow Meter Technique<sup>3</sup>

## 3. Terminology

### 3.1 Definitions of Terms Specific to This Standard:

3.1.1 *average temperature*—the average temperature of a surface is the area-weighted mean temperature of that surface.

3.1.2 *heat flux transducer (HFT)*—a device that produces an electrical output that is a function of the heat flux, in a predefined and reproducible manner.

3.1.3 *thermal conductance (C)*—the time rate of heat flux through a unit area of a body induced by unit temperature difference between the body surfaces.

3.1.4 *thermal conductivity ( $\lambda$ ), of a solid material*—the time rate of heat flow, under steady conditions, through unit area, per unit temperature gradient in the direction perpendicular to the area.

3.1.5 *thermal resistance (R)*—the reciprocal of thermal conductance.

### 3.2 Symbols:

$\lambda$	= thermal conductivity, $\text{W}/(\text{m}\cdot\text{K})$ , $\text{Btu}\cdot\text{in}/(\text{h}\cdot\text{ft}^2\cdot^\circ\text{F})$
$C$	= thermal conductance, $\text{W}/(\text{m}^2\cdot\text{K})$ , $\text{Btu}/(\text{h}\cdot\text{ft}^2\cdot^\circ\text{F})$
$R$	= thermal resistance, $\text{m}^2\cdot\text{K}/\text{W}$ , $\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$
$\Delta x$	= specimen thickness, mm, in
$A$	= specimen cross sectional area, $\text{m}^2$ , $\text{ft}^2$
$Q$	= heat flow, W, Btu/h
$\phi$	= heat flux transducer output, mV
$N$	= heat flux transducer calibration constant, $\text{W}/(\text{m}^2\cdot\text{mV})$ , $\text{Btu}/(\text{h}\cdot\text{ft}^2\cdot\text{mV})$
$N\phi$	= heat flux, $\text{W}/\text{m}^2$ , $\text{Btu}/(\text{h}\cdot\text{ft}^2)$
$\Delta T$	= temperature difference, $^\circ\text{C}$ , $^\circ\text{F}$
$T_g$	= temperature of guard heater, $^\circ\text{C}$ , $^\circ\text{F}$
$T_u$	= temperature of upper heater, $^\circ\text{C}$ , $^\circ\text{F}$
$T_l$	= temperature of lower heater, $^\circ\text{C}$ , $^\circ\text{F}$
$T_1$	= temperature of one surface of the specimen, $^\circ\text{C}$ , $^\circ\text{F}$
$T_2$	= temperature of the other surface of the specimen, $^\circ\text{C}$ , $^\circ\text{F}$
$T_m$	= mean temperature of the specimen, $^\circ\text{C}$ , $^\circ\text{F}$
$s$	= unknown specimen
$r$	= known calibration or reference specimen
$o$	= contacts

## 4. Summary of Test Method

4.1 A specimen and a heat flux transducer (HFT) are sandwiched between two flat plates controlled at different temperatures, to produce a heat flow through the test stack. A reproducible load is applied to the test stack by pneumatic or

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee D02 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.05.0E on Properties of Fuels, Petroleum Coke and Carbon Materials.

Current edition approved Dec. 10, 2001. Published February 2002.

<sup>2</sup> *Annual Book of ASTM Standards*, Vol 04.06.

<sup>3</sup> *Annual Book of ASTM Standards*, Vol 14.02.

hydraulic means, to ensure that there is a reproducible contact resistance between the specimen and plate surfaces. A cylindrical guard surrounds the test stack and is maintained at a uniform mean temperature of the two plates, in order to minimize lateral heat flow to and from the stack. At steady-state, the difference in temperature between the surfaces contacting the specimen is measured with temperature sensors embedded in the surfaces, together with the electrical output of the HFT. This output (voltage) is proportional to the heat flow through the specimen, the HFT and the interfaces between the specimen and the apparatus. The proportionality is obtained through prior calibration of the system with specimens of known thermal resistance measured under the same conditions, such that contact resistance at the surface is made reproducible.

**5. Significance and Use**

5.1 This test method is designed to measure and compare thermal properties of materials under controlled conditions and their ability to maintain required thermal conductance levels.

**6. Apparatus**

6.1 A schematic rendering of a typical apparatus is shown in Fig. 1. The relative position of the HFT to sample is not important (it may be on the hot or cold side) as the test method is based on maintaining axial heat flow with minimal heat losses or gains radially. It is also up to the designer whether to choose heat flow upward or downward or horizontally, although downward heat flow in a vertical stack is the most common one.

**6.2 Key Components of a Typical Device:**

6.2.1 The compressive force for the stack is to be provided by either a regulated pneumatic or hydraulic cylinder (1) or a

spring loaded mechanism. In either case, means must be provided to ensure that the loading can be varied and set to certain values reproducibility.

6.2.2 The loading force must be transmitted to the stack through a gimball joint (2) that allows up to 5° swivel in the plane perpendicular to the axis of the stack.

6.2.3 Suitable insulator plate (3) separates the gimball joint from the top plate (4).

6.2.4 The top plate (assumed to be the hot plate for the purposes of this description) is equipped with a heater (5) and control thermocouple (6) adjacent to the heater, to maintain a certain desired temperature. (Other means of producing and maintaining temperature may also be used as long as the requirements under 6.3 are met.) The construction of the top plate is such as to ensure uniform heat distribution across its face contacting the sample (8). Attached to this face (or embedded in close proximity to it), in a fashion that does not interfere with the sample/plate interface, is a temperature sensor (7) (typically a thermocouple, thermistor) that defines the temperature of the interface on the plate side.

6.2.5 The sample (8) is in direct contact with the top plate on one side and an intermediate plate (9) on the other side.

6.2.6 The intermediate plate (9) is an optional item. Its purpose is to provide a highly conductive environment to the second temperature sensor (10), to obtain an average temperature of the surface. If the temperature sensor (10) is embedded into the face of the HFT, or other means are provided to define the temperature of the surface facing the sample, the use of the intermediate plate is not mandatory.

6.2.7 Heat flux transducer (HFT) is a device that will generate an electrical signal in proportion to the heat flux

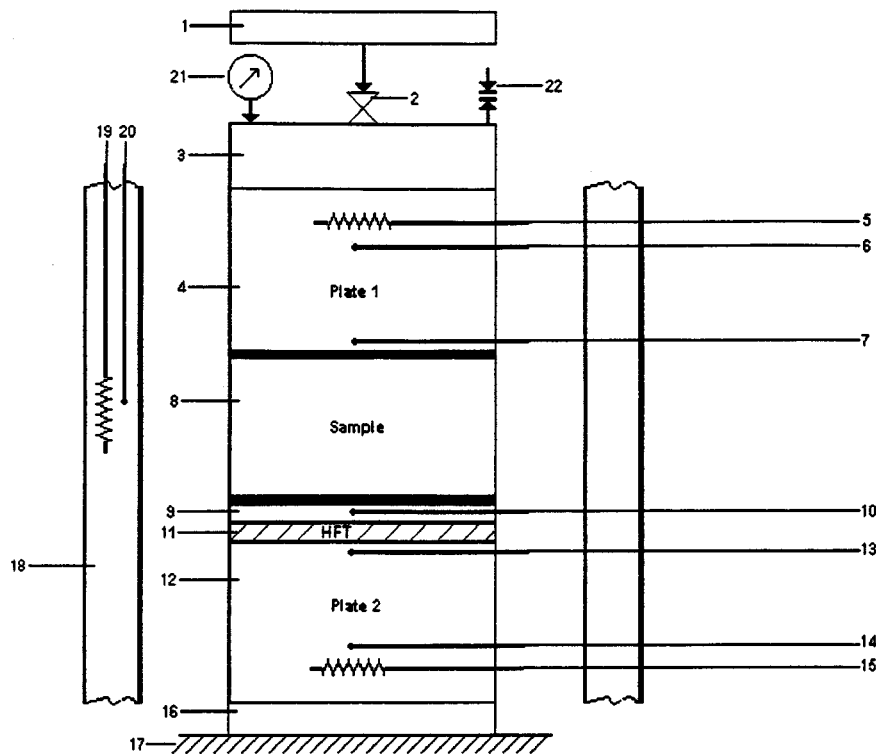


FIG. 1 Key Components of a Typical Device

across it. The level of output required (sensitivity) greatly depends on the rest of the instrumentation used to read it. The overall performance of the HFT and its readout instrumentation shall be such as to meet the requirements in Section 13.

6.2.8 The lower plate (12) is constructed similarly to the upper plate (4), except it is positioned as a mirror image.

6.2.9 An insulator plate (16) separates the lower plate (12) from the heat sink (17). In case of using circulating fluid in place of a heater/thermocouple arrangement in the upper and/or lower plates, the heat sink may or may not be present.

6.2.10 The entire stack is surrounded by a cylindrical guard (18) equipped with a heater (19) and a control thermocouple (20) to maintain it at the mean temperature between the upper and lower plates. A small, generally unfilled gap separates the guard from the stack. For instruments limited to operate in the ambient region, no guard is required. A draft shield is recommended in place of it.

NOTE 2—It is permissible to use thin layers of high conductivity grease or elastomeric material on the two surfaces of the sample to reduce the thermal resistance of the interface and promote uniform thermal contact across the interface area.

NOTE 3—The cross sectional area of the sample may be any, however, most commonly circular and rectangular cross sections are used. Minimum size is dictated by the magnitude of the disturbance caused by thermal sensors in relation to the overall flux distribution. The most common sizes are 25 mm round or square to 50 mm round.

### 6.3 Requirements:

6.3.1 Temperature control of upper and lower plate is to be  $\pm 0.1$  °C ( $\pm 0.18$  °F) or better.

6.3.2 Reproducible load of 0.28 MPa (40 psi) has been found to be satisfactory for solid samples. Minimum load shall not be below 0.07 MPa (10 psi).

6.3.3 Temperature sensors are usually fine gage or small diameter sheath thermocouples, however, ultraminiature resistance thermometers and linear thermistors may also be used.

6.3.4 Operating range of a device using a mean temperature guard shall be limited to  $-100$  °C to  $300$  °C, when using thermocouples as temperature sensors, and  $-180$  °C to  $300$  °C with platinum resistance thermometers.

## 7. Test Specimen

7.1 The specimen to be tested shall be representative for the sample material. The recommended specimen configuration is a  $50.8 \pm 0.25$  mm ( $2 \pm 0.010$  in.) diameter disk, having smooth flat and parallel faces,  $\pm 0.025$  mm ( $\pm 0.001$  in.), such that a uniform thickness within  $0.025$  mm ( $\pm 0.001$  in.) is attained in the range from  $12.7$  to  $25.4$  mm ( $0.5$  to  $1.0$  in.)

## 8. Sampling and Conditioning

8.1 Cut representative test specimens from larger pieces of the sample material or body.

8.2 Condition the cut specimens in accordance with the requirements of the appropriate material specifications, if any.

## 9. Calibration

9.1 Select the mean temperature and load conditions required. Adjust the upper heater temperature ( $T_u$ ) and lower heater temperature ( $T_l$ ) such that the temperature difference at the required mean temperature is no less than  $30$  to  $35$  °C and

the specimen  $\Delta T$  is not less than  $3$  °C. Adjust the guard heater temperature ( $T_g$ ) such that it is at approximately the average of  $T_u$  and  $T_l$ .

9.2 Select at least two calibration specimens having thermal resistance values that bracket the range expected for the test specimens at the temperature conditions required.

9.3 Table 1 contains a list of several available materials commonly used for calibration, together with corresponding thermal resistance ( $R_s$ ) values for a given thickness. This information is provided to assist the user in selecting optimum specimen thickness for testing a material and in deciding which calibration specimens to use.

9.4 The range of thermal conductivity for which this test method is most suitable is such that the optimum thermal resistance range is from  $10 \times 10^{-4}$  to  $400 \times 10^{-4}$  m<sup>2</sup>·K/W. The most commonly used calibration materials are the Pyrex 7740, Pyroceram 9606, and stainless steel.

9.5 Measure the thickness of the specimen to  $25$  μm.

9.6 Coat both surfaces of a calibration specimen with a very thin layer of a compatible heat sink compound or place a thin layer of elastomeric heat transfer medium on it to help minimize the thermal resistance at the interfaces of adjacent contacting surfaces.

9.7 Insert the calibration specimen into the test chamber. Exercise care to ensure that all surfaces are free of any foreign matter.

9.8 Close the test chamber and clamp the calibration specimen in position between the plates at the recommended compressive load of  $0.28$  MPa.

9.9 Wait for thermal equilibrium to be attained. This should be seen when all the temperatures measured do not drift more than  $0.1$  °C in  $1$  min. Read and record all temperatures and the output of the heat flux transducer.

NOTE 4—The time to attain thermal equilibrium is dependent upon the thickness of the specimen and its thermal properties. Experience shows that approximately  $1$  h is needed for thermal equilibrium to be attained, when testing a sample with the thermal conductivity within the optimum operating range of the instrument.

9.10 Repeat the procedure in 9.5 to 9.9 with one or more calibration specimens, having different thermal resistance values covering the expected range for the test specimen.

## 10. Thermal Conductivity of an Unknown Specimen

10.1 Tests shall only be conducted at a temperature in a

**TABLE 1 Typical Thermal Resistance Values of Specimens of Different Materials**

Material	Approximate Thermal Conductivity, W/(m·K) at 30°C	Thickness, mm	Approximate Thermal Resistance, $10^{-4}$ m <sup>2</sup> ·K/W at 30 °C
Pyroceram 9606 <sup>A</sup>	4	20	50
Pyroceram 9606 <sup>A</sup>	4	10	25
Pyrex 7740 <sup>A</sup> Glass	1	20	200
Pyrex 7740 <sup>A</sup> Glass	1	10	100
Pyrex 7740 <sup>A</sup> Glass	1	1	10
304 Stainless Steel	14	20	14
304 Stainless Steel	14	10	7
Vespel <sup>B</sup>	0.4	2	50

<sup>A</sup> Pyrex 7740 and Pyroceram 9606 are products and trademarks of Corning Glass Co., Corning, WV.

<sup>B</sup> Vespel is a product of DuPont Co.

range and under applied load conditions for which valid calibration data exists.

10.1.1 When automatic control of temperature of the heaters is involved, the controller settings should be checked to ensure that they are the same as those for the desired temperature level for the calibration.

10.2 Measure the thickness of the specimen to 25  $\mu\text{m}$ .

10.3 Apply a thin layer of heat sink compound or place a thin layer of elastomeric heat transfer medium on the surfaces of the test specimen.

NOTE 5—Exercise care to ensure that any material applied to the surfaces of the specimen does not change its thermal properties by soaking into it.

10.4 Repeat the procedure in 9.7 to 9.9 using the test specimen.

NOTE 6—Experience has indicated that for reliable measurements on a single specimen, the minimum thickness (mm) is given by  $\Delta x \geq 3\lambda$  (W/(m·K)).

10.5 *Automated Systems*—Computerized or otherwise automated systems may require different operating steps, and may or may not provide intermediate readings described in 9.9. For these devices, follow the operating and calibrating procedures prescribed by the manufacturer.

NOTE 7—For an automated system to meet the requirements of this test method, the calibrating, testing, and calculational methods built into it shall at minimum include the steps or principles set forth in Section 10, and all applicable guidelines given in Section 6, 9, 12 and 13.

## 11. Calculation

11.1 At equilibrium, the Fourier heat flow equation applied to the system becomes as follows:

$$R_s = \frac{N(T_1 - T_2)}{Q} - R_0 \quad (1)$$

and:

$$C_s = \frac{1}{R_s} \quad (2)$$

11.1.1 For homogeneous materials:

$$R_s = \frac{\Delta x}{\lambda} \quad (3)$$

11.1.2 In Eq 1,  $N$  and  $R_0$  are temperature- and load-dependent parameters obtained by calibration at each particular set of conditions. Once obtained, they should remain fixed for the particular settings used to attain the conditions.

NOTE 8—Since  $N$  is also determined by the particular HFT utilized, the calibration should be checked occasionally to ensure that continuous heating/cycling does not affect the HFT.

NOTE 9—The parameter  $R_0$  depends on the parallelism of the two surface plates and should be reproducible unless the test section is altered mechanically in any way. If this occurs, recalibration is necessary.

11.2 There are three methods of data analysis to determine  $R_s$ ,  $C_s$ , and  $\lambda$ . In each case, utilize relevant input parameters determined to the stated precision levels and use all available decimal places through the calculation stages to the final result. Calculate the thermal resistance  $R_s$  to the nearest whole number in practical units of  $10^{-4} \text{ m}^2\cdot\text{K}/\text{W}$  and derive values of thermal conductivity to the second significant figure level of precision.

11.2.1 *Graphical Method*—At each set of conditions, Eq 1 is represented by a straight line on a graph of  $R_s$  versus  $(T_1 - T_2)/Q$ . Plot the test result of the calibration specimens on the graph, and draw a best-fit straight line through the data points as illustrated in Fig. 2. When measuring the thermal conductivity of a test specimen, obtain  $R_s$  by drawing a vertical line at the appropriate value of  $(T_1 - T_2)/Q$  to intersect the calibration line. Obtain values of  $C_s$  and  $\lambda_s$  from Eq 2 and Eq 3.

11.2.2 *Analytical Method*—At each set of conditions, solve Eq 1 mathematically for  $N$  and  $R_0$  after measuring a pair of reference specimens to yield two sets of data for  $R_s$  and  $(T_1 - T_2)/Q$ . Eq 1 can be used subsequently to determine  $R_s$  of the test specimen following measurement of  $T_1$ ,  $T_2$ , and  $Q$  providing the calculated  $R_s$  falls within the calibration range corresponding to the particular pair of reference specimens in accordance with 9.2. By calibrating with additional reference specimens of different thermal resistances, several linear equations can be generated, each covering a part of the overall range.

11.2.3 *Computer-Aided Analysis*:

11.2.3.1 At each set of conditions, solve Eq 1 mathematically for  $N$  and  $R_0$ , using a linear regression analysis of the results for several sets of data for  $R_s$  and  $(T_1 - T_2)/Q$  produced as a result of testing several calibration specimens. A similar series of tests carried out at the different temperatures provides new values of  $N$  and  $R_0$ .

11.2.3.2 Determine a polynomial relationship between  $N$  and temperature, and between  $R_0$  and temperature, so that Eq 1 becomes:

$$R_s = f_1(T) \cdot \frac{T_1 - T_2}{Q} - f_2(T) \quad (4)$$

where:

$f_1(T)$  = temperature dependent value of  $N$ ,  
 $f_2(T)$  = temperature dependent value of  $R_0$ , and  
 $T$  = test temperature.

11.2.3.3  $R_2$  and  $\lambda$  of the test specimen are calculated automatically, once  $T_1$ ,  $T_2$ , and  $Q$  have been measured. Results are accurate provided that the test temperatures fall within the limits used during calibration, and that  $R_s$  does not fall outside the calibration range obtained with the reference specimens.

## 12. Report

12.1 Report the following information:

12.1.1 Complete identification and description of material and specimen including any conditioning procedure;

12.1.2 Details of reference specimen materials used for calibration;

12.1.3 Details of temperatures of appropriate surfaces, guard and ambient,  $^{\circ}\text{C}$  ( $^{\circ}\text{F}$ );

12.1.4 Applied load, Pa (psi);

12.1.5 Specimen thickness, mm (in.);

12.1.6 Mean temperature,  $^{\circ}\text{C}$  ( $^{\circ}\text{F}$ );

12.1.7 Measured thermal resistance to the nearest whole number in practical units,  $10^{-4} \text{ m}^2\cdot\text{K}/\text{W}$  ( $\text{h}\cdot\text{ft}^2\cdot^{\circ}\text{F}/\text{Btu}$ ) and derived thermal conductivity to the second significant figure in  $\text{W}/(\text{m}\cdot\text{K})$  ( $\text{Btu}\cdot\text{in.}/(\text{h}\cdot\text{ft}^2\cdot^{\circ}\text{F})$ ); include details of the calculation method used (for manual instruments, omit for automated systems);

Thermal Resistance vs.  $(T1-T2) / Q$

Figure 2

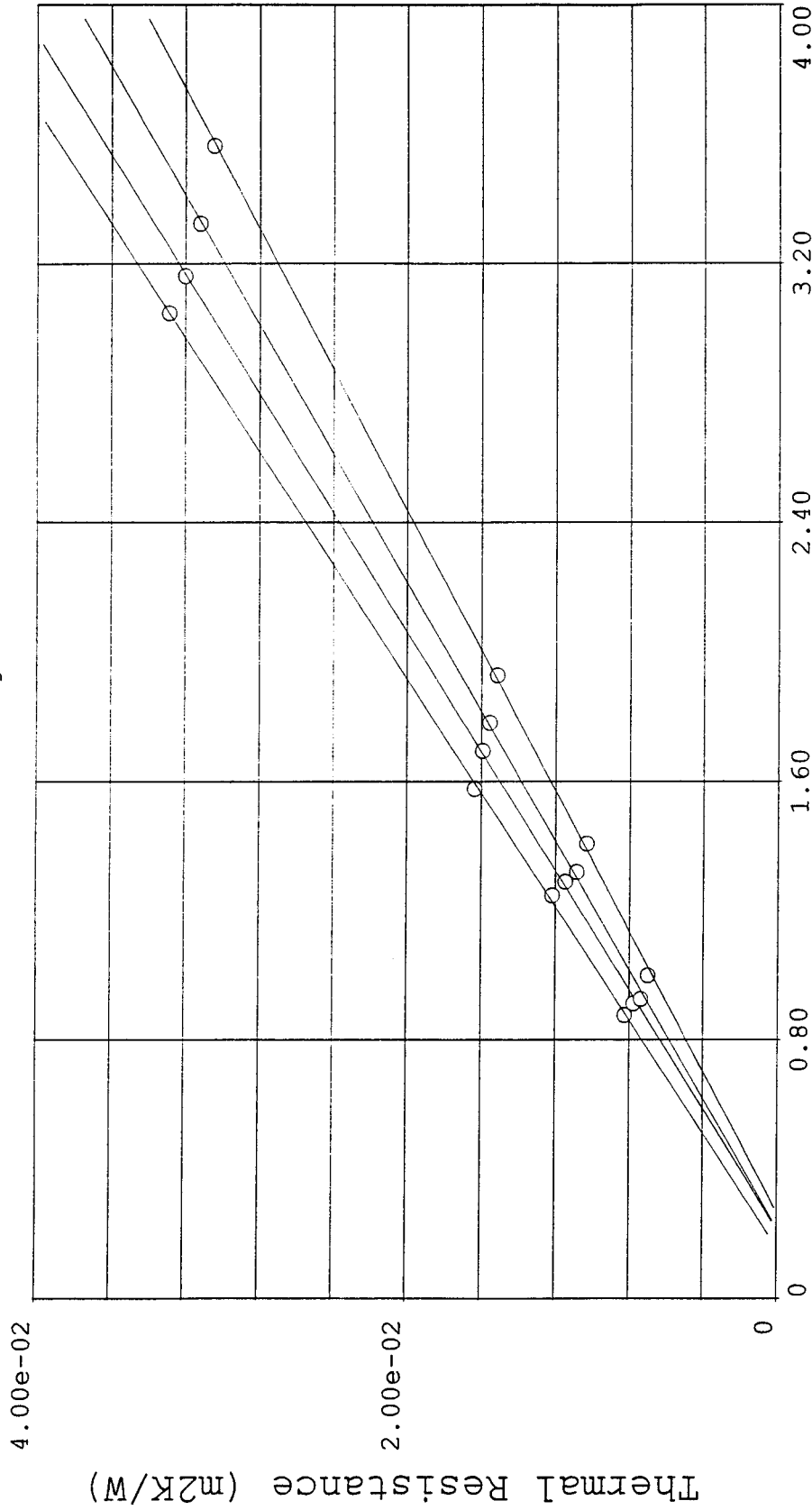


FIG. 2 Thermal Resistance Versus  $(T1-T2) / Q$

12.1.8 The sample's mean temperature and the direction and orientation of thermal transmission through the sample, since some bodies are not isotropic with respect to thermal conductivity; and

12.1.9 Designation of model/make in case a commercial device is used.

### **13. Precision and Bias**

13.1 A round robin program is in progress.

### **14. Keywords**

14.1 heat flow meter; heat flux transducer; thermal conductance; thermal conductivity; thermal resistance

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