ASTM INTERNATIONAL

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Standard Test Method for
Thermal Conductivity of Solids Using the Guarded-Comparative-Longitudinal Heat Flow Technique[1]

1. Scope

1.1 This test method describes a steady state technique for the determination of the thermal conductivity, λ, of homogeneous-opaque solids (see Notes 1 and 2). This test method is applicable to materials with effective thermal conductivities in the range $0.2 < \lambda < 200$ W/($m \cdot K$) over the temperature range between 90 K and 1300 K. It can be used outside these ranges with decreased accuracy.

NOTE 1—For purposes of this technique, a system is homogeneous if the apparent thermal conductivity of the specimen, λ_A, does not vary with changes of thickness or cross-sectional area by more than $\pm 5\%$. For composites or heterogeneous systems consisting of slabs or plates bonded together, the specimen should be more than 20 units wide and 20 units thick, respectively, where a unit is the thickness of the thickest slab or plate, so that diameter or length changes of one-half unit will affect the apparent λ_A by less than $\pm 5\%$. For systems that are non-opaque or partially transparent in the infrared, the combined error due to inhomogeneity and photon transmission should be less than $\pm 5\%$. Measurements on highly transparent solids must be accompanied with infrared absorption coefficient information, or the results must be reported as apparent thermal conductivity, λ_A.

NOTE 2—This test method may also be used to evaluate the contact thermal conductance/resistance of materials and composites.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E230 Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *thermal conductivity, λ, n*—the time rate of heat flow, under steady conditions, through unit area, per unit temperature gradient in the direction perpendicular to the area.

3.1.2 *apparent thermal conductivity, n*—when other modes of heat transfer through a material are present in addition to conduction, the results of the measurements performed according to this test method will represent the apparent (or effective) thermal conductivity for the material tested.

3.2 *Symbols:*

$\lambda_M(T)$	=	thermal conductivity of meter bars (reference materials) as a function of temperature, (W/($m \cdot K$))
λ_M^1	=	thermal conductivity of top meter bar, (W/($m \cdot K$))
λ_M^2	=	thermal conductivity of bottom meter bar, (W/($m \cdot K$))
$\lambda_S(T)$	=	thermal conductivity of specimen corrected for heat exchange where necessary, (W/($m \cdot K$))
$\lambda'_S(T)$	=	thermal conductivity of specimen calculated by ignoring heat exchange correction, (W/($m \cdot K$))
$\lambda_I(T)$	=	thermal conductivity of insulation as a function of temperature, (W/($m \cdot K$))
T	=	absolute temperature (K)

Z	= position as measured from the upper end of the column, (m)
l	= specimen length, (m),
T_i	= the temperature at Z_i, (K)
q'	= heat flow per unit area, (W/m^2)
$\delta\lambda, \delta T$, etc.	= uncertainty in λ, T, etc.
r_A	= specimen radius, (m)
r_B	= guard cylinder inner radius, (m)
$T_g(z)$	= guard temperature as a function of position, z, (K)

4. Summary of Test Method

4.1 A test specimen is inserted under an applied load between two similar specimens of a material of known thermal properties and a thickness such that the thermal conductance is of similar order to that of the specimen. A temperature gradient is established in the test stack and heat losses are minimized by use of a longitudinal guard having approximately the same temperature gradient. At equilibrium conditions, the thermal conductivity is derived from the measured temperature gradients in the respective specimens and the thermal conductivity of the reference materials.

4.2 *General Features of Test Method:*

4.2.1 The general features of the guarded longitudinal heat flow technique are shown in Fig. 1. A specimen of unknown thermal conductivity, λ_S, but having an estimated thermal conductance of λ_S / l_S, is mounted between two similar meter bars of known conductivity λ_M, of the same cross-section and similar thermal conductance, λ_M / l_M. A more complex but suitable arrangement is a column consisting of a disk heater with a specimen and a meter bar on each side between heater and heat sink. Approximately one-half of the power would then flow through each specimen. When the meter bars and specimen are right-circular cylinders of equal diameter the technique is described as the cut-bar method. When the cross-sectional dimensions are larger than the thickness it is described as the flat slab comparative method. Essentially, any shape can be used, as long as the meter bars and specimen have the same conduction areas.

4.2.2 A mechanical or pneumatic force is applied to the column to ensure good contact between specimens. The stack is surrounded by a thermal insulation material of thermal conductivity, λ_I, enclosed in a guard shell with a radius, r_B, held at the temperature, $T_g(z)$. A temperature gradient is imposed on the column usually by maintaining the top at a temperature, T_T, and the bottom at a lower temperature T_B. $T_g(z)$ is usually a linear temperature gradient matching approximately the gradient established in the test stack. However, an isothermal guard with $T_g(z)$ equal to the average temperature of the specimen may also be used. An unguarded system is not recommended due to the potential very large heat losses, particularly at elevated temperatures (1).[3] At steady state, the temperature gradients along the sections are calculated from measured temperatures along the meter bars and the specimen.

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[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

The value of λ_S, as uncorrected for heat shunting, can then be determined using the following equation where the notation is shown in Fig. 1:

$$\lambda_s = \frac{Z_4 - Z_3}{T_4 - T_3} \cdot \frac{\lambda_M}{2} \cdot \left(\frac{T_2 - T_1}{Z_2 - Z_1} + \frac{T_6 - T_5}{Z_6 - Z_5} \right) \quad (1)$$

This is a highly idealized situation, however, since it assumes no heat exchange between the column and insulation at any position and uniform heat transfer at each meter bar-specimen interface. The errors caused by these two assumptions vary widely and are discussed in Section 10. Because of these two effects, restrictions must be placed on this test method, if the desired accuracy precision is to be achieved.

5. Significance and Use

5.1 The comparative method of measurement of thermal conductivity is especially useful for engineering materials including ceramics, polymers, metals and alloys, refractories, carbons, and graphites including combinations and other composite forms of each.

5.2 Proper design of a guarded-longitudinal system is difficult and it is not practical in a method of this type to try to establish details of construction and procedures to cover all contingencies that might offer difficulties to a person without technical knowledge concerning theory of heat flow, temperature measurements, and general testing practices. Standardization of this test method is not intended to restrict in any way the future development by research workers of new or methods or improved procedures. However, new or improved techniques must be thoroughly tested. Requirements for qualifying an apparatus are outlined in Section 10.

6. Requirements

6.1 *Meter Bar Reference Materials:*

6.1.1 Reference materials or transfer standards with known thermal conductivities must be used for the meter bars. *Since the minimum measurement error of the method is the uncertainty in λ_M, it is preferable to use standards (SRM or CRM) available from a national metrology institute.* Other reference materials are available due to numerous measurements of λ having been made by a number of organizations including national metrology institutes, and with general acceptance of the values. Table 1 lists the recommended reference materials and contain thermal conductivity values for the appropriate temperature range. Fig. 2 illustrates the approximate variation of λ_M with temperature.

6.1.2 Table 1 is not exhaustive and other materials may be used as references providing the property values that are used are those for the specific material referenced (1). The reference material and the source of λ_M values shall be stated in the report.

6.1.3 The requirements for any reference material include stability over the temperature range of operation, compatibility with other system components, reasonable cost, ease of temperature sensor attachment, and an accurately known thermal conductivity. Since heat shunting errors for a specific λ_I increase as λ_M / λ_s varies from unity (2), the reference which has a λ_M nearest to λ_S should be used for the meter bars.
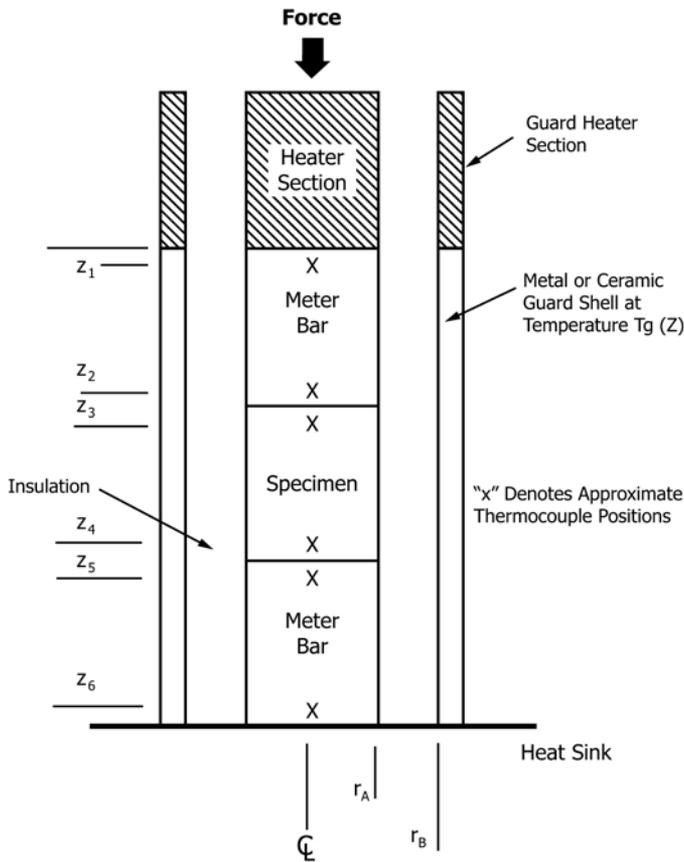
FIG. 1(a) Schematic of a Comparative-Guarded-Longitudinal Heat Flow System Showing Possible Locations of Temperature Sensors
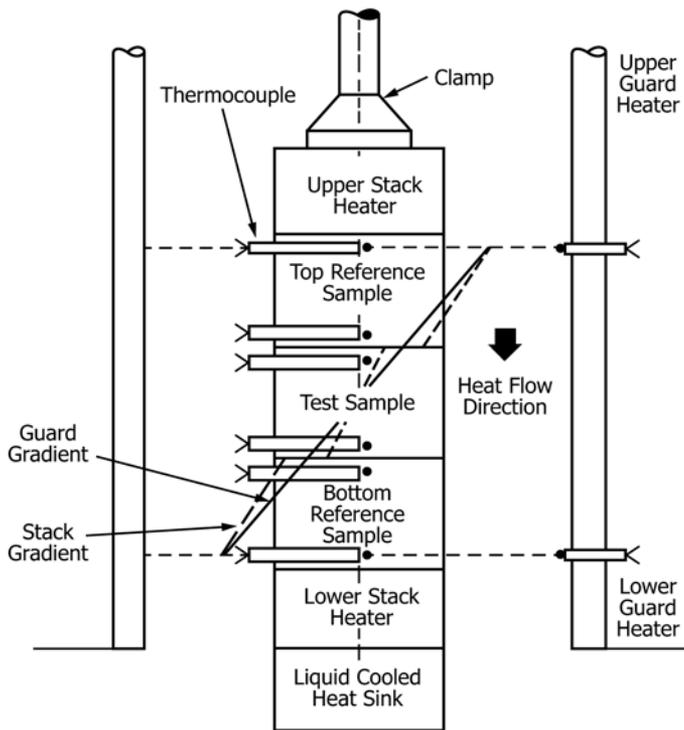

FIG. 1(b) Schematic of Typical Test Stack and Guard System Illustrating Matching of Temperature Gradients

FIG. 1 Schematics

6.1.4 If the thermal conductivity λ_s of the specimen is between the values for two reference materials, the reference material with the higher λ_M should be used in order to reduce the total temperature drop along the column.

6.2 *Insulation Materials:*

6.2.1 A variety of powder, particulate, and fiber materials exists for reducing both radial heat flow in the column-guard annulus and surrounds, and for heat shunting along the column. Several factors must be considered during selection of the most appropriate insulation. The insulation shall be stable over the anticipated temperature range, have a low λ_I, and be easy to handle. In addition, the insulation should not contaminate system components such as the temperature sensors, it must have low toxicity, and it should not conduct electricity. In general, powders and particulates are used since they pack readily. However, low density fiber blankets can be used.

6.2.2 Recommended thermal insulations are listed in Table 6.

6.3 *Temperature Sensors:*

6.3.1 There shall be a minimum of two temperature sensors on each meter bar and two on the specimen. Whenever possible, the meter bars and specimen should each contain three sensors. The extra sensors are useful in confirming linearity of temperature versus distance along the column, or indicating an error due to a temperature sensor decalibration.

6.3.2 The type of temperature sensor depends on the system size, temperature range, and the system environment as controlled by the insulation, meter bars, specimen, and gas within the system. Any sensor possessing adequate accuracy may be used for temperature measurement (3) and be used in large systems where heat flow perturbation by the temperature sensors would be negligible. Thermocouples are normally employed. Their small size and the ease of attachment are distinct advantages.

6.3.3 When thermocouples are employed, they should be fabricated from wires of temperature grade materials and should be 0.1 mm diameter or less and with the individual wires in suitable twin-bore protective insulation. A constant temperature reference shall always be provided for all cold junctions. This reference can be an ice-cold slurry (4), a constant temperature zone box, or an electronic ice point reference. All thermocouples shall be fabricated from either calibrated thermocouple wire (5) or from wire that has been certified by the supplier to be within the limits of error specified in Table 1 of Standard E230.

6.3.4 Thermocouple attachment is important to this technique in order to ensure that reliable temperature measurements are made at specific points. The various techniques are illustrated in Fig. 3. Intrinsic junctions can be obtained with metals and alloys by welding individual thermo-elements to the surfaces (Fig. 3a). Butt or bead welded thermocouples junctions can be rigidly attached by peening, cementing, or welding in fine grooves or small holes (Fig. 3b, 3c, and 3d).

6.3.5 In Fig. 3b, the thermocouple resides in a radial slot, and in Fig. 3c the thermocouple is pulled through a radial hole in the material. When a sheathed thermocouple or a thermocouple with both thermoelements in a two-hole electrical insulator is used, the thermocouple attachment shown in Fig.