Standard Test Method for Thermal Transmission Properties of Thin Thermally Conductive Solid Electrical Insulation Materials[1]

1. Scope

1.1 This standard covers a test method for measuring thermal impedance of thin electrical insulation materials.

1.2 This test method is useful with either homogeneous or composite thermally conductive sheet material ranging from 0.02 to 10 mm in thickness.

1.3 This test method measures steady-state heat flux through a flat specimen. Calculations are made as if the specimens were homogeneous. In fact, these materials are usually not homogeneous, but the assumption does not detract from the usefulness of the test methods.

1.4 The term "thermal conductivity" applies only to homogeneous materials. Thermally conductive electrical insulating materials are usually heterogeneous since they typically include fillers, binders, reinforcements such as glass fiber mesh, or a layer of polymeric film. To avoid confusion, this test method uses "apparent thermal conductivity" for measurements of both homogeneous and non-homogeneous materials.

1.5 A limitation of using this test method to calculate apparent thermal conductivity is the problem of accurately determining the specimen thickness. To reflect the commercial practice of measuring thickness as manufactured rather than measuring thickness in an assembly, thickness is determined from measurements made at room temperature in accordance with Method C of Test Methods D 374.

1.6 Thermal impedance test data are influenced by contact pressures, specimen surface characteristics, and the existence of alternate paths for heat transmission which are not through the specimen. This test method determines thermal conduction properties under a specific set of conditions (including a 50°C average test temperature) which may not agree exactly with the conditions in an application. As a result, the degree of correlation between this test method and any particular application needs to be determined.

1.7 The values stated in SI units are to be regarded as standard.

1.8 *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.*

NOTE 1—Earlier versions of this document included a Method B (the Roiseland Method). This method is now deleted because of a lack of general support.

2. Referenced Documents

2.1 *ASTM Standards:*

D 374 Test Methods for Thickness of Solid Electrical Insulation [2]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[3]

E 1225 Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique[3]

2.2 *Military Specification:*

MIL-I-49456 Insulation Sheet, Electrical, Silicone Rubber, Thermally Conductive, Fiberglass Reinforced[4]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *average temperature (of a surface)*, *n*— the area-weighted mean temperature.

3.1.2 *composite*, *n*—a material made up of distinct parts which contribute, either proportionally or synergistically, to the properties of the combination.

3.1.3 *homogeneous material*, *n*—a material in which relevant properties are not a function of the position within the material.

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[1] This test method is under the jurisdiction of ASTM Committee D09 on Electrical and Electronic Insulating Materials and is the direct responsibility of Subcommittee D09.19 on Dielectric Sheet and Roll Products.

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[2] *Annual Book of ASTM Standards*, Vol 10.01.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

[4] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

3.1.4 *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.

3.1.5 *thermal impedance* (θ), *n*—the total opposition that an assembly (material, material interfaces) presents to the flow of heat.

3.1.6 *thermal interfacial impedance (contact resistance)*, *n*—the temperature difference required to produce a unit of heat flux at the contact planes between the specimen surfaces and the hot and cold surfaces in contact with the specimen under test. The symbol for contact resistance is R_I.

3.1.7 *thermal resistivity*, *n*—the reciprocal of thermal conductivity. Under steady-state conditions, the temperature gradient, in the direction perpendicular to the isothermal surface per unit of heat flux.

3.2 *Symbols:Symbols Used in This Standard:*

3.2.1 λ = thermal conductivity, watt per metre-K.

3.2.2 T_A = temperature of hot surface in contact with a specimen, K.

3.2.3 T_B = temperature of hot surface of a specimen, K.

3.2.4 T_C = temperature of cold surface of a specimen, K.

3.2.5 T_D = temperature of cold surface in contact with a specimen, K.

3.2.6 A = area of a specimen, m^2.

3.2.7 X = thickness of specimen, m.

3.2.8 Q = time rate of heat flow, W or J/s.

3.2.9 q = heat flux, or time rate of heat flow per unit area, W/m^2.

3.2.10 θ = thermal impedance, temperature difference per unit of heat flux, $(K \cdot m^2)/W$.

4. Summary of Test Method

4.1 In this test method (a modification of Test Method E 1225), a specimen is sandwiched between two metal masses, compressed, and supplied with a measured amount of heat energy. At equilibrium, temperatures are measured and a thermal impedance is calculated. The thermal impedance and thickness are used to compute apparent thermal conductivity.

5. Significance and Use

5.1 This test method measures the thermal transmission properties of low-modulus (deformable) dielectric materials. These materials are used to aid heat transfer in electrical and electronic applications.

NOTE 2—This test method is useful with high-modulus materials if layers of low-modulus materials are combined with test specimens to exclude air from test interfaces.

5.2 This test method is especially useful for generating thermal data on specimens that are too thin to be fitted with thermocouples for temperature sensing. This test method may avoid problems of measurement due to nonuniform pressures, surface conditions, or techniques used to assemble electronic equipment.

5.3 In effect, this test method assumes that specimen layers coalesce and that there is no effective interfacial resistance between layers. The slope of the plot of thermal impedance against cumulative thickness permits the determination of thermal conductivity without regard to thermal interfacial impedance.

5.4 This test method is approved for use by the Department of Defense, and is included in Military Specification MIL-I-49456.

TEST METHOD

6. Apparatus

6.1 General features are shown in Fig. 1 and Fig. 2. The apparatus shown in Fig. 1 uses a reference calorimeter to determine the rate of heat flow through the specimen. Optionally omit the reference calorimeter (Fig. 2). The rate of heat flow in the specimen is determined from the electrical power applied to the heater. Smoothly finish all contacting surfaces to within 0.4 μm to approximate a true plane for the metre bars in contact with the specimen surface.

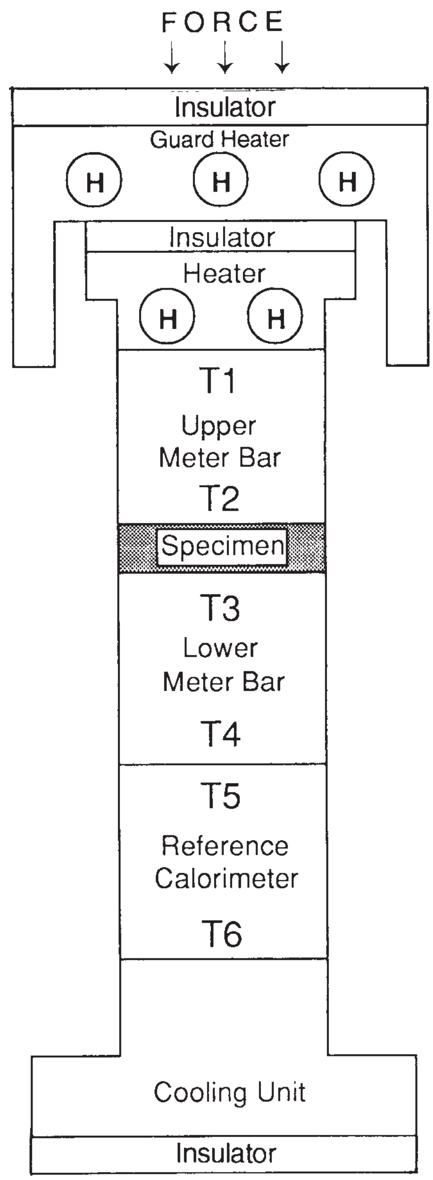

FIG. 1 Guarded Heater with Reference Calorimeter

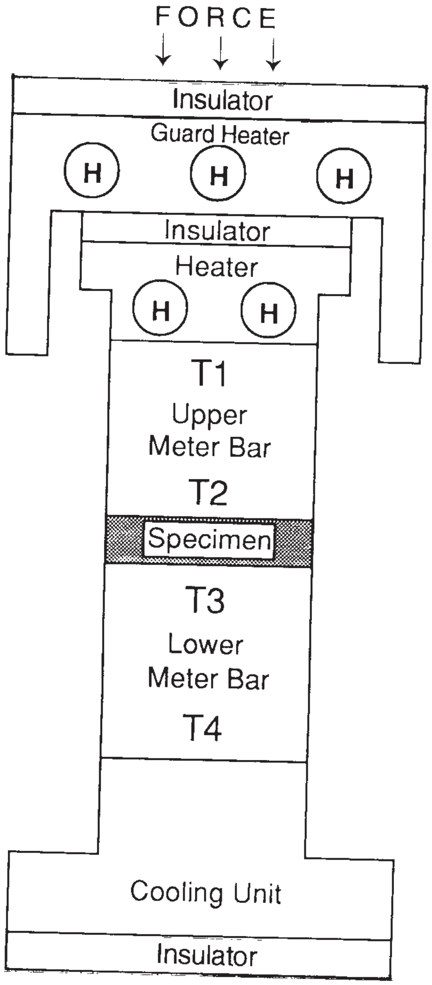

FIG. 2 Guarded Heater

6.2 The heater unit (or block) is made of copper or other highly conductive material, containing cartridge or similar wire wound heaters. It is separated from a surrounding guard heater by a layer of thermal insulation material (epoxy FR-4 or similar) 5 mm thick. The guard heater is also insulated from the press and ensures that all measured energy is transformed to the upper metre bar.

6.3 Metre bars are constructed from high-thermal conductivity material having parallel working surfaces. A suitable material of construction is a high-purity grade aluminum.

6.4 The reference calorimeter is constructed from a material which has a known thermal conductivity over the range of test temperatures to be used. A recommended material is SRM-1462 austenitic stainless steel. Test Method E 1225 lists other useful materials of construction.

6.5 The cooling unit is a metal block cooled by fluid supplied from a constant temperature bath such that the temperature is maintained uniformly within ±0.2 K.

6.6 The press is capable of transmitting the specified force to the test fixture through a free-floating spherical seat attachment, to prevent offset loads and uneven pressures on the test specimen.

6.7 Insulation surrounding the specimen stack, if used, is a fibrous thermal insulating blanket (see 8.8).

7. Test Specimens

7.1 *For Thermal Impedance*—make the specimen from a piece of the test material, the same area (length and width) as the metering bars. Unless previously known, and prior to placement into the assembly, measure the thickness of the piece in accordance with Test Method C of Test Methods D 374.

7.2 *For Apparent Thermal Conductivity*—prepare a sufficient number of specimens to provide the required number of layers (see 8.11).

7.3 *Specimen Conditioning*—Unless otherwise specified, test the specimens in the as-received state. Remove any dirt or other obvious secondary contamination by a suitable non-reaction solvent prior to testing. To ensure the removal of cleaning solvents, use suitable drying procedures after any cleaning.

8. Procedure

8.1 At room temperature, measure the specimen thickness in accordance with Test Method C of Test Methods D 374.

8.2 Center the specimen between the two metre bars.

8.3 Insert the reference calorimeter, if used, between the lower metre bar and the cooling unit.

8.4 Place the assembled test stack into the press.

8.5 With the press, apply a force to the stack such that 3.0 ± 0.1-MPa pressure is applied to the specimen. Maintain this pressure on the stack for the duration of the test.

NOTE 3—A pressure of 3.0 MPa is adequate to reduce to a negligible level the effects of contact resistance between the specimen and the water bars due to minor surface irregularities.

8.6 Circulate cooling fluid and apply power to the heating element. Maintain the guard heater temperature to within ±0.2 K of the heater temperature.

8.7 Since the pressure may increase during heatup, monitor and adjust the applied force in the press to counteract the increased pressure on the specimen due to thermal expansion.

8.8 Conduct the testing under conditions that produce an average specimen temperature of 50°C. For measurements made at temperatures above 300 K, it is necessary to apply a fibrous thermal insulating blanket loosely around the calorimeter sections.

8.9 Record the temperatures of the metre bars and the reference calorimeter at equilibrium. In the absence of a reference calorimeter, record the voltage and current applied to the heater. Equilibrium is attained when 2 successive sets of temperature readings are taken at 15-min intervals and the differences between the two are less than ±0.2 K.

8.10 Calculate the mean specimen temperature and the thermal impedance. Label the calculated thermal impedance for the single-layer specimen as the "thermal impedance" of the specimen.

8.11 Determine the thermal impedance of multiple layers. Maintain the mean temperature of the multiple-layered specimens within ±2 K of the single layer specimen temperature by reducing the heat flux as the number of layers is increased.

9. Calculation

9.1 *Thermal Impedance*:

9.1.1 *Heat Flow Using Reference Calorimeter*—Calculate the heat flow from the reference calorimeter readings as follows:

$$Q = \frac{\lambda_R \times A}{d} \times [T_5 - T_6] \quad (1)$$

where:

Q = heat flow, W,
λ_R = thermal conductivity of the reference calorimeter material, W/(m·K),
A = area of the reference calorimeter, m^2,
$T_5 - T_6$ = temperature difference between thermocouples of the reference calorimeter, K, and
d = distance between thermocouples in the reference calorimeter, m.

9.1.2 *Heat Flow When Not Using Reference Calorimeter*—Calculate the heat flow from the applied electrical power as follows:

$$Q = V \times I \quad (2)$$

where:

Q = heat flow, W,
V = electrical potential applied to the heater, V, and
I = electrical current flow in the heater, A.

9.2 Derive the temperature of the upper metre bar surface in contact with the specimen from the following:

$$T_A = T_2 - \frac{d_B}{d_A}(T_1 - T_2) \quad (3)$$

where:

T_A = temperature of the upper metre bar surface in contact with the specimen, K,
T_1 = upper temperature of the upper metre bar, K,
T_2 = lower temperature of the upper metre bar, K,
d_A = distance between temperature sensors, m, and
d_B = distance from the lower sensor to the lower surface of the upper metre bar, m.

9.3 Derive the temperature of the lower metre bar surface in contact with the specimen from the following:

$$T_D = T_3 + \frac{d_D}{d_C}(T_3 - T_4) \quad (4)$$

where:

T_D = temperature of the lower metre bar surface in contact with the specimen, K,
T_3 = upper temperature of the lower metre bar, K,
T_4 = lower temperature of the lower metre bar, K,
d_C = distance between temperature sensors, m, and
d_D = distance from the upper sensor to the upper surface of the lower metre bar, m.

9.4 Calculate the thermal impedance from

$$\theta = (T_A - T_D) \times A/Q \quad (5)$$

and express it in units of $(K \cdot m^2)/W$.

9.5 Obtain apparent thermal conductivity from a plot of thermal impedance for single- and multiple-layered specimens against the respective specimen thickness. Plot values of the specimen thickness on the *x* axis and specimen thermal impedance on the *y* axis.

9.5.1 The curve is a straight line whose slope is the reciprocal of the apparent thermal conductivity. The intercept at zero thickness is the thermal interfacial impedance, R_I, specific to the sample, clamping force used, and the clamping surfaces.

9.5.2 As a preferred alternative, compute the slope and the intercept using least mean squares.

10. Report

10.1 Report the following information:

10.1.1 Specimen identification:

10.1.1.1 Name of the manufacturer,

10.1.1.2 Batch or lot number,

10.1.1.3 Grade designation,

10.1.1.4 Nominal thickness, and

10.1.1.5 Any other information pertinent to the identification of the material.

10.1.2 Number of layers used in the test.

10.1.3 Average temperature of the specimen, if other than 323 K.

10.1.4 Pressure used during testing, if other than 3.0 MPa.

10.1.5 Thermal transmission properties:

10.1.5.1 Apparent thermal conductivity,

10.1.5.2 Thermal impedance from 9.4, and

10.1.5.3 Thermal interfacial impedance from 9.5.1.

11. Precision and Bias

11.1 A round robin was conducted on five materials having different constructions and thicknesses. Six laboratories tested specimens from all of the materials using either the specified test method or additional Test Method B of this standard, which is now deleted. Table 1, prepared in accordance with Practice E 691, summarizes the results of the round robin. Data obtained during the round-robin testing are being made available in a research report.

11.2 From the data used to generate Table 1 the following conclusion is made:

11.2.1 Thermal conductivity values for the same material measured in different laboratories are expected to be within 18 % of the mean of the values from all of the laboratories.

11.3 Bias for this test method is currently under investigation subject to the availability of a suitable reference material.

12. Keywords

12.1 apparent thermal conductivity; guarded heater method; MIL-I-49456; thermal conductivity; thermal impedance; thin

TABLE 1 Precision for Conductivity Measurement

NOTE 1—Values are in units of watt per metre Kelvin.

Material Identity	Average	S_r[A]	S_R[B]	r[C]	R[D]
Material B	0.923	0.0383	0.163	0.107	0.456
Material E	1.245	0.0834	0.175	0.234	0.491
Material C	1.311	0.0423	0.192	0.119	0.536
Material A	2.732	0.2010	0.311	0.563	0.872
Material D	5.445	0.5691	0.711	1.594	1.991

[A] S_r = within-laboratory standard deviation of the average.
[B] S_R = between-laboratories standard deviation of the average.
[C] r = within-laboratory repeatability limit = 2.8 × S_r.
[D] R = between-laboratories reproducibility limit = 2.8 × S_R.

thermally conductive electrical insulation