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

This standard is issued under the fixed designation D5470; 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 (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope*

1.1 This standard covers a test method for measurement of thermal impedance and calculation of an apparent thermal conductivity for thermally conductive electrical insulation materials ranging from liquid compounds to hard solid materials.

1.2 The term "thermal conductivity" applies only to homogeneous materials. Thermally conductive electrical insulating materials are usually heterogeneous and to avoid confusion this test method uses "apparent thermal conductivity" for determining thermal transmission properties of both homogeneous and heterogeneous materials.

1.3 The values stated in SI units are to be 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:*[2]

D374 Test Methods for Thickness of Solid Electrical Insulation (Withdrawn 2013)[3]

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E1225 Test Method for Thermal Conductivity of Solids Using the Guarded-Comparative-Longitudinal Heat Flow Technique

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

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

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

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

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

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 resistance (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 Used in This Standard:*

3.2.1 λ = apparent thermal conductivity, W/m·K.

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

3.2.3 d = thickness of specimen, m.

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

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

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

4. Summary of Test Method

4.1 This standard is based on idealized heat conduction between two parallel, isothermal surfaces separated by a test

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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] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

***A Summary of Changes section appears at the end of this standard**

specimen of uniform thickness. The thermal gradient imposed on the specimen by the temperature difference between the two contacting surfaces causes the heat flow through the specimen. This heat flow is perpendicular to the test surfaces and is uniform across the surfaces with no lateral heat spreading.

4.2 The measurements required by this standard when using two meter bars are:

T_1 = hotter temperature of the hot meter bar, K,
T_2 = colder temperature of the hot meter bar, K,
T_3 = hotter temperature of the cold meter bar, K,
T_4 = colder temperature of the cold meter bar, K,
A = area of the test surfaces, m^2, and
d = specimen thickness, m.

4.3 Based on the idealized test configuration, measurements are taken to compute the following parameters:

T_H = the temperature of the hotter isothermal surface, K,
T_C = the temperature of the colder isothermal surface, K,
Q = the heat flow rate between the two isothermal surfaces, W,
thermal impedance = the temperature difference between the two isothermal surfaces divided by the heat flux through them, $K \cdot m^2/W$, and
apparent thermal conductivity = calculated from a plot of specimen thermal impedance versus thickness, W/m·K.

4.4 Interfacial thermal resistance exists between the specimen and the test surfaces. These contact resistances are included in the specimen thermal impedance computation. Contact resistance varies widely depending on the nature of the specimen surface and the mechanical pressure applied to the specimen by the test surfaces. The clamping pressure applied to the specimen should therefore be measured and recorded as a secondary measurement required for the method except in the case of fluidic samples (Type I, see section 5.3.1) where the applied pressure is insignificant. The computation for thermal impedance is comprised of the sum of the specimen thermal resistance plus the interfacial thermal resistance.

4.5 Calculation of apparent thermal conductivity requires an accurate determination of the specimen thickness under test. Different means can be used to control, monitor, and measure the test specimen thickness depending on the material type.

4.5.1 The test specimen thickness under test can be controlled with shims or mechanical stops if the dimension of the specimen can change during the test.

4.5.2 The test specimen thickness can be monitored under test with an in situ thickness measurement if the dimension of the specimen can change during the test.

4.5.3 The test specimen thickness can be measured as manufactured at room temperature in accordance with Test Methods D374 Test Method C if it exhibits negligible compression deflection.

5. Significance and Use

5.1 This standard measures the steady state thermal impedance of electrical insulating materials used to enhance heat transfer in electrical and electronic applications. This standard is especially useful for measuring thermal transmission properties of specimens that are either too thin or have insufficient mechanical stability to allow placement of temperature sensors in the specimen as in Test Method E1225.

5.2 This standard imposes an idealized heat flow pattern and specifies an average specimen test temperature. The thermal impedances thus measured cannot be directly applied to most practical applications where these required uniform, parallel heat conduction conditions do not exist.

5.3 This standard is useful for measuring the thermal impedance of the following material types.

5.3.1 *Type I*—Viscous liquids that exhibit unlimited deformation when a stress is applied. These include liquid compounds such as greases, pastes, and phase change materials. These materials exhibit no evidence of elastic behavior or the tendency to return to initial shape after deflection stresses are removed.

5.3.2 *Type II*—Viscoelastic solids where stresses of deformation are ultimately balanced by internal material stresses thus limiting further deformation. Examples include gels, soft, and hard rubbers. These materials exhibit linear elastic properties with significant deflection relative to material thickness.

5.3.3 *Type III*—Elastic solids which exhibit negligible deflection. Examples include ceramics, metals, and some types of plastics.

5.4 The apparent thermal conductivity of a specimen can be calculated from the measured thermal impedance and measured specimen thickness if the interfacial thermal resistance is insignificantly small (nominally less than 1 %) compared to the thermal resistance of the specimen.

5.4.1 The apparent thermal conductivity of a sample material can be accurately determined by excluding the interfacial thermal resistance. This is accomplished by measuring the thermal impedance of different thicknesses of the material under test and plotting thermal impedance versus thickness. The inverse of the slope of the resulting straight line is the apparent thermal conductivity. The intercept at zero thickness is the sum of the contact resistances at the two surfaces.

5.4.2 The contact resistance can be reduced by applying thermal grease or oil to the test surfaces of rigid test specimens (Type III).

TEST METHOD

6. Apparatus

6.1 The general features of an apparatus that meets the requirements of this method are shown in Figs. 1 and 2. This apparatus imposes the required test conditions and accomplishes the required measurements. It should be considered to be one possible engineering solution, not a uniquely exclusive implementation.

6.2 The test surfaces are to be smooth within 0.4 microns and parallel to within 5 microns.

6.3 The heat sources are either electrical heaters or temperature controlled fluid circulators. Typical electrical heaters are made by embedding wire wound cartridge heaters in a highly conductive metal block. Circulated fluid heaters consist of a metal block heat exchanger through which a controlled temperature fluid is circulated to provide the required heat flow as well as temperature control.

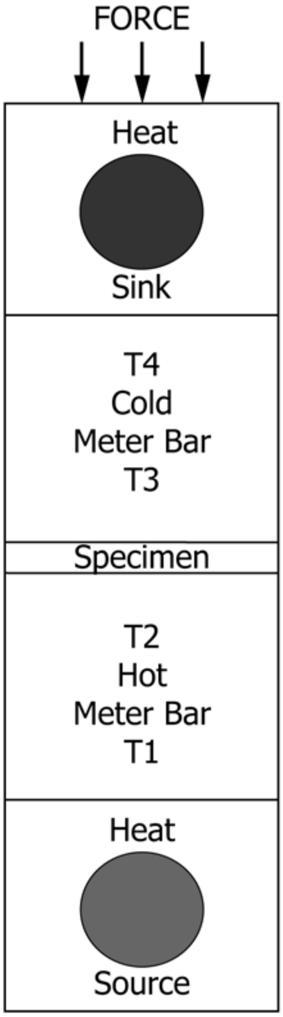

FIG. 1 Test Stack Using the Meter Bars as Calorimeters

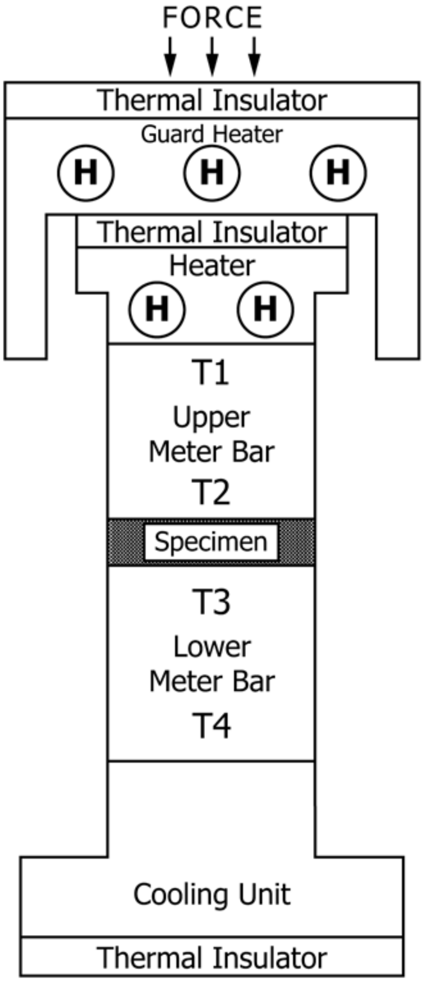

FIG. 2 Guarded Heater Test Stack

6.4 Heat flow through the specimen can be measured with meter bars regardless of the type of heater used.

6.4.1 Electrical heaters offer convenient measurement of the heating power generated but must be combined with a guard heater and high quality insulation to limit heat leakage away from the primary flow through the specimen.

6.4.2 Heat flow meter bars can be constructed from high conductivity materials with well documented thermal conductivity within the temperature range of interest. The temperature sensitivity of thermal conductivity must be considered for accurate heat flow measurement. The thermal conductivity of the bar material is recommended to be greater than 50 W/m·K.

6.4.3 Guard heaters are comprised of heated shields around the primary heat source to eliminate heat leakage to the environment. Guard heaters are insulated from the heat source and maintained at a temperature within ±0.2 K of the heater. This effectively reduces the heat leakage from the primary heater by nullifying the temperature difference across the insulation. Insulation between the guard heater and the heat source should be at least the equivalent of one 5 mm layer of FR-4 epoxy material.

6.4.4 If the heat flow meter bars are used on both the hot and cold surfaces, guard heaters and thermal insulation is not required and the heat flow through the test specimen is computed as the average heat flow through both meter bars.

6.5 Meter bars can also be used to determine the temperature of the test surfaces by extrapolating the linear array of meter bar temperatures to the test surfaces. This can be done for both the hot side and cold side meter bars. Surface temperatures can also be measured with thermocouples that are located in extreme proximity to the surfaces although this can be mechanically difficult to achieve. Meter bars can be used for both heat flow and surface temperature measurement or for exclusively one of these functions.

6.6 The cooling unit is commonly implemented with a metal block cooled by temperature controlled circulating fluid with a temperature stability of ±0.2 K.

6.7 The contact pressure on the specimen can be controlled and maintained in a variety of ways, including linear actuators, lead screws, pneumatics, and hydraulics. The desired range of forces must be applied to the test fixture in a direction that is perpendicular to the test surfaces and maintains the parallelism and alignment of the surfaces.

7. Preparation of Test Specimens

7.1 The material type will dictate the method for controlling specimen thickness. In all cases, prepare specimens of the same area as the contacting test surfaces. If the test surfaces are not of equal size, prepare the specimen equal to the dimension of the smaller test surface.

7.1.1 *Type I*—Use shims or mechanical stops to control the thickness of the specimen between the test surfaces. Spacer beads of the desired diameter can also be used in approximately 2 % volumetric ratio and thoroughly mixed into the sample prior to being applied to the test surfaces.

7.1.2 *Type II*—Use an adjustable clamping pressure to deflect the test specimen by 5 % of its uncompressed thickness. This represents a trade-off between lower surface contact resistance and excessive sample deflection.

7.1.3 *Type III*—Measure the sample thickness in accordance with Test Method C of Test Methods D374.

7.2 Prepare specimens from material that is in original, as-manufactured condition or as noted otherwise. Remove any contamination and dirt particles. Do not use solvent that will react with or contaminate the specimens.

8. Procedure

8.1 Determination of test specimen thickness.

8.1.1 Machines with in situ thickness measurement apparatus.

8.1.1.1 Close the test stack and apply the clamping pressure required for the specimen to be tested.

8.1.1.2 Turn on the heating and cooling units and let stabilize at the specified set points to give an average sample temperature of 50°C (average of T_2 and T_3), unless otherwise specified.

8.1.1.3 Zero the thickness measuring device (micrometer, LVDT, laser detector, encoder, etc.).

8.1.2 Machines without an in situ thickness measuring apparatus.

8.1.2.1 At room temperature, measure the specimen thickness in accordance with Test Method C of Test Methods D374.

8.2 Load the specimen on the lower test stack.

8.2.1 Dispense Type I grease and paste materials onto the lower test stack surface. Melt phase change compounds to dispense onto the stack.

8.2.2 Place Type II and III specimens onto the lower test stack.

8.3 Close the test stack and apply clamping pressure.

8.3.1 Type I materials being tested with shims to control the test thickness require only enough pressure to squeeze out excess material and contact the shim but not too much pressure that will result in the shim damaging the surfaces of the test stacks.

8.3.1.1 For machines with screw stops, electromechanical, or hydraulic actuators controlling the position of the upper test stack, the magnitude of the clamping pressure is not critical.

8.3.1.2 Raise the temperature of the test stack above the specimen melting point to enable phase change materials to flow and permit closing of the test stacks. After the material has flowed, return the heating and cooling units to the required set points to maintain an average specimen temperature of 50°C before beginning the test, unless otherwise specified.

8.3.2 Type II materials require enough pressure to coalesce stacked specimens together and minimize interfacial thermal resistances. Too much pressure can damage the specimens. This can be as low as 0.069 MPa (10 psi) for softer specimens or as high as 3.4 MPa (500 psi) for harder specimens. Alternatively, screws or linear actuators can be used to control the specimen thickness under test for easily deformable Type II materials.

8.3.3 Type III materials require enough pressure to exclude excess thermal grease from the interface and to flatten specimens that are not flat. This can be as low as 0.69 MPa (100 psi) for flat specimens with low viscosity thermal grease or as high as 3.4 MPa (500 psi) for non-flat specimens or when using high viscosity thermal grease.

8.4 Record the temperatures of the meter bars and the voltage and current applied to electrical heaters at equilibrium. Equilibrium is attained when, at constant power, 2 sets of temperature readings taken at 5 minute intervals differ by less than ±0.1°C, or if the thermal impedance has changed by less than 1 % of the current thermal impedance over a 5 minute time span.

8.5 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 sample.

8.6 Determine the thermal impedance of at least 3 specimen thicknesses. Maintain the mean temperature of the specimens at 50 ± 2°C (unless otherwise specified) by reducing the heat flux as the specimen thickness is increased.

8.6.1 For specimens that need to be stacked to get different thicknesses, first measure the thermal impedance of one layer alone, then measure the thermal impedance of 2 layers stacked together, and then measure the thermal impedance of 3 layers stacked together.

8.6.2 For specimens of 3 different thicknesses A, B, and C, first measure the thermal impedance of specimen A alone, then measure the thermal impedance of specimen B alone, then measure the thermal impedance of specimen C alone.

9. Calculation

9.1 *Heat Flow:*

9.1.1 *Heat Flow When Using the Meter Bars For Calorimeters*—Calculate the heat flow from the meter bar readings as follows:

$$Q_{12} = \frac{\lambda_{12} \times A}{d} \times [T_1 - T_2] \tag{1}$$

$$Q_{34} = \frac{\lambda_{34} \times A}{d} \times [T_3 - T_4] \tag{2}$$

$$Q = \frac{Q_{12} + Q_{34}}{2} \tag{3}$$

where:

Q_{12} = heat flow in hot meter bar, W,
Q_{34} = heat flow in cold meter bar, W,
Q = average heat flow through specimen, W,
λ_{12} = thermal conductivity of the hot meter bar material, W/(m·K),

λ_{34} = thermal conductivity of the cold meter bar material, W/(m·K),
A = area of the reference calorimeter, m^2,
$T_1 - T_2$ = temperature difference between temperature sensors of the hot meter bar, K,
$T_3 - T_4$ = temperature difference between temperature sensors of the cold meter bar, K, and
d = distance between temperature sensors in the meter bars, m.

9.1.2 *Heat Flow When Not Using the Meter Bars for Calorimeters*—Calculate the heat flow from the applied electrical power as follows:

$$Q = V \times I \quad (4)$$

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 hot meter bar surface in contact with the specimen from the following:

$$T_H = T_2 - \frac{d_B}{d_A} \times [T_1 - T_2] \quad (5)$$

where:

T_H = temperature of the hot meter bar surface in contact with the specimen, K,
T_1 = warmer temperature of the hot meter bar, K,
T_2 = cooler temperature of the hot meter bar, K,
d_A = distance between T_1 and T_2, m, and
d_B = distance from T_2 to the surface of the hot meter bar in contact with the specimen, m.

9.3 Derive the temperature of the cold meter bar surface in contact with the specimen from the following:

$$T_C = T_3 + \frac{d_D}{d_C} \times [T_3 - T_4] \quad (6)$$

where:

T_C = temperature of the cold meter bar surface in contact with the specimen, K,
T_3 = warmer temperature of the cold meter bar, K,
T_4 = cooler temperature of the cold meter bar, K,
d_C = distance between T_3 and T_4, m, and
d_D = distance from T_3 to the surface of the cold meter bar in contact with the specimen, m.

9.4 Calculate the thermal impedance from Eq 7 and express it in units of $(K\cdot m^2)/W$:

$$\theta = \frac{A}{Q} \times [T_H - T_C] \quad (7)$$

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 resistance, 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 or linear regression analysis.

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,

10.1.5 Thermal transmission properties:

10.1.5.1 Apparent thermal conductivity from 9.5, and

10.1.5.2 Thermal impedance from 9.4 (normalized to nominal thickness for Type II materials).

11. Precision and Bias

11.1 A round robin was conducted on five Type II 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 E691, 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.

TABLE 1 Precision for Conductivity Measurement

NOTE 1—Values are in units of watt per meter 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.

12. Keywords

12.1 apparent thermal conductivity; guarded heater method; thermal conductivity; thermal impedance; thermally conductive electrical insulation

SUMMARY OF CHANGES

Committee D09 has identified the location of selected changes to this test method since the last issue, D5470 – 01, that may impact the use of this test method. (Approved April 1, 2006)

(*1*) The test method was heavily revised throughout to remove non-mandatory language and to clarify mandatory aspects in the method, apparatus, specimens, and procedures.

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