



# Standard Test Method for Thermal Conductivity and Thermal Diffusivity by Modulated Temperature Differential Scanning Calorimetry<sup>1</sup>

This standard is issued under the fixed designation E 1952; 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 the determination of thermal conductivity of homogeneous, non-porous solid materials in the range of 0.10 to 1.0 W/(K • m) by modulated temperature differential scanning calorimeter. This range includes many polymeric, glass, and ceramic materials. Thermal diffusivity, which is related to thermal conductivity through specific heat capacity and density, may also be derived. Thermal conductivity and diffusivity can be determined at one or more temperatures over the range of 0 to 90 °C.

1.2 Electronic instrumentation or automated data analysis and reduction systems or treatments equivalent to this test method may be used.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are provided for information purposes only.

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:

E 473 Terminology Relating to Thermal Analysis<sup>2</sup>

E 967 Practice for Temperature Calibration of Differential Scanning Calorimeters and Differential Thermal Analyzers<sup>2</sup>

E 968 Practice for Heat Flow Calibration of Differential Scanning Calorimeters<sup>2</sup>

<sup>1</sup> This test method is under the jurisdiction of Committee E37 on Thermal Measurements and is the direct responsibility of Subcommittee E37.01 on Test Methods and Recommended Practices.

Current edition approved August 10, 2001. Published October 2001. Originally published as E 1952 – 98. Last previous edition E 1952 – 98.

The process described in this test method is covered by a patent (Marcus, S. M. and Reading, M., U. S. Patent 5 335 993, 1994) held by TA Instruments, Inc., 109 Lukens Drive, New Castle DE 19720. Interested parties are invited to submit information regarding the identification of acceptable alternatives to this patented method to the Committee on Standards, ASTM Headquarters, 100 Barr Harbor Drive, West Conshohocken PA 19428-2959. Your comments will receive careful considerations at a meeting of the responsible technical committee which you may attend.

<sup>2</sup> *Annual Book of ASTM Standards*, Vol 14.02.

E 1142 Terminology Relating to Thermophysical Properties<sup>2</sup>

E 1231 Practice for Calculation of Hazard Potential Figures-of-Merit for Thermally Unstable Materials<sup>2</sup>

## 3. Terminology

### 3.1 Definitions:

3.1.1 Specific technical terms used in this document are defined in Terminologies E 473 and E 1142.

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

3.2.1 *modulated temperature differential scanning calorimeter*—a version of differential scanning calorimetry that provides a sinusoidally varying temperature program to the test specimen in addition to the traditional isothermal or temperature ramp programs. Results from analysis shall include apparent and specific heat capacity.

## 4. Summary of Test Method

4.1 The heat capacity of a test specimen may be determined using the modulated temperature approach in which an oscillatory or periodically repeating temperature program (around an average temperature) is imposed upon a test specimen producing an oscillatory (periodic) heat flow into or out of the specimen. The heat capacity of the test specimen may be obtained from the amplitude of the resultant heat flow divided by the amplitude of the oscillatory (periodic) temperature that produces it. Specific heat capacity is obtained by normalizing the heat capacity to specimen mass.

4.1.1 The accuracy of the heat capacity thus obtained depends upon experimental conditions. When a thin test specimen encapsulated in a specimen pan of high thermal conductivity is treated with temperature oscillations of long period (low frequency), the test specimen is assumed to achieve a uniform temperature distribution and the resultant heat capacity information will be comparable with those of other non-oscillatory test methods.

4.1.2 When one end of a thick test specimen is exposed to the temperature oscillations of short period (high frequency), the test specimen will achieve a temperature distribution over its length related to its thermal diffusivity.

4.1.3 The apparent heat capacity information thus obtained is lower than that of the uniform temperature distribution case

described above and is proportional to the square root of thermal conductivity of the test specimens.<sup>3</sup> The thermal conductivity of the test specimen may be derived from the apparent heat capacity of a thick specimen, the actual heat capacity of a thin specimen, and a series of geometric and experimental constants.

4.2 If the thermal conductivity of the test specimen is low, approaching that of the purge gas surrounding it, a correction to the measured thermal conductivity is required to compensate for heat losses from the thick test specimen.

4.3 Thermal diffusivity is derived from the determined thermal conductivity, specific heat capacity, and density of the test specimen.

## 5. Significance and Use

5.1 Thermal conductivity is a useful design parameter for the rate of heat transfer through a material.

5.2 The results of this test method may be used for design purposes, service evaluation, manufacturing control, research and development, and hazard evaluation. (See Practice E 1231.)

## 6. Interferences

6.1 Because the specimen size used in thermal analysis is on the order of 10 to 100 mg, care must be taken to ensure it is homogeneous or representative of the material, or both.

6.2 The calculation of thermal conductivity requires knowledge of this specimen geometry. This test method requires a specific specimen size and shape. Other geometries may be used with the appropriate modifications to the calculating equations.

## 7. Apparatus

7.1 A modulated temperature differential scanning calorimeter consisting of:

7.1.1 *A Differential Scanning Calorimetry (DSC) Test Chamber*, of (1) a furnace to provide uniform controlled heating/cooling of a specimen and reference to a constant temperature or at a constant rate within the applicable range of this test method; (2) a temperature sensor (or other signal source) to provide an indication of the specimen temperature readable to 0.01°C; (3) a differential sensor to detect a heat flow difference between the specimen and reference equivalent to 0.001 mW; and (4) a means of sustaining a test temperature environment of inert nitrogen purge gas at a rate of 50 mL/min ± 10 mL/min.

7.1.2 *A Temperature Controller*, capable of executing a specific temperature program by (1) operating the furnace between selected temperature limits at a rate of temperature change of 1°C/min, (2) holding at an isothermal temperature over the temperature range of 0 to 90 °C within ± 0.1°C, and (3) sinusoidal varying temperature with an amplitude of ±0.2 to 0.7°C and a period of 60 to 100 seconds (frequency of 10 to 16 mHz).

7.1.3 *A Calculating Device*, capable of transforming the experimentally determined modulated temperature and modu-

lated specimen heat flow signals into the required continuous output forms of heat capacity (preferably in units of mJ/°C), specific heat capacity (preferably in units of J/(g°C)), and average test temperature to the required accuracy and precision.

7.1.4 *A Recording Device*, to record and display heat capacity, specific heat capacity, and average temperature on the ordinate (Y axis) and elapsed time (preferably in units of minutes) on the abscissa (X axis) with a sensitivity of 0.001 mJ/K for heat capacity, 0.001 J/(g • K) for specific heat capacity, 0.1°C for average temperature, and 0.1 min for time.

7.1.5 *A Coolant System*, to provide oscillatory heating and cooling rates of at least 3°C/min.

7.1.6 *Inert Nitrogen*, or other low conductivity purge gas flowing at a rate of 50 mL/min (see 7.1.1).

NOTE 1—Helium, a commonly used purge gas, is unacceptable for this purpose, due to its very high thermal conductivity which results in reduced range, precision, and accuracy.

7.2 *A Balance*, with a range of at least 200 mg to weigh specimens or containers, or both, (pans, crucibles, etc.) to ±0.01 mg.

7.3 *Calipers* or other length-measuring device with a range greater than 4 mm, readable to 0.01 mm.

7.4 *Sapphire Disk Calibration Material*, 10 to 15 mg.

7.5 *Polystyrene Thermal Conductivity Calibration Material*, of known thermal conductivity and specific heat capacity, in the shape of a right circular cylinder, 6.3 ± 0.2 mm in diameter and 3.5 ± 0.3 mm thickness.

7.5.1 *Polystyrene Specific Heat Capacity Reference Material*, composed of the same material as the thermal conductivity calibration material, in the shape of a right circular cylinder or disk, 6.3 ± 0.2 mm in diameter and 0.4 ± 0.1 mm in thickness.

7.6 *Circular Aluminum Disk*, 6.3 mm in diameter and 0.01 mm or thinner in thickness.

7.7 *Containers* (pans, crucibles, etc.) that are inert to the specimen and are of suitable structural shape and integrity to contain the specimen in accordance with the specific requirements of this test method.

7.8 *Silicone Heat Transfer Fluid*, with no thermal transitions over the temperature range from -10 to 100°C.

NOTE 2—Silicone oil with a viscosity of about 1 Pa • s (10 poise) has been found satisfactory for this application.

7.9 While not required, users may find the following optional apparatus and materials useful for this determination.

7.9.1 *Polymeric Thermal Conductivity Performance Material*, a right circular cylinder, 6.3 ± 0.2 mm in diameter and 3.5 ± 0.3 mm in length.

7.9.2 *Polymetric Specific Heat Capacity Reference Material*, composed of the same material as the thermal conductivity standard reference material, a right circular cylinder or disk, 6.3 ± 0.2 mm in diameter and 0.4 ± 0.1 mm in thickness.

## 8. Sampling

8.1 Select two right circular cylinders, both nominally 6.3 mm in diameter. The first of these test specimens is nominally 0.4 mm thick and the second is nominally 3.5 mm thick. These test specimens are most conveniently obtained by cutting from

<sup>3</sup> Marcus, S.M., and Blaine, R.L., *Thermochim. Acta*, Vol 243, 1994, pp. 231-239.

0.25 in. diameter rod, a common material form.

NOTE 3—Other fabrication techniques, such as cutting from sheet stock using cork borers, machining from stock, or molding may also be used.

8.1.1 Polish the circular end surfaces of the test specimens smooth and parallel to within  $\pm 30 \mu\text{m}$  with 600 grit emery paper.

## 9. Calibration

9.1 Calibrate the temperature signal from the apparatus in accordance with Practice E 967 using an indium reference material and a heating rate of  $1 \text{ }^\circ\text{C}/\text{min}$ .

9.2 Calibrate the heat flow signal from the apparatus in accordance with Practice E 968 using an indium reference material.

9.3 Calibrate the apparatus for heat capacity measurements in accordance with the instructions of the manufacturer as described in the instrument manual using isothermal temperature conditions (at the mid point of the temperature range of interest), the sapphire calibration material (from 7.4)  $\pm 0.5 \text{ }^\circ\text{C}$  amplitude and 80 s period (12.5 MHz frequency).

## 10. Procedure

10.1 Measure thermal conductivity under quasi-isothermal conditions at an operator-selected temperature within the range from 0 to  $90 \text{ }^\circ\text{C}$ . If measurements at additional temperatures are desired, repeat the procedure at those additional temperatures.

10.2 A common set of experimental conditions are used for each measurement:

10.2.1 Select the modulated mode on the DSC and record the heat capacity signal. Equilibrate the apparatus at the test temperature selected by the operator. Modulate the temperature with an amplitude of  $\pm 0.5 \text{ }^\circ\text{C}$  and a period ( $P$ ) of 80 s (12.5 MHz). After 15 min equilibration time, record the average test temperature ( $T$ ) and the specific heat capacity ( $C_p$ ) or apparent heat capacity ( $C$ ) as called for in the appropriate section.

10.3 Determine the thermal conductivity calibration factor,  $D$ .

10.3.1 Weigh the thin (0.4 mm) polystyrene (or other) calibration disk (from 7.5.1); record the mass as  $m$ . Enter it as an experimental parameter into the apparatus calculator. Encapsulate the thin polystyrene calibration disk in a standard aluminum sample container with lid.

10.3.2 Place the encapsulated test specimen in the DSC on the specimen sensor. Use an empty aluminum container and lid on the reference side.

NOTE 4—Matching the combined weights of the reference container and lid to those of the specimen container and lid within  $\pm 0.1 \text{ mg}$  produces the best results.

10.3.3 Measure the heat capacity of the thin polystyrene calibration material using the conditions of 10.2.1. Record the specific heat capacity ( $C_p$ ) in units of  $\text{J}/(\text{g} \cdot \text{K})$ .

NOTE 5—This value for the specific heat capacity of polystyrene may be compared against the literature values listed in Table 1 as a performance criteria test.

10.3.4 Weight the thick (3.5 mm) polystyrene calibration disk (from 7.5); record the mass as  $m$ ; and enter it into the experimental parameters screen on the measuring apparatus.

**TABLE 1 Polystyrene Specific Heat Capacity<sup>A</sup>**

Temperature		Specific Heat Capacity <sup>B</sup> ( $\text{J}/(\text{g} \cdot \text{K})$ )
( $^\circ\text{C}$ )	(K)	
6.8	280.0	1.1326
16.8	290.0	1.1775
26.8	300.0	1.2230
36.8	310.0	1.2691
46.8	320.0	1.3156
50.0	323.2	1.3305
56.8	330.0	1.3626
66.8	340.0	1.4100
76.8	350.0	1.4577
86.8	360.0	1.5056
96.8	370.0	1.5539

<sup>A</sup>Gaur, U., and Wunderlich, B, *J. Phys. Chem. Ref. Data*, Vol 11 (2), 1982, p. 313.

<sup>B</sup>The values in this table were determined under special highly accurate test conditions that are not attainable by or applicable to this test method. The actual precision of this test method is given in Section 13.

10.3.5 Measure and record the diameter ( $d$ ) and length ( $L$ ) of the polystyrene calibration test specimen.

10.3.6 Place a small drop of silicone oil on the DSC sample and reference sensors. Place a thin aluminum disk over each drop of oil. Carefully place the thick sample (which has been wetted with oil on the bottom side) on the aluminum disk covering the sample sensor.

NOTE 6—Ensure that silicone oil does not change the characteristics of the test specimen.

NOTE 7—Use the minimum amount of oil that will provide complete contact between the specimen disk and the DSC sensor. Wiping the surface with a cotton swab moistened with the oil is usually sufficient.

10.3.7 Measure the apparent heat capacity of the specimen in accordance with the conditions of 10.2.1. Record the apparent heat capacity ( $C$ ) in the units of  $\text{mJ}/^\circ\text{C}$ .

10.3.8 Using the values of  $P$  (from 10.2.1),  $C_p$  (from 10.3.3); and  $m$ ,  $L$ , and  $d$  (from 10.3.4 and 10.3.5), calculate the observed thermal conductivity ( $\lambda_o$ ) for polystyrene using Eq 1 (see 11.1).

NOTE 8—An example calculation is presented in 11.5.1.

10.3.9 Determine the value for thermal conductivity of polystyrene ( $\lambda_r$ ) for the corresponding temperature ( $T$ ) (from 10.2.1) from Table 2, linearly interpolating between values if necessary.

10.3.10 Using the values for  $\lambda_o$  from 10.3.8 and the value for  $\lambda_r$  from 10.3.9, calculate the thermal conductivity calibration constant ( $D$ ) for temperature  $T$  using Eq 2.

**TABLE 2 Polystyrene Thermal Conductivity<sup>A</sup>**

Temperature		Thermal Conductivity <sup>B</sup> ( $\text{W}/(\text{m} \cdot \text{K})$ )
( $^\circ\text{C}$ )	(K)	
-13	260	0.1480
0	273	0.1506
7	280	0.1514
20	293	0.1529
27	300	0.1539
47	320	0.1562
67	340	0.1582
87	360	0.1605
97	370	0.1616

<sup>A</sup>Ho, C.Y., Desai, P.D., Wu, K.T., Havill, T.N., Lee, T.Y., NBS Publication GCR-77-83, 1977.

<sup>B</sup>The values in this table were determined under special highly accurate steady-state conditions, which are not attainable by or applicable to this test method. The actual precision of this test method is given in Section 13.

NOTE 9—An example calculation is presented in 11.5.2.

NOTE 10—Typical values for  $D$  range from approximately 0.0100 to 0.0500 W/(m • K).

10.4 Determine the thermal conductivity of the test specimen.

10.4.1 Weigh the thin (0.4 mm) test specimen and record the mass as  $m$ . Enter this value into the experimental parameters screen of the apparatus.

10.4.2 Encapsulate the thin specimen in a standard aluminum sample container with lid.

10.4.3 Place the encapsulated test specimen on the DSC sample sensor. Place an empty aluminum container and lid on the DSC reference sensor.

NOTE 11—Matching the weights of the reference container and lid to the specimen container and lid within  $\pm 0.1$  mg produces the best results.

10.4.4 Measure the specific heat capacity of the thin test specimen using the conditions in 10.2.1. Record the specific heat capacity ( $C_p$ ) in units J/(g • K).

10.4.5 Weigh the thick test specimen, recording its mass as  $m$ .

10.4.6 Measure and record the diameter ( $d$ ) and length ( $L$ ) of the test specimen.

10.4.7 Place a small drop of silicone oil on the DSC sample and reference sensors. Place a thin aluminum disk over each drop of oil. Carefully position the thick test specimen (which has been wetted with oil on the bottom side) on the aluminum disk covering the DSC sample sensor (see Note 6 and Note 7).

10.4.8 Measure the apparent heat capacity of the test specimen in accordance with the conditions in 10.2.1. Record the apparent heat capacity ( $C$ ) in units of mJ/°C.

10.4.9 Using the value for  $P$  (from 10.2.1),  $C_p$  (from 10.4.4), and  $M$ ,  $L$ , and  $d$  (from 10.4.6 and 10.4.7), calculate the observed thermal conductivity ( $\lambda_o$ ) for the test specimen using Eq 1.

NOTE 12—An example calculation is presented in 11.5.1.

10.4.10 Using the value for  $\lambda_o$  (from 10.4.10) and the value of  $D$  (from 10.3.10), calculate the value for  $\lambda$  of the test specimen using Eq 3.

NOTE 13—An example calculation is presented in 11.5.3.

10.4.11 Using the value for  $\lambda$  (from 10.4.11), the value of  $C_p$  (from 10.4.4), and the values of  $m$  and  $L$  (from 10.4.6 and 10.4.7), calculate the thermal diffusivity ( $a$ ) for the test specimen using Eq 4.

NOTE 14—An example calculation is presented in 11.5.4.

10.4.12 Report values for thermal conductivity ( $\lambda$ ) and thermal diffusivity ( $a$ ) at temperature ( $T$ ) as the mean values of duplicate determinations. Also report the range of measurements between the high and the low value.

10.5 *Performance Criteria for Test Apparatus:*

10.5.1 The apparatus used for this test method is considered adequate if the value for thermal conductivity for a suitable reference material is within  $\pm 10$  %.

10.5.2 A suitable reference material is described in Section 12.

## 11. Calculation

11.1 Determine the observed thermal conductivity ( $\lambda_o$ ) in

accordance with Eq 1.

$$\lambda_o = (8 L C^2) / (C_p m d^2 P) \quad (1)$$

where:

$\lambda_o$  = observed thermal conductivity (W/(K • m)),

$L$  = specimen length (mm),

$C$  = apparent heat capacity (mJ/K),

$C_p$  = specific heat capacity (J/(g • K)),

$m$  = thick specimen mass (mg),

$d$  = thick specimen diameter (mm), and

$P$  = period (s).

NOTE 15—When performing these calculations, retain all available decimal places in the measured values and in intermediate values. The final result should be rounded to two significant places in the standard deviation, as indicated in Section 13.

11.2 Calculate the thermal conductivity calibration constant ( $D$ ) in W/(m • K) using Eq 2.

$$D = (\lambda_o \lambda_r)^{\frac{1}{2}} - \lambda_r \quad (2)$$

where:

$\lambda_r$  = reference thermal conductivity (W/(m • K))

11.3 Calculate the test specimen thermal conductivity ( $\lambda$ ) using Eq 3.

$$\lambda = \frac{[\lambda_o - 2 D + (\lambda_o^2 - 4 D \lambda_o)^{\frac{1}{2}}]}{2} \quad (3)$$

11.4 Calculate thermal diffusivity ( $a$ ) using Eq 4 (Appendix X1).

$$a = (\pi \lambda d^2 L) / (4 C_p m) \quad (4)$$

11.5 Example calculations:

11.5.1 If the following set of values were measured for a polystyrene thermal conductivity calibration material, the value for  $\lambda_o$  from Eq 1 becomes:

$$\begin{aligned} L &= 3.45 \text{ mm,} \\ C &= 61.65 \text{ mJ/K,} \\ C_p &= 1.20 \text{ J/(g • K),} \\ m &= 127.0 \text{ mg,} \\ d &= 6.73 \text{ mm, and} \\ P &= 80 \text{ s.} \end{aligned}$$

then:

$$\lambda_o = (8 \times 3.45 \text{ mm} \times 61.65 \text{ mJ/K} \times 61.65 \text{ mJ/K}) / (1.20 \text{ J/(g • K)} \times 127.0 \text{ mg} \times 6.73 \text{ mm} \times 6.73 \text{ mm} \times 80 \text{ s})$$

recognizing that 1 W = 1 J/s, then

$$\lambda_o = 0.1900 \text{ W/(m • K)}$$

11.5.2 If the thermal conductivity value of  $\lambda_r = 0.1552$  W/(m • K) is taken from Table 2 at 38.5°C, and the value for  $\lambda_o$  is taken from 11.5.1, then Eq 2 is calculated to be:

$$\begin{aligned} D &= (0.1900 \text{ W/(m • K)} \times 0.1552 \text{ W/(m • K)})^{0.5} - 0.1552 \\ &\quad \text{W/(m • K)} \\ &= (0.1717 - 0.1552) \text{ W/(m • K)} \\ D &= 0.0165 \text{ W/(m • K).} \end{aligned}$$

11.5.3 If a value of the observed thermal conductivity for a

test specimen is found to be

$$\begin{aligned} \lambda_o &= 0.2821 \text{ W/(m} \cdot \text{K)}, \text{ then from Eq 3:} \\ \lambda &= [0.2821 \text{ W/(m} \cdot \text{K)} - (2 \times 0.0165 \text{ W/(m} \cdot \text{K)}) + \\ &\quad \{0.2821 \text{ W/(m} \cdot \text{K)} \times 0.2821 \text{ W/(m} \cdot \text{K)}\} - \{4 \times \\ &\quad 0.0165 \text{ W/(m} \cdot \text{K)} \times 0.2821 \text{ W/(m} \cdot \text{K)}\}^{0.5}] / 2 \\ \lambda &= \{0.2821 - 0.0330 + (0.07958 - 0.01862)^{0.5}\} \text{ W/(m} \cdot \text{K)} \\ &\quad / 2 \\ \lambda &= [0.2491 + 0.2469] \text{ W/(m} \cdot \text{K)} / 2 \\ \lambda &= 0.248 \text{ W/(m} \cdot \text{K)}. \end{aligned}$$

11.5.4 From Eq 4:

$$a = \frac{(3.141 \times 0.248 \text{ W/(m} \cdot \text{K)} \times 6.73 \text{ mm} \times 6.73 \text{ mm} \times 3.45 \text{ mm})}{(4 \times 1.20 \text{ J/(g} \cdot \text{K)} \times 127.0 \text{ mg})} \quad (5)$$

$$a = 0.200 \text{ mm}^2/\text{s}$$

## 12. Performance Criteria

12.1 Poly(methyl methacrylate) or other material of known thermal conductivity may be used to verify performance in this application. Specific heat capacity and thermal conductivity values for a poly(methyl methacrylate) reference material (7.9.1 and 7.9.2) are presented in Table 3.

NOTE 16—Poly(methyl methacrylate), polyethylene and polyamide samples of known thermal conductivity are available from the National Physical Laboratory, Teddington, Middlesex, TW11 0LW, England. Also samples of borosilicate glass reference material are available from the Institute of Reference Materials and Measurements, Commission of the European Community, Retieussweg 2410, Geel, Belgium.

## 13. Precision and Bias

13.1 An interlaboratory study (ILS)<sup>4</sup> was conducted in 2000 involving participation by 14 laboratories. Polystyrene (PS) was used as a calibration material. Each laboratory characterized a polymethylmethacrylate (PMMA) certified thermal conductivity performance standard obtained from the National Physical Laboratory, the UK national standards laboratory. The results of this interlaboratory test are on file at ASTM Headquarters

<sup>4</sup> Supporting data are available from ASTM Headquarters, Request E37-1026.

**TABLE 3 Poly(methyl methacrylate) Specific Heat Capacity and Thermal Conductivity<sup>A,B</sup>**

Temperature		Specific Heat Capacity (J/g · K)	Thermal Conductivity <sup>C</sup> (W/(m · K))
(°C)	(K)		
7.2	280.0	1.2951	0.192
17.2	290.0	1.3353	0.193
27.2	300.0	1.3756	0.194
37.2	310.0	1.4158	0.196
47.2	320.0	1.4561	0.197

<sup>A</sup>Gaur, U., Lau., S.F., Wunderlich, B.B., *J. Phys. Chem. Ref. Data*, Vol 11 (4), 1982, p. 1068.

<sup>B</sup>The values in this table were determined under special highly accurate steady-state conditions, which are not attainable by or applicable to this test method. The actual precision of this test method is given in Section 13.

<sup>C</sup>Salmon, D.R., National Physical Laboratory, Teddington, Middlesex, TW11 0LW, England, 1993.

## 13.2 Precision:

13.2.1 Within laboratory variability may be described using the repeatability value (r), obtained by multiplying the repeatability standard deviation by 2.8. The repeatability value estimates the 95 % confidence limit.

13.2.1.1 Thermal conductivity repeatability (relative) standard deviation values of 13 and 8.7 % were obtained for PS and the PMMA performance standard, respectively. The pooled repeatability (relative) standard deviation for these two values is 12 %.

13.2.1.2 Specific heat capacity repeatability (relative) standard deviation values of 3.0 and 1.9 % were obtained for PS and PMMA, respectively. The pooled repeatability (relative) standard deviation for these three values is 2.7 %.

13.2.1.3 From the principle of propagation of uncertainties, thermal diffusivity repeatability (relative) standard deviation is estimated to be 12 %.

13.2.2 Between laboratory variability may be described using the reproducibility value (R) obtained by multiplying the reproducibility standard deviation by 2.8. The reproducibility value estimates the 95 % confidence limit.

13.2.2.1 Thermal conductivity reproducibility (relative) standard deviation values of 27 and 10 % were obtained for PS and PMMA performance standard, respectively. The pooled (relative) standard deviation for these two values is 23 %.

13.2.2.2 Specific heat capacity reproducibility (relative) standard deviation values of 9.1 and 5.8 % were obtained for PS and PMMA, respectively. The pooled repeatability (relative) standard deviation of these three values is 8.2 %.

13.2.2.3 From the principle of propagation of uncertainties, thermal diffusivity reproducibility (relative) standard deviation is estimated to be 24 %.

## 13.3 Bias:

13.3.1 An estimation of bias is obtained by comparing the mean values obtained for each performance standard to its certified or literature value. That is, bias = (mean value) - (certified value).

13.3.2 The mean thermal conductivity value for the PMMA performance standard at 47 °C is 0.185 W m<sup>-1</sup>K<sup>-1</sup> with 28 degrees of freedom. The certified thermal conductivity value at this same temperature is 0.197 W m<sup>-1</sup>K<sup>-1</sup>(1)<sup>5</sup>. This represents a bias of - 0.012 W m<sup>-1</sup>K<sup>-1</sup> or -6.1 %.

13.3.3 The mean specific heat capacity value for PS at 47 °C is 1.403 J g<sup>-1</sup>K<sup>-1</sup> with 52 degrees of freedom. The literature specific heat capacity value at this same temperature is 1.316 J g<sup>-1</sup>K<sup>-1</sup>(2). This represents a bias of 0.087 J g<sup>-1</sup>K<sup>-1</sup> or 6.6 %.

13.3.4 The mean specific heat capacity value for PMMA at 47 °C is 1.538 J g<sup>-1</sup>K<sup>-1</sup> with 24 degrees of freedom. The literature specific heat value at this same temperature is 1.436 J g<sup>-1</sup>K<sup>-1</sup>(3). This represents a bias of 0.102 J g<sup>-1</sup>K<sup>-1</sup> or 7.1 %.

13.3.5 The weighted bias for these two determinations of specific heat capacity is 6.8 %.

## 14. Report

14.1 Report the following information:

<sup>5</sup> The boldface numbers given in parentheses refer to a list of references at the end of the text.

14.1.1 Complete identification and description of the material tested, including source, manufacturer code, and any thermal or mechanical pretreatment.

14.1.2 Description of the instrumentation used for the test, such as manufacturer and model number.

14.1.3 Description of calibration procedure, including values for calibration constant(s) such as  $D$ .

14.1.4 Test specimen dimensions, including diameter, length, and mass.

14.1.5 Mean thermal conductivity ( $W/(m \cdot K)$ ) and thermal diffusivity ( $mm^2/s$ ) at their measurement temperature.

## 15. Keywords

15.1 ceramics; differential scanning calorimetry (DSC); glasses; modulated differential scanning calorimetry (MDSC); modulated temperature differential scanning calorimetry; polymers; thermal analysis; thermal conductivity; thermal diffusivity

## APPENDIX

### (Nonmandatory Information)

#### X1.

X1.1 Thermal diffusivity ( $a$ ) of a material is related to its thermal conductivity ( $\lambda$ ), a geometry specific property, through the material's specific heat capacity ( $C_p$ ), and density ( $\rho$ ) by the Eq X1.1.

$$a = \lambda / (C_p \rho) \quad (X1.1)$$

X1.2 By definition, density is mass ( $m$ ) per unit volume ( $V$ ) as in Eq X1.2.

$$\rho = m/V \quad (X1.2)$$

X1.3 For a right cylinder, the volume is given by Eq X1.3.

$$V = \pi d^2 L / 4 \quad (X1.3)$$

X1.4 Substituting Eq X1.2 and Eq X1.3 into Eq X1.1 yields Eq X1.4, the working Eq 4 of 11.4.

$$a = (\pi \lambda d^2 L) / (4 C_p m) \quad (X1.4)$$

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