Designation: C518 – 17

Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[1]

This standard is issued under the fixed designation C518; 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 test method covers the measurement of steady state thermal transmission through flat slab specimens using a heat flow meter apparatus.

1.2 The heat flow meter apparatus is used widely because it is relatively simple in concept, rapid, and applicable to a wide range of test specimens. The precision and bias of the heat flow meter apparatus can be excellent provided calibration is carried out within the range of heat flows expected. This means calibration shall be carried out with similar types of materials, of similar thermal conductances, at similar thicknesses, mean temperatures, and temperature gradients, as expected for the test specimens.

1.3 This a comparative, or secondary, method of measurement since specimens of known thermal transmission properties shall be used to calibrate the apparatus. Properties of the calibration specimens must be traceable to an absolute measurement method. The calibration specimens should be obtained from a recognized national standards laboratory.

1.4 The heat flow meter apparatus establishes steady state one-dimensional heat flux through a test specimen between two parallel plates at constant but different temperatures. By appropriate calibration of the heat flux transducer(s) with calibration standards and by measurement of the plate temperatures and plate separation. Fourier's law of heat conduction is used to calculate thermal conductivity, and thermal resistivity or thermal resistance and thermal conductance.

1.5 This test method shall be used in conjunction with Practice C1045. Many advances have been made in thermal technology, both in measurement techniques and in improved understanding of the principles of heat flow through materials. These advances have prompted revisions in the conceptual approaches to the measurement of the thermal transmission properties (**1-4**).[2] All users of this test method should be aware of these concepts.

1.6 This test method is applicable to the measurement of thermal transmission through a wide range of specimen properties and environmental conditions. The method has been used at ambient conditions of 10 to 40°C with thicknesses up to approximately 250 mm, and with plate temperatures from –195°C to 540°C at 25-mm thickness (**5**, **6**).

1.7 This test method may be used to characterize material properties, which may or may not be representative of actual conditions of use. Other test methods, such as Test Methods C236 or C976 should be used if needed.

1.8 To meet the requirements of this test method the thermal resistance of the test specimen shall be greater than 0.10 $m^2 \cdot K/W$ in the direction of the heat flow and edge heat losses shall be controlled, using edge insulation, or a guard heater, or both.

1.9 It is not practical in a test 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 pertinent technical knowledge. Thus users of this test method shall have sufficient knowledge to satisfactorily fulfill their needs. For example, knowledge of heat transfer principles, low level electrical measurements, and general test procedures is required.

1.10 The user of this method must be familiar with and understand the Annex. The Annex is critically important in addressing equipment design and error analysis.

1.11 Standardization of this test method is not intended to restrict in any way the future development of improved or new methods or procedures by research workers.

1.12 Since the design of a heat flow meter apparatus is not a simple matter, a procedure for proving the performance of an apparatus is given in Appendix X3.

[1] This test method is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this test method.

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

1.14 *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 consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.15 *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:*[3]

C167 Test Methods for Thickness and Density of Blanket or Batt Thermal Insulations

C168 Terminology Relating to Thermal Insulation

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C236 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box (Withdrawn 2001)[4]

C687 Practice for Determination of Thermal Resistance of Loose-Fill Building Insulation

C976 Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box (Withdrawn 2002)[4]

C1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions

C1046 Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components

C1058 Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation

C1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus

E230/E230M Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples

E178 Practice for Dealing With Outlying Observations

E456 Terminology Relating to Quality and Statistics

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

2.2 *ISO Standard:*

ISO 8301:1991 Thermal Insulation—Determination of Steady-State Thermal Resistance and Related Properties—Heat Flow Meter Apparatus[5]

[3] 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.

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

[5] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3. Terminology

3.1 *Definitions*—For definitions of terms and symbols used in this test method, refer to Terminology C168 and to the following subsections.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration, n*—the process of establishing the calibration factor for a particular apparatus using calibration specimens having known thermal transmission properties.

3.2.2 *calibration transfer specimen, n*—(CTS) a thermal calibration specimen that has been measured by a national standards laboratory (**7**).

3.2.3 *cold surface assembly, n*—the plate that provides as isothermal boundary at the cold surface of the test specimen(s).

3.2.4 *controlled environment, n*—an environment sometimes employed in the apparatus to limit lateral heat flows.

3.2.5 *edge insulation, n*—auxiliary insulation used to limit lateral heat flows, these are sometimes permanently mounted in the apparatus.

3.2.6 *guard, n*—promotes one-dimensional heat flow. Primary guards are planar, additional coplanar guards can be used and secondary or edge guards are axial.

3.2.7 *heat flow meter apparatus, n*—the complete assemblage of the instrument, including hot and cold isothermal surfaces, the heat flux transducer(s), and the controlled environment if used, and instrumentation to indicate hot and cold surface temperatures, specimen thickness, and heat flux.

3.2.8 *hot surface assembly, n*—the plate that provides an isothermal boundary at the hot surface of the test specimen(s).

3.2.9 *heat flux transducer, n*—a device containing a thermopile, or an equivalent, that produces an output which is a function of the heat flux passing through it. The metering area usually consists of a number of differently connected temperature sensors placed on each face of a core and surface sheets to protect the assembly. A properly designed transducer will have a sensitivity that is essentially independent of the thermal properties of the specimen.

3.2.10 *metering area, n*—the area of the specimen(s) in contact with the sensor area of the heat flux transducer.

3.2.11 *secondary transfer standard, n*—a specimen, which has been measured in a heat flow meter apparatus, which has been calibrated with primary standards, used to calibrate additional apparatuses.

3.2.12 *sensitivity, n*—the ratio of the heat flux passing through the transducer to the electrical output of the heat flux transducer.

3.2.13 *standard reference material (SRM), n*—a lot of material that has been characterized by a national standards laboratory (**7**).

3.2.14 *thermal transmission properties, n*—those properties of a material or system that define the ability of the material or system to transfer heat. Properties, such as thermal resistance, thermal conductance, thermal conductivity, and thermal resistivity would be included, as defined in Terminology C168.

3.3 *Symbols and Units*—The symbols used in this test method have the following significance:

3.3.1 λ—thermal conductivity, $W/(m \cdot K)$.

3.3.2 C—thermal conductance, $W/(m^2 \cdot K)$

3.3.3 R—thermal resistance, $(m^2 \cdot K)/W$.

3.3.4 q—heat flux (heat flow rate, Q, through area A), W/m^2.

3.3.5 Q—heat flow rate in the metered area, W.

3.3.6 A—metering area, m^2.

3.3.7 L—separation between the hot and cold plate assemblies during testing, m.

3.3.8 T_m—mean temperature, $(T_h + T_c)/2$, K.

3.3.9 ΔT—temperature difference across the specimen, K.

3.3.10 ρ—(bulk) density of the material tested, kg/m^3.

3.3.11 S—calibration factor of the heat flux transducer, $(W/m^2)/V$.

3.3.12 E—heat flux transducer output, V.

3.3.13 T_h—temperature of the hot plate surface, K.

3.3.14 T_c—temperature of the cold plate surface, K.

3.4 *Subscripts:*

3.4.1 h—hot.

3.4.2 c—cold

3.4.3 a, b—first and second specimen.

3.4.4 m—mean.

3.4.5 α—statistical term used to define significance level.

4. Significance and Use

4.1 This test method provides a rapid means of determining the steady-state thermal transmission properties of thermal insulations and other materials with a high level of accuracy when the apparatus has been calibrated appropriately.

4.2 Proper calibration of the heat flow meter apparatus requires that it be calibrated using specimen(s) having thermal transmission properties determined previously by Test Methods C177, or C1114.

NOTE 1—Calibration of the apparatus typically requires specimens that are similar to the types of materials, thermal conductances, thicknesses, mean temperatures, and temperature gradients as expected for the test specimens.

4.3 The thermal transmission properties of specimens of a given material or product may vary due to variability of the composition of the material; be affected by moisture or other conditions; change with time; change with mean temperature and temperature difference; and depend upon the prior thermal history. It must be recognized, therefore, that the selection of typical values of thermal transmission properties representative of a material in a particular application should be based on a consideration of these factors and will not apply necessarily without modification to all service conditions.

4.3.1 As an example, this test method provides that the thermal properties shall be obtained on specimens that do not contain any free moisture although in service such conditions may not be realized. Even more basic is the dependence of the thermal properties on variables, such as mean temperature and temperature difference. These dependencies should be measured or the test made at conditions typical of use.

4.4 Special care shall be taken in the measurement procedure for specimens exhibiting appreciable inhomogeneities, anisotropies, rigidity, or especially high or low resistance to heat flow (see Practice C1045). The use of a heat flow meter apparatus when there are thermal bridges present in the specimen may yield very unreliable results. If the thermal bridge is present and parallel to the heat flow the results obtained may well have no meaning. Special considerations also are necessary when the measurements are conducted at either high or low temperatures, in ambient pressures above or below atmospheric pressure, or in special ambient gases that are inert or hazardous.

4.5 The determination of the accuracy of the method for any given test is a function of the apparatus design, of the related instrumentation, and of the type of specimens under test (see Section 10), but this test method is capable of determining thermal transmission properties within ± 2 % of those determined by Test Method C177 when the ambient temperature is near the mean temperature of the test (T (ambient) = T (mean) ± 1°C), and in the range of 10 to 40°C. In all cases the accuracy of the heat flow meter apparatus can never be better than the accuracy of the primary standards used to calibrate the apparatus.

4.5.1 When this test method is to be used for certification testing of products, the apparatus shall have the capabilities required in A1.7 and one of the following procedures shall be followed:

4.5.1.1 The apparatus shall have its calibration checked within 24 h before or after a certification test using either secondary transfer standards traceable to, or calibration standards whose values have been established by, a recognized national standards laboratory not more than five years prior to the certification date. The average of two calibrations shall be used as the calibration factor and the specimen(s) certified with this average value. When the change in calibration factor is greater than 1 %, the standard specimen shall be retested and a new average calculated. If the change in calibration factor is still greater than 1 % the apparatus shall be calibrated using the procedure in Section 6.

4.5.1.2 Where both the short and long term stability of the apparatus have been proven to be better than 1 % of the reading (see Section 10), the apparatus may be calibrated at less frequent intervals, not exceeding 30 days. The specimens so tested cannot be certified until after the calibration test following the test and then only if the change in calibration factor from the previous calibration test is less than 1 %. When the change in calibration is greater than 1 %, test results from this interval shall be considered void and the tests repeated in accordance with 4.5.1.1.

4.5.2 The precision (repeatability) of measurements made by the heat flow meter apparatus calibrated as in Section 6.6 normally are much better than ±1 % of the mean value. This precision is required to identify changes in calibration and is desirable in quality control applications.

5. Apparatus

5.1 The construction guidelines given in this section should be understood by the user of this test method. While it is mandatory that these details be followed carefully when constructing an apparatus, it behooves the user to verify that the equipment is built as specified. Serious errors of measurement may result from this oversight.

5.2 *General:*

5.2.1 The general features of a heat flow meter apparatus with the specimen or the specimens installed are described in Section 6 and shown in Figs. 1-3. A heat flow meter apparatus consists of two isothermal plate assemblies, one or more heat flux transducers and equipment to control the environmental conditions when needed. Each configuration will yield equivalent results if used within the limitations stated in this test method. There are distinct advantages for each configuration in practice and these are discussed in Appendix X2.

NOTE 2—Further information can be found in ISO 8301:1991, which is the equivalent ISO standard for the Heat Flow Meter Apparatus.

5.2.2 Further design considerations such as plate surface treatment, flatness and parallelism, temperature requirements and measuring system requirements can be found in Annex A1.

6. Calibration

6.1 The calibration of a heat flow meter apparatus is a very critical operation. Since lateral heat losses or gains of heat are not controlled or eliminated automatically, but only lessened by increasing the size of the guard area and edge insulation, there is no guarantee that the heat losses or gains are negligible under all testing conditions. To ensure that the equipment is performing properly with specimens of different thermal resistances, the apparatus shall be calibrated with materials having similar thermal characteristics and thicknesses as the materials to be evaluated. The apparatus shall be calibrated with the specimen in the same orientation and the heat flux in the same direction under which the primary, CTS or SRM, or secondary transfer standards were characterized, if known. The material selected for the calibration standard shall have properties that are not affected by convection over the range of calibration parameters (temperature difference, thickness, density, and so forth) of interest. The apparatus shall be calibrated as a unit, with the heat flux transducer(s) installed in the apparatus.

6.2 This procedure applies to the calibration of a heat flow meter apparatus over a wide range of heat flow rates and temperatures, which permits the testing of a wide variety of insulation materials over an extended temperature range.

6.3 The following calibration procedure is used to compute the calibration factor, *S* for a heat flow meter apparatus, and must be used by anyone who desires to produce meaningful heat flux measurements from a heat flow apparatus.

6.4 *Calibration Standards:*

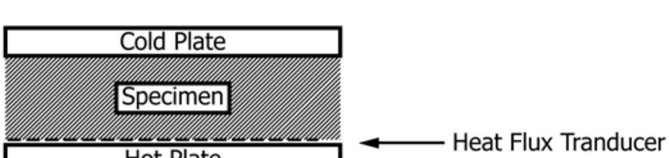

FIG. 1 Apparatus with One Heat Flux Transducer and One Specimen

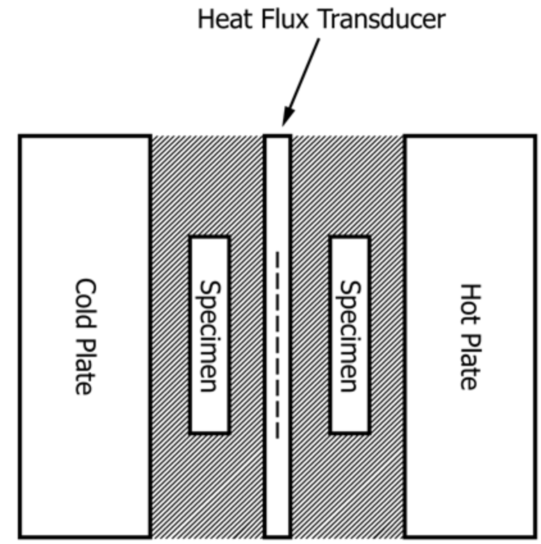

FIG. 2 Apparatus with One Heat Flux Transducer and Two Specimens

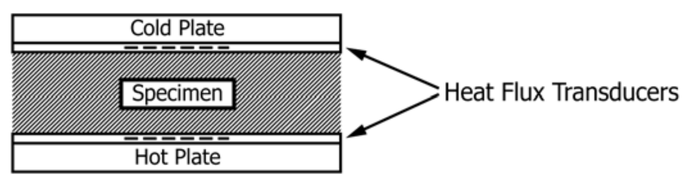

FIG. 3 Apparatus with Two Heat Flux Transducers and One Specimen

6.4.1 Calibration standards may be good for many years if handled carefully but shall be checked periodically to confirm lack of change.

6.4.2 It is recommended that the primary standards obtained from a national standards laboratory should not be used on a daily basis, but secondary or working standards should be produced. Create a record on the secondary standards with the following information.

6.4.2.1 Name of national laboratory to which it is traceable.

6.4.2.2 Date the secondary standard is produced.

6.4.2.3 Date the secondary standard is last tested.

6.4.2.4 Direction of heat flux during calibration.

6.4.2.5 Thermal value of the secondary standard.

6.4.2.6 Range of parameters for which it is valid.

6.4.2.7 Estimate of bias of the primary and secondary standards.

6.5 *Calibration Procedure:*

6.5.1 Calibrate the heat flow meter apparatus under the same conditions of plate temperatures, temperature gradient, specimen thickness, heat flow direction, and apparatus orientation as those for which data are available for the standard.

6.5.2 *Single Temperature Point*—If the calibration standard is tested at a single mean temperature, conduct the calibration and subsequent tests near the same mean temperature. Use engineering judgment or an error analysis to determine how closely the mean temperature must be maintained. As assessment of the sensitivity of the calibration standard to test conditions should be determined by the user of the transfer standard to determine its limitations of use.

6.5.3 *Multiple Temperature Points*—If the calibration standard is tested at three or more mean temperatures, calibrate the heat flow meter apparatus at the same temperatures using the same temperature gradients (**8**). A smooth curve can be fitted to the points such that a calibration factor can be interpolated for any given mean temperature. It is not permissible to extrapolate above or below the mean temperature range of the calibration standard measurements. Changing the plate temperature of a heat flow meter apparatus has the potential of changing apparatus calibration. When changing plate temperatures, take steps to determine if the heat flux transducer calibration factor has changed.

6.5.4 *Single Thickness Point*—If the original calibration standard is tested at only one thickness, the heat flow meter apparatus can be calibrated for that thickness without an exhaustive thickness study. If tests are to be conducted at thicknesses other than the calibrated thickness, make a thorough study of the error of the heat flow meter apparatus at other thicknesses. Several references on this subject are listed at the end of this test method (**4, 7, 8-12, 13, 14**).

6.5.5 *Multiple Thickness Points*—If the original standard is tested at three or more thicknesses, the heat flow meter apparatus can be calibrated over the same thickness range. A smooth curve can be fitted to the points such that a calibration factor can be interpolated for any given thickness. If tests are to be conducted at thicknesses above or below the calibrated thicknesses, make a thorough study of the error of the heat flow meter apparatus at these thicknesses.

6.6 *Calibration of Various Designs:*

6.6.1 There are several configurations of heat flow meter apparatuses that use one or two heat flux transducers and one or two specimens in the apparatus. While it is not practical to list all of the possible combinations of apparatus and specimen configurations, this section contains the equations for calculating the calibration factor of three common apparatuses. The calibration and testing configuration should be identical. The calibration factor of a heat flow meter apparatus is determined by running the same standard specimens a number of times, not consecutively, but over a period of time with the standard removed each time.

6.6.2 *One Calibration Standard*—Apparatus with one heat flux transducer and one standard (see Fig. 1).

$$S = C \cdot (Th - Tc)/E \tag{1}$$

6.6.3 *Two Calibration Standards*—Apparatus with one heat flux transducer and one specimen configuration (same as that for 6.6.2).

6.6.3.1 The two calibration standards need to be the same thickness and of similar material but need not be identical. With the following equation, it is not necessary to know the thermal conductance of each calibration standard, but it is necessary to know the average thermal conductance of the two standards:

$$S = \frac{C_a + C_b}{\left(\frac{E_a}{(T_{ha} - T_{ca})} + \frac{E_b}{(T_{hb} - T_{cb})} \right)} \tag{2}$$

6.6.3.2 *Two Calibration Standards*—Apparatus with one heat flux transducer and two specimens (see Fig. 2).

6.6.3.3 Again, the standards need to be the same thickness and of similar material but not necessarily identical.

$$S = \frac{C_a + C_b}{E \cdot \left(\frac{1}{(T_{ha} - T_{ca})} + \frac{1}{(T_{hb} - T_{cb})} \right)} \tag{3}$$

6.6.4 *One Calibration Standard*—Apparatus with two heat flux transducers and one specimen (see Fig. 3).

6.6.4.1 Assuming the two transducers physically are identical and have similar outputs, one can sum the outputs of the two transducers and then calibrate as a single transducer apparatus. In this case, it is very important to keep the mean temperature and the plate temperatures equal to those used in testing the standard. It is essential that each of the transducers be at steady state.

$$S = \frac{C \cdot (Th - Tc)}{(E1 + E2)} \tag{4}$$

6.6.4.2 In the case where multiple transducers are used, a similar calculation can be utilized to calculate the calibration factor.

6.6.4.3 As an alternative, each heat flux transducer can be calibrated as an independent apparatus as in 6.6.1.

7. Test Procedures

7.1 *Foreword on Testing Procedures*—The relative simplicity of this test method may lead one to overlook very important factors, which may affect the results. To ensure accurate measurement, the operator shall be instructed fully in the operation of the equipment. Furthermore, the equipment shall be calibrated properly with reference materials having similar heat transfer characteristics. Also it is necessary that the specimen be prepared properly for evaluation.

7.2 *Sampling and Preparation of Specimens:*

7.2.1 *Test Specimens*—One- or two-piece specimens may be used, depending on the configuration selected for the test. Where two pieces are used, they shall be selected from the same material to be essentially identical in construction, thickness, and density. For loose fill materials, the method specified in the material specification or in Practice C687 shall be used to produce a specimen or specimens of the desired density.

7.2.2 *Selection of Specimens*—The specimen or specimens shall be of such size as to cover the plate assembly surfaces and shall either be of the actual thickness to be applied in use or of sufficient thickness to give a true average representation of the material to be tested. If sufficient material is not available, the specimen shall at least cover the metering area, and the rest of the plate surfaces must be covered with a mask with a thermal conductivity as close to that of the specimen as possible.

7.3 *Specimen Conditioning*—Details of the specimen selection and conditioning preferably are given in the material specification. Where such specifications are not given, the specimen preparation shall be conducted in accordance with the requirement that materials shall not be exposed to temperatures that will change the specimens in an irreversible manner.

Typically, the material specifications call for specimen conditioning at 22°C and 50 % R.H. for a period of time until less than a 1 % mass change is observed over a 24-h period. For some materials, such as cellulose, considerably longer times may be required for both conditioning and testing.

7.4 *Specimen Preparation:*

7.4.1 Use the following guidelines when the material specification is unavailable. In general, the surfaces of the specimen should be prepared to ensure that they are parallel with and have uniform thermal contact with the hot and cold plates.

7.4.2 *Compressible Specimens*—The surfaces of the uncompressed specimens may be comparatively uneven so long as surface undulations are removed under test compression. It may be necessary to smooth the specimen surfaces to achieve better plate-to-specimen contact. If the apparent thermal conductivity of the contact void is greater than that of the specimen, compressible or otherwise, the measured heat flux will be greater than the heat flux that would be obtained if the voids were absent. This may often be the case at higher temperatures where radiant heat transfer predominates in the void. For the measurement of compressible specimens, the temperature sensors are often mounted directly in the plate surfaces. Also, plate spacers may be required for the measurement of compressible specimens.

7.4.3 *Rigid and High Conductance Specimens*—The measurement of rigid specimens or high conductance specimens requires careful surface preparation. First, the surfaces should be made flat and parallel to the same degree as the heat-flow-meter. If the specimen has a thermal resistance that is sufficiently high compared to the specimen-to-plate interface resistance, temperature sensors mounted in the plates may be adequate.

7.5 *Measurements on Specimens:*

7.5.1 *Blanket and Batt-Type Materials*—When specified, the test thickness of blankets and batt-type materials shall be determined before testing in accordance with Test Methods C167, provided that good contact is maintained between the specimen and the isothermal plates. Also, it is recommended highly that the thickness during the actual test be measured. At the conclusion of the test, the density in the metering area should be determined.

7.5.2 *Loose-fill Materials*—These materials generally are tested in open test frames as spelled out in Practice C687. The requirement to measure the density in the metering area is again critical.

7.6 *Limitations on Specimen Thickness:*

7.6.1 *General*—The combined thickness of the specimen or specimens, the heat flux transducer and any damping material, which in total equals the distance between the cold and hot plates, must be restricted in order to limit the effect of edge losses on the measurements. In addition edge losses are affected by the edge insulation and the ambient temperature, so the requirements on both of these parameters must be met.

7.6.2 *Maximum Spacing Between Hot and Cold Plates*—The maximum allowable distance between the hot and cold plates during a test, is related to the dimensions of the heat flux transducer, the metering area, the size of the plate assembly, the construction of the heat meter apparatus, and the properties of the specimen. No suitable theoretical analysis is available to predict the maximum allowable thickness of specimens. It is possible to use the results of an analysis for a similarly sized guarded hot plate as a guide (**15, 16-17**).

7.7 *Procedure of Measurement:*

7.7.1 *Temperature Difference*—For any test, make the temperature difference across the specimen not less than 10 K. For specimens that are expected to have a large thermal resistance, a larger temperature difference in the specimen is recommended (see Practice C1058 for the selection of the plate temperatures). The actual temperature difference or gradient is best specified in the material specifications or by agreement of the parties concerned.

7.7.2 *Edge Insulation*—Enclose the edges of the specimens with thermal insulation to reduce edge heat losses to an acceptable level if this edge insulation is not built into the apparatus (see A1.6).

7.7.3 *Settling Time and Measurement Interval*—Verify the existence of thermal equilibrium by observing and recording, the emf output of the heat flux transducer, the mean temperature of the specimens, the temperature drop across the specimen, and a calculated λ value. Make observations at time intervals of at least 10 min until five successive observations yield values of thermal conductivity, which fall within ½ % of the mean value for these five readings. If the five readings show a monotonically increasing or decreasing trend, equilibrium has not been attained. In this case, additional sets of readings shall be taken. If experience has shown that a shorter time interval may be used, follow the same criteria for stability. For high density specimens ($\rho > 40$ kg/m^3) or for low conductance specimens ($C < 0.05$ $W/K{\cdot}m^2$) the time between readings may have to be increased to 30 min or longer (**18**).

8. Calculation

8.1 *Density and Change in Mass*—When required, calculate the density of the dry specimen as tested, ρ, the mass change due to conditioning of the material, and the mass change of the specimen during test.

8.1.1 *Density of Batt and Blanket Specimens*—It has been found that it is important to measure the mass of the specimens in contact with the metering area. The area of the specimen directly measured shall be cut out and its mass determined after testing, unless the specimen must be retained for further testing.

8.2 *Thermal Properties for One Specimen*—When only one specimen is used, calculate the thermal conductance of the specimen as follows:

$$C = S \cdot E/\Delta T \tag{5}$$

and where applicable, calculate the thermal conductivity, as follows:

$$\lambda = S \cdot E \cdot (L/\Delta T) \tag{6}$$

8.3 *Thermal Properties for Two Specimens*—When two specimens are used, calculate the total thermal conductance, C, as follows:

$$C = S \cdot E/(\Delta T_a + \Delta T_b) \tag{7}$$

The λ factor, that is, the average thermal conductivity of the specimen is calculated as follows:

$$\lambda_{ave} = (S \cdot E/2) \cdot (L_a + L_b)/(\Delta T_a + \Delta T_b) \tag{8}$$

where the subscripts refer to the two specimens.

8.4 Other derived thermal properties may be calculated but only under the provisions given in Practice C1045.

8.5 *Thermal Properties for Two Transducers*—All pertinent equations of 8.2 and 8.3 apply to this configuration, provided $S \cdot E$ will be replaced by $(S' \cdot E' + S'' \cdot E'')/2$, where the superscripts ' and " refer to the first and second heat flux transducer, respectively.

9. Report

9.1 The report of the results of each test shall include the following information with all data to be reported in both SI and inch-pound units unless specified otherwise.

9.1.1 The report shall be identified with a unique numbering system to allow traceability back to the individual measurements taken during the test performed.

9.1.2 Name and any other pertinent identification of the material including a physical description.

9.1.3 Description of the specimen and its relationship to the sample, including a brief history of the specimen, if known.

9.1.4 Thickness of the specimen as received and as tested.

9.1.5 Method and environment used for conditioning, if used.

9.1.6 Density of the conditioned specimen as tested, kg/m^3.

9.1.7 Mass loss of the specimen during conditioning and testing, in percentage of conditioned mass, if measured.

9.1.8 Mass regain of the specimen during test, in percentage of conditioned mass, if measured.

9.1.9 Average temperature gradient in the specimen during test as computed from the temperatures of the hot and cold surfaces, *K/m*.

9.1.10 Mean temperature of the test, *K* or °C.

9.1.11 Heat flux amount and direction through the specimen, W/m^2.

9.1.12 Thermal conductance, $W/m^2 \cdot K$.

9.1.13 Duration of the measurement portion of the test, min or h.

9.1.14 For loose-fill materials, report the specimen preparation followed.

9.1.15 Date of test, the date of the last heat meter calibration, and the type or types of materials used.

9.1.16 Estimated or calculated uncertainty in reported values. It is optional as to which of the error analysis methods given in Annex A2 is used by the laboratory.

9.1.17 Orientation and position of the heat meter apparatus during test (vertical, horizontal, etc.), and whether the meter was against the hot or cold surface of the specimen and whether the edges of the specimen(s) were sealed or open to the ambient.

9.1.18 For direct reading apparatus, the results of the calibration of electronic circuitry and equipment or a statement of compliance including date, and a statement of compliance on linearity requirements.

9.2 In many cases a laboratory is requested to provide only the thermal conductivity at a specified mean temperature and a few pertinent physical properties, such as density, and test thickness. An abridged test report shall state "Abridged ASTM C518 Test Report" and shall include the thermal transmission property of interest, mean temperature, test thickness, and bulk density. It is mandated that an uncertainty statement shall be transmitted with the thermal transmission property. Compliance to Test Method C518 requires that the other test parameters specified in 9.1.1 – 9.4 to be recorded in the laboratory records.

9.3 For certification testing only, the specimens used in calibration shall be identified as to the type, thermal resistance, date of specimen certification, source of certification, expiration date of calibration, and the certification test number. Where applicable include a statement of the laboratory accreditation of the test facility, including the date of the latest inspection.

9.4 Statement of compliance, or where circumstances or requirements preclude complete compliance with the procedures of the test, agreed exceptions. A suggested wording is "This test conformed with all requirements of ASTM C518– with the exception of (a complete list of exceptions follows)."

10. Precision and Bias

10.1 This section on precision and bias for heat flow meter apparatus includes a discussion of; general statistical terms; statistical control; factors affecting test results; ruggedness tests; interlaboratory comparisons conducted by ASTM Committee C16; proficiency testing conducted under the auspices of the National Voluntary Laboratory Accreditation Program (NVLAP); and error propagation formulae.

10.2 The accuracy of a test result refers to the closeness of agreement between the observed value and an accepted reference value. When applied to a set of observed values, the accuracy includes a random component (imprecision) and a systematic component (bias). The variability associated with the set of observed values is an indication of the uncertainty of the test result. Additional information on statistical terminology is available in Terminology .

10.3 The user of the heat-flow-meter apparatus shall demonstrate that the apparatus is capable of performing in a consistent manner over time (**19, 20**). The use of control charts (see Manual 7 (**21**)) to monitor the operation of the heat-flow-meter is one recommended way to monitor the control stability of the apparatus. When possible, it is recommended that a reference material traceable to a national standards laboratory be used as the control specimen. Ideally, the long-term variation should be no greater than the short-term variability.

10.4 A series of three round robins was conducted between 1976 and 1983, as reported by Hust and Pelanne (**22**), and employed low density fiberglass specimens from 2.54 to 10.2 cm. thick with densities ranging from 10 to 33 kg/m^2. A total of twelve laboratories were involved in these studies. The interlaboratory imprecision, at the two standard deviation level

TABLE 1 Summary of Precision Statistics for Thermal Resistivity Reproducibility

Material	Average^A (m K / W) $\bar{x}$	Reproducibility Standard Deviation^A (m K / W) S_R	Reproducibility Limit^B (m K / W) R
A (n=13)	29.76	0.31	0.88 2.94 %
B (n=13)	30.02	0.27	0.75 2.50 %

^A Calculated from all reporting laboratories (n=13 for materials A & B).
^B 95 % reproducibility limit is 2.8 times the reproducibility standard deviation (between laboratory).

TABLE 2 Summary of Precision Statistics for Thermal Resistivity Repeatability

Material	Average^A (m K / W) $\bar{x}$	Repeatability Standard Deviation^A (m K / W) S_r	Repeatability Limit^B (m K / W) r
A (n=10)	29.73	0.18	0.50 1.68 %
B (n=8)	29.99	0.15	0.41 1.37 %

^A Calculated from all reporting laboratories (n=10 for material A, n=8 for material B).
^B 95 % repeatability limit is 2.8 times the repeatability standard deviation (within laboratory).

when analyzed using Practice E691, was found to vary from 1.92 to 3.54 % between 2.54 and 10.2 cm.

10.5 A round robin conducted in 1987, as reported by Adams and Hust, included eleven participating laboratories testing a fiberglass blanket and several types of loose-fill insulations (**23**). The blanket insulation had an interlaboratory imprecision of 3.7 % at the two standard deviation level. The loose-fill interlaboratory imprecision was found to be > 10 % for different materials at the two standard deviation level. It has been suggested that the principal cause for the significant differences observed is the various specimen preparation techniques used by the various laboratories.

10.6 A round robin conducted in 1990, as reported by McCaa and Smith, et. al., included ten participating laboratories testing a fiberglass blanket and several type of loose-fill insulation (**24**). The blanket insulation had an interlaboratory imprecision of 2.8 % at the two standard deviation level. The loose-fill interlaboratory imprecision was found to be 5.0 % for perlite, 5.8 % for cellulose, 9.4 % for unbonded fiberglass, and 10.5 % for mineral wool at the two standard deviation level. This represented a significant improvement over the 1987 results and is attributed to a more concise specimen preparation procedure in Practice C687.

10.7 An Interlaboratory "Pilot Run" of Small Heat-Flow-Meter Apparatus for ASTM C518 was reported in 1999 (**25**). A precision statement was prepared in accordance with Practice E691. The precision statement is provisional because an insufficient number of materials were involved. Within 5 years additional data will be obtained and processed that meet the requirements of Practice E691. A bias statement was prepared following Test Method C177. Bias as compared to results from the Test Method C177 apparatus was found to be statistically insignificant at the $\alpha = 5$ % level (95 % confidence interval) for the materials studied.

10.8 *Proficiency Tests*—Interlaboratory testing carried out between nine laboratories under the National Voluntary Laboratory Accreditation Program currently is showing an interlaboratory imprecision of 2.12 % at the two standard deviation level based on testing of similar but not identical specimens (**26, 27**).

10.9 An interlaboratory study[6] was performed in 2002-2004. A total of thirteen laboratories participated in the study, testing two specimens for both thickness and thermal resistivity. Two 25 mm thick expanded polystyrene (EPS) foam board specimen (A and B) of similar thickness and thermal performance were used for this study. Each test result was to be repeated for a total of two determinations. The precision and bias statements were determined through statistical examination of two individual results, from the participating laboratories, on two samples. The results are shown in Table 1 and Table 2.

11. Keywords

11.1 calibration; error analysis; heat flow meter apparatus, thermal resistance; heat flux; instrument verification; thermal conductivity; thermal testing

[6] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:C16-1047. Contact ASTM Customer Service at service@astm.org.

ANNEXES

(Mandatory Information)

A1. EQUIPMENT DESIGN

A1.1 The exposed surfaces of the plates and the heat flux transducer, that is, the surfaces making contact with the specimens, shall be painted or otherwise treated to have a total hemispherical emittance of greater than 0.8 at their operating temperatures (see Note A1.1).

NOTE A1.1—Hard anodizing of aluminum produces a surface with a total hemispherical emittance of approximately 0.85. Several paints are available, which when applied as directed, produce a total hemispherical emittance of approximately 0.86.

A1.2 *Plate Assemblies, Hot and Cold*—The two plate assemblies should provide isothermal surfaces in contact with either side of the test specimen. The assemblies consist of heat source or sink, a high conductivity surface, means to measure surface temperature, and means of support. A heat flux transducer may be attached to one, both, or neither plate assembly, depending upon the design, (see Section 6). In all cases, the area defined by the sensor of the heat flux transducer is called the metering area and the remainder of the plate is the guard area.

A1.2.1 A means shall be provided to maintain the temperature of the plate assemblies at the desired level. Examples are fluid baths, electrical heaters, or thermoelectric coolers, or a combination thereof **(28-30)**.

A1.2.2 If a heat flux transducer is located at the midplane of the specimens (see Fig. 2), then means shall be provided to determine the average temperature of the transducer in order to apply temperature corrections to the calibration, except when the test temperatures are equal to those used in calibration, in which case no correction is required. If a matched pair of specimens is tested, the temperature of the transducer can be computed from the temperatures of the plate assemblies.

A1.2.3 The plate assemblies shall be sufficiently rigid to maintain flatness and parallelism. For an apparatus designed to be used over wide ranges of conductivity and thickness (thermal resistances) the flatness and parallelism of the plates should be 0.02 % of the maximum linear dimensions of the plates (see Note A1.2). One way to check this is to use standard gauge blocks to generate a map over the metering area **(15)**.

NOTE A1.2—The planeness of the surface can be checked with a straightedge, of a length greater than the width or diameter of the unit, held against the surface and viewed with a light behind the straightedge. Departures as small as 25 mm are readily visible, and larger departures can be measured using shimstock or thin paper.

A1.2.3.1 It is important to maintain the parallelism of the plates for several reasons. In most cases it is the plate separation, which is measured in order to determine specimen thickness. Furthermore, the plate parallelism is important in maintaining consistent surface contact with specimens in repeat testing, such as calibration, and is required to maintain a uniform temperature difference across the specimen(s). If the plate temperatures are cycled continuously during testing, the flatness needs to be checked periodically.

A1.2.4 Plate flatness may become critical when measuring specimens with less thermal resistance than the calibration standards, irrespective of the thickness or rigidity of the calibration standard. For rigid thin specimens the criteria given in A1.2.3 may not be sufficient.

A1.2.5 The rigidity, flatness, and parallelism of the plates may impede the testing of rigid specimens where it is not possible to obtain good surface contact. In such cases, the use of a thin sheet of suitable homogeneous material may be interposed between the specimen and the plates surfaces. This thin sheet should have a low thermal resistance relative to the specimen. The resistance of the thin sheet should be determined using a Test Method C177 apparatus. The resistance of the composite sandwich (sheet-rigid specimen-sheet) then is determined and the value of the sheet resistance subtracted from the total resistance. Caution should be exercised when using such a practice as it is prone to adding more uncertainty to this method.

A1.3 *Temperature Measuring and Control Systems*:

A1.3.1 The surfaces of the plate assemblies in contact with the specimen(s) shall be instrumented with precision temperature sensors such as thermocouples, platinum resistance thermometers (RTD), and thermistors. Temperature sensors shall be mounted in grooves so as to be flush with the surface in contact with the specimen(s).

A1.3.2 No strict specification is given as the number of temperature sensors that shall be used for each surface; however, the user shall report the uncertainty of the temperature measurement, including the component due to temperature nonuniformity across the surface. In some cases where temperature mapping of the plate surfaces has indicated high uniformity under all conditions of use, one thermal sensor per surface has been used satisfactorily.

A1.3.2.1 Special precautions should be taken to ensure that the temperature sensors are anchored thermally to the surface to be measured and that the temperature gradients along the wires leading to the sensors are minimized. If thermocouples on opposing surfaces are connected differentially, they shall be electrically insulated from the plates with a resistance of 1 megaohm or greater **(5, 6)**.

A1.3.2.2 Thermocouples mounted in the surfaces of the plates or set into the surfaces of specimens should be made of wire no longer than 0.25 mm in diameter (No. 30 B and S gage). For highest accuracy only "special limit" thermocouples should be used. In addition, even these "special limit" thermocouples should be checked for nonhomogeneities in the wire. For information concerning voltage output and accuracy of thermocouples in the cryogenic temperature range, and installation, see Refs **(28, 29)**.

A1.3.2.3 Temperature sensors should be calibrated to an accuracy equivalent to that for thermocouples conforming to

Tables E230/E230M. The precision of the temperature measuring system may need to be better than this to detect the effect of drift on the results discussed in Appendix X3. The accuracy required by a heat flow meter apparatus can best be determined by carrying out an error analysis (see Annex A2), and then calibrating the temperature sensors to the degree required.

A1.3.2.4 In the special case where the heat flow meter apparatus is used only for repetitive tests on one material and the same plate temperatures are used for calibration, (and where the standards are tested at the same temperatures) the accuracy of the calibration of the temperature sensors will not be as critical since any errors will remain constant and be included in the calibration.

A1.4 *Heat Flux Transducer*:

A1.4.1 *Types of Heat Flux Transducer*—The types of heat flux transducers are described in Practice C1046. The gradient type, often used in the heat flow meter apparatus, consists of a slab of material, the "core," across which the temperature gradient is measured, normally with a thermopile. The main transducer surfaces are assumed to be isothermal, so the heat flow will be normal to them. Precautions shall be taken to limit the effect of heat flow through the leads on the output of the thermopile. Often the heat flux transducer also is instrumented to measure one of the surface temperatures of the specimen(s).

A1.4.2 *Surface Sheets*—Both surfaces of the transducer should be covered with a layer of material as thin as is compatible with protection from thermal shunting of the thermopile. The exposed surfaces of the heat flux transducer shall be finished smoothly to conform to the desired geometric shape to within the limits of A1.2.4.

A1.5 *Plate Separation, Specimen Thickness*—A means shall be provided to determine the average separation between the heating and cooling plate surfaces during operation. Rigid specimens generally act as the spacers themselves, and plate separation is determined by their thickness at operating temperature. In this case, a small constant force generally is applied to hold the plates against the specimen. It is unlikely that a pressure greater than 2.5 kPa will be required. For easily compressible specimens, small stops interposed between the corners of the hot and cold plates, or some other positive means shall be used to limit the compression of the specimens (see Note A1.3). Provision shall be made for checking the linearity of any thickness measuring system.

NOTE A1.3—Because of the changes of specimen thickness possible as a result of temperature or compression by the plates, it is recommended that specimen thickness be measured in the apparatus, at the existing test temperature and compression conditions whenever possible.

A1.6 *Edge Insulation*—Heat loss from the outer edges of the heat flow meter apparatus and specimens shall be restricted by edge insulation or by governing the surrounding air temperature or by both methods. The three different configurations differ in their susceptibility to edge heat losses as is discussed in Appendix X2 (**2**, **4**, **30**, **15**).

A1.6.1 For all three configurations, the susceptibility to edge heat losses is related strongly to the sensitivity of the transducer to temperature differences along its main surfaces, and therefore, only experimental checks while changing environmental conditions can confirm, for each operating condition, the magnitude of the effect of edge heat losses on measured heat flux. This error should be smaller than 0.5 %.

A1.7 *Measuring System Requirements*—The apparatus measuring system shall have the following capabilities:

A1.7.1 The uncertainty of the measurement of the temperature difference across the specimens shall be within ± 0.5 % of the actual temperature difference.

A1.7.2 A voltage accuracy of better than 0.2 % of the minimum output (from the transducer) to be measured.

A1.7.3 Sufficient linearity so that the system contributes less than 0.2 % error at all outputs.

A1.7.4 Sufficient input impedance so that the system contributes less than 0.1 % error for all readings.

A1.7.5 Sufficient stability so that the system contributes less than 0.2 % error during the period between calibrations, or 30 days, whichever is greater.

A1.7.6 Adequate noise immunity so that less than 0.2 % rms noise occurs in the readings.

A1.8 *Proven Performance*—The test results obtained by this test method only can be assured if the limitations of the apparatus are known. See Appendix X3 for further details. To establish these limitations, one must prove the performance by comparing the results with materials of similar thermal properties previously tested on a guarded hot plate apparatus as those to be evaluated.

A1.8.1 A single point of reference may lead to serious errors. Select a range of transfer standards having known thermal transmission properties, which cover the range of values to be tested, in both resistance and thickness. If a range of standards is not available running tests on a single standard at different ΔT's will provide verification of linearity. On equipment with fixed plate temperatures provision shall be made for calibration of electronic circuitry independent of the remainder of the apparatus.

A1.8.2 If the apparatus is to be used at thicknesses greater than that of the available reference materials, a series of calibration measurements shall be performed to insure that the equipment does not introduce additional errors, which may be due to lateral heat losses or gains brought about by insufficient guarding (**4**, **15**). One means of checking for these errors is to use multiple thicknesses of the calibration standards. If these are stacked with a radiation blocking septum between each of the standards, the first approximation is that the total thermal resistance is the sum of the individual thermal resistances.

A1.9 *Environmental Control*—In many applications, it is desirable to control the environment surrounding the test specimen to reduce edge heat losses, and it is especially important when the mean test temperature is below the ambient temperature, in order to avoid condensation on the cold plate. A cabinet or enclosure surrounding the isothermal plates and the specimens to maintain the ambient temperature at the mean temperature of the specimen also may be used as a means to maintain the dew point temperature at least 5 K lower than the temperature on the cold plates, in order to prevent condensation and moisture pickup by the specimen. Any environmental control system employed in conjunction with a heat flow meter apparatus shall be capable of maintaining its set point condition within ± 1°C in temperature.

A2. EQUIPMENT ERROR ANALYSIS

A2.1 A complete error analysis is complex; however, some form of error analysis is mandated for compliance with this test method. Such an error analysis is useful for estimating which parameters may contribute to the overall uncertainty in the measurements. It is the option of the manufacturer or user of the apparatus to follow the guidelines given in A2.9 or A2.10 to determine the uncertainties. It is mandated, however, that any result shall be accompanied with its uncertainty.

A2.2 For any one given apparatus, a careful error analysis as outlined here, in most cases, will show up any major difficulties, which may need correcting in order to improve the measurement accuracy of the heat flow meter apparatus. The performance of this analysis involves consideration of the following points.

A2.3 Estimates of errors in each individual measurement procedure and propagation of these errors to the final result.

A2.4 Measurements to determine apparatus variability to intentional deviations from normal operations.

A2.5 Measurements on reference materials and participation in round-robin programs.

A2.6 For a more complete discussion of error analysis the reader is directed to the ISO "Guide to the Expression of Uncertainty in Measurements" (**31**).

A2.7 *Calibration Errors*:

A2.7.1 Heat flux transducer calibration is temperature dependent and must be considered if the transducer temperature is changed.

A2.7.2 Specimen temperature gradient may affect the calibration factor.

A2.7.3 Heat flow meter apparatus calibration may be dependent on heat flux.

A2.7.4 Temperature sensor inaccuracy may result in the standard being tested at inappropriate temperature conditions.

A2.7.5 Hot and cold plate surface emittance shall be similar to the primary apparatus on which the standard was measured.

A2.7.6 Heat loss from specimen edges may be significant under some conditions. Factors to be considered when evaluating edge losses are thickness of specimen, conductivity of specimen, width of guard, amount of external insulation, and edge ambient temperature.

A2.7.7 Plate separation and parallelism inaccuracies can produce errors.

A2.7.8 Check the voltage output of the heat flux transducer to be sure that when the heat flux is zero there is no voltage output by the heat flux transducer. If there is a voltage output with no temperature gradient, analyze the problem and make corrections before proceeding with testing. The state of zero heat flux is usually accomplished by leaving the apparatus completely turned off in a constant temperature room for a sufficient length of time such that the entire apparatus is at the same temperature.

A2.7.9 Some heat flux transducers may be pressure sensitive.

A2.7.10 Decisions on outlying calibration points should have statistical basis, including input from documents such as Practice E178.

A2.7.11 Lackey et al (**32**) studied the impact of material, thickness, mean temperature and temperature difference and on calibration. The study involved 91 individual measurements and 6 transfer standards. Testing was carried out over a period of six months. Specimen thickness varied between 26 to 158 mm, mean temperatures between 0 to 40°C, temperature differences between 10 and 40°K and two types of insulating material. Results showed that all these factors did not significantly influence the calibration procedure adopted for the apparatus used. The calibration method was also successfully applied to two other heat flow meter apparatus.

A2.8 *Error and Uncertainty Estimates*:

A2.8.1 The uncertainties in measurements on the heat flow meter apparatus can be divided into the three general categories of *(1)* uncertainty of the precision of the calibrating specimen, *(2)* uncertainty in the precision of the apparatus, and *(3)* uncertainty due to the fact that the calibrating specimen and test specimen are not identical.

A2.8.2 National standards laboratories generally express the expanded uncertainty of a measurement artifact (that is, calibration specimen) as defined by current international guidelines (**31, 33**). The user must evaluate their measurement uncertainty by proper inclusion of the uncertainty of the calibration specimen reported by the national standards laboratory.

A2.8.3 The repeatability of a heat flow meter apparatus can be determined by making independent replicate measurements on the same specimen by the same operator in the shortest practical time. Independent measurements require the removal, re-conditioning, and subsequent installation of the specimen.

NOTE A2.1—With the application of proper laboratory procedures, the user could realize a repeatability coefficient of variation (CV %) of 0.5 % or less. By conducting replicate measurements at regular time intervals, the user can demonstrate that the apparatus is capable of performing in a consistent manner over time. The use of control charts is recommended to monitor the control stability of the heat flow meter apparatus.

A2.8.4 The third category of uncertainties is much more difficult to evaluate. This involves the uncertainties due to errors associated with the calibration standard and unknown test specimen not having identical heat transfer properties. A list of potential uncertainties is given in 8.1. An example of this is a laboratory having standards at 25.4 mm, 76.2 mm, and 152.4 mm and running a test at 127 mm. While it is possible to reduce the uncertainty by following good laboratory procedures, there is always a small but real uncertainty.

A2.9 Interlaboratory comparison results can be found in Refs (**22**, **26**, **27**, **23**, **34**, **35**, **36**). In addition there was a workshop on measurement errors and methods of calibration of the Heat Flow Meter Apparatus held by ASTM C-16 at Williamsburg, VA, on April 10, 1994 (**9**, **10**, **19**, **32**, **37**).

A2.10 To illustrate a procedure of error analysis estimation, consider the operational definition of thermal conductivity:

$$\lambda = S \cdot E \cdot L / \Delta T \tag{A2.1}$$

The uncertainties in S, E, L, and ΔT (δS, δE, δL, and $\delta \Delta T$) can be used to form the uncertainty $\delta\lambda$ by the usual error propagation formula where the total uncertainty is calculated from the square root of the sums of the squares of the individual standard deviations.

$$(\delta\lambda/\lambda)^2 = (\delta S/S)^2 + (\delta E/E)^2 + (\delta L/L)^2 + (\delta\Delta T/\Delta° T)^2 \tag{A2.2}$$

This equation assumes that the errors in S, E, etc., are random and independent of each other since the covariance terms are omitted. This is valid here if different instrumentation is used for measurements on each of the variables (**31**). In order to use Eq 2, the operator must estimate the maximum uncertainty for each variable and examine the sources of error to determine which can occur randomly and which can occur simultaneously.

A2.10.1 Care shall be taken to evaluate properly all of the uncertainties in the variables S, E, L, etc. For example, obvious sources of error in E are those caused by extraneous transverse heat flow along leads and deviations from one dimensional heat flow; however, an often neglected but important heat leak is that caused by a temperature drift of the transducer itself. This can be estimated readily from the heat capacity of the transducer assembly and the drift detection limit of the measurement system. The error in ΔT, δT, can be caused by calibration errors and measurement errors, but also by incorrect placement, incorrect thermal anchoring, and disturbances introduced by the thermocouple itself.

A2.11 Experiments should be performed to determine the variability of the test results to deviations from normal operating conditions. This variability combined with the estimated control stability under normal operating conditions can be used to estimate the error from this source. As one example, the effect of an imperfect guard balance control can be determined by purposely offsetting the guard, if this is possible, by a sufficient ΔT in both directions and measuring the differences in the measured output.

A2.11.1 Care should be taken to not use such large offsets that nonlinear effects occur in the specimens. These results combined with the probable value of the offset during normal operation yield the error due to imperfect guard balance.

A2.12 The total estimated imprecision can be listed in a table of errors, such as shown in Table A2.1. This table is shown as an example only and does not represent any one particular heat flow meter apparatus since the errors will be specific to each apparatus.

TABLE A2.1 Estimation of Random and Systematic Errors at Room Temperature

Variable	Absolute Variations		Percent Variations	
	Random	Systematic	Random	Systematic
ΔT	0.01 K	0.02 K	0.04	0.40
L	0	0.1 mm	0	0.40
E	0	0.01 V	0	0.01
S	0	2 mW	0	0.2
Temperature				
drift	0.05 K	0.05K	0.01	0.01
calibration	0	0.1 K	0	0.4
Heat flow				
drift	1 mW/m^2	1 mW/m^2	0.2	0.2
lateral	1 mW/m^2	2 mW/m^2	0.2	0.2
λ	0.2 mW/m^2·K	0.3 mW/m^2·K	0.8	1.2

APPENDIXES

(Nonmandatory Information)

X1. (SEE FIGURES)

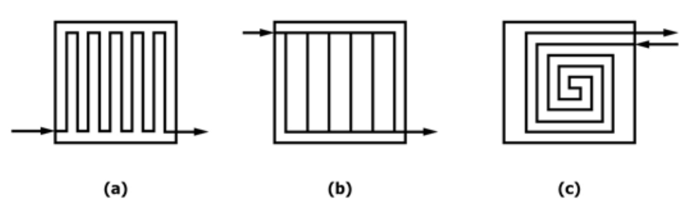

FIG. X1.1 Some Layouts of the Liquid Paths in Heating or Cooling Plates

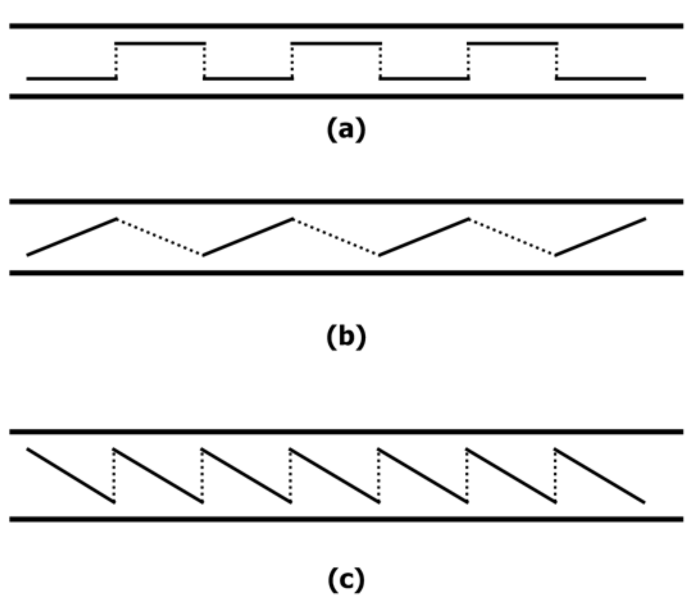

FIG. X1.2 Schematic Designs of Transducers

X2. RESPONSE OF HEAT FLUX TRANSDUCERS

X2.1 *Configurations* —The general features of a heat flow meter apparatus with the specimen or the specimens installed are shown in Section 6. A heat flow meter apparatus consists of two isothermal plate assemblies, one or more heat flux transducers, equipment to measure and control temperatures, thickness, and measure the output of the heat flux transducers and equipment to control the environmental conditions when needed. Each configuration will yield equivalent results if used within the limitations stated in this test method (**23**). For a particular heat flux transducer, the test configuration that has the fastest response, that is the shortest settling time, is best determined by experiment. Four specimens of different materials, such as an urethane foam, ceramic fiber board, a rubber, and a high conductivity, low-thermal capacity material, should be tested in each configuration. A study of these results will allow either the selections of the proper configuration for each type of material or the selection of a reasonable configuration for all types.

X2.1.1 In order to predict settling times for all types of specimens, each of the above specimens shall be retested after being conditioned to temperatures both below and above the mean temperature of the test.

X2.2 *Time Response of Heat Flux Transducers*:

X2.2.1 *High Thermal Resistance Transducer*—A transducer with a high thermal resistance generally is used when the transducer is attached to one or both of the isothermal plates. When the specimens are preconditioned to the mean temperature of the test and when the plates are capable of both heating and cooling the specimens, the time response of a high resistance transducer will be more rapid than a comparable guarded hot plate apparatus. If the heat flux transducer has appreciable mass, the response will not be rapid.

X2.2.1.1 When two transducers are used and attached to the isothermal plates, these can be used to obtain a very rapid response times if both plates are capable of heating and cooling and if the outputs of both transducers are summed (**24**).

X2.2.2 *Low Thermal Resistance Transducers*—The low-thermal resistance, gradient-type heat flux transducer is better suited to the configuration where the transducer is not attached to either plate. The temperature drop across the low-resistance transducer is small enough that the two specimens can be considered as halves of a single specimen. When the specimens are first conditioned to the mean temperature of the test and when the specimens are identical, the response is sufficiently rapid to be used for quality control work.

X2.2.2.1 Where half thicknesses of the normal specimen can be used, it can be more rapid than the single transducer configuration, especially when each of the specimens is first conditioned to the mean temperature at which it will be tested.

X2.3 *Sensitivity of Configurations to Edge Losses*:

X2.3.1 Heat loss from specimen edges may be significant under some conditions. Factors to be considered when evaluating edge losses are thickness of specimen, conductivity of specimens, width of the guard, amount of external insulation, and edge ambient temperature.

X2.3.2 The configuration with the transducer mounted on one isothermal plate is similar to the guarded hot plate apparatus regarding edge heat losses through the specimen. The edge heat losses in the transducer may be much more significant than those in the guarded hot plate apparatus because they may produce errors due to the temperature nonuniformity on the side of the transducer in contact with the specimen.

X2.3.3 The configuration with two transducers mounted on the isothermal plates is the most insensitive to edge conditions if the average of the readings of the two meters is assumed to be the measured heat flux per unit area through the specimen. If the plates are perfectly uniform in temperature, if the two transducers are exactly equal in the layout of the thermopile junctions, and if the specimen has thermal conductivity independent of temperature, this configuration is nearly insensitive to edge conditions. Even under these ideal conditions, however, the use of this configuration does not eliminate edge losses, but only reduces the apparatus susceptibility to variations in the boundary temperatures.

X2.3.4 The configuration with the transducer between the two specimens is very sensitive to edge heat losses on the heat flux transducer since the power that flows through the edges is supplied, not by a heavy isothermal metal plates, but by the specimens, so that their surface temperatures may not be uniform. If the transducer is sensitive to temperature differences along its main surfaces, edge heat losses may now create serious errors. Edge heat losses within the specimens are similar to those in the guarded hot plate when the surrounding temperature is that of the hot or cold plate.

X3. PROVEN PERFORMANCE OF A HEAT FLOW APPARATUS

X3.1 *Proven Performance*—Any heat flow meter apparatus that is new or has been modified shall be tested for the following characteristics and corrections shall be made where a change of greater than one percent occurs in the transducer output due to the effects of X3.1.1 – X3.2 over the range of operation and are recommended for changes of 0.3 % over the range of operation.

X3.1.1 *Zero Offset*—This condition can be achieved by assuring that both plate assemblies are at the same temperature. If there is any output from the transducer for zero heat flux, this may be due to any or all of the following:

X3.1.1.1 Electrical contact resistance on a transducer with low output. This may be corrected if one can improve the connections to eliminate the problem. This type of output may be temperature dependent.

X3.1.1.2 Also, check grounding circuits because such a signal may be due to AC pickup in the leads from the transducer.

X3.1.1.3 If after checking X3.1.1.1 and X3.1.1.2 there is still a zero off-set, it may be possible to correct for this by assuring that the calibration curve of output versus heat flux is linear over the range of operating conditions.

X3.1.1.4 Susceptibility to warm or cold plate temperature nonuniformity. Check for temperature nonuniformity under all operating conditions and over a range of specimen thermal resistances.

X3.1.1.5 Drift in the transducer due to material aging of delamination. If such a change is noted, this should be used to determine the required calibration frequency.

X3.1.1.6 Temperature coefficient of the transducer sensitivity. This depends on the type of temperature detectors used in the transducer (thermocouple materials used in the thermopile) and the type of material used for the transducer core. If it is found that the sensitivity is temperature dependent, a curve of sensitivity versus temperature shall be developed and used to correct measurement data.

X3.1.1.7 Heat flow down the transducer leads. One possible way to check for this is to move one's hand across the surface of the transducer between the metering area and the point where the leads exit the plate assembly, while observing the transducer output. In a well designed plate or transducer assembly there should be no observable output from the transducer except in the metering area.

X3.1.1.8 Effect of the thermal conductivity of the specimen on the sensitivity of the transducer. A "thermal shorting" effect between elements caused by low thermal resistance between the sensors of the thermopile or a funneling of heat through the sensors can change the sensitivity of the transducer. This can best be tested by running specimens with widely different thermal resistances.

X3.1.1.9 Effect of loading pressure on the transducer sensitivity. This should only be a problem if the transducer core is flexible.

X3.2 Finally, measurements shall be performed on transfer standards or accepted reference materials, to prove the performance of the apparatus. Care should be taken to ensure that the reference materials have characteristics similar to the specimens to be tested, and that the uncertainties of the standards themselves are known.

REFERENCES

(1) Tye, R.P., Ed., *Thermal Conductivity* Vols I and II, Academic Press, London and New York, 1969.

(2) Degenne, M., Klarsfeld, S., Barthe, P., "Measurement of the Thermal Resistance of Thick Low-Density Mineral Fiber Insulation," *Thermal Transmission Measurements of Insulation, ASTM STP 660*, ASTM, 1978, p.130.

(3) Pelanne, C.M., "Does the Insulation Have a Thermal Conductivity? The Revised ASTM Test Standards Require an Answer," *Thermal Transmission Measurements of Insulation, ASTM STP 660*, ASTM 1978, pp. 69–70.

(4) Pelanne, C.M., "Discussion on Experiments to Separate the Effect of Thickness from the Systematic Equipment Errors in Thermal Transmission Measurements," DOE/ASTM C 16.00 Thermal Insulation Conference October 22–25, 1978. Tampa, FL, *ASTM STP 718*, ASTM, 1980, pp. 322–334.

(5) Zabawsky, Z., "Construction and Calibration of a Heat Flow Meter for Thermal Conductivity Measurements," *Paper No. 68–520, ISA,* 1968, pp. 1–6.

(6) Hollingsworth, M., Jr., "An Apparatus for Thermal Conductivity at Cryogenic Temperatures Using a Heat Flow Meter," *Symposium of Thermal Conductivity Measurements of Insulating Materials at Cryogenic Temperatures, ASTM STP 411,*1967, p. 43.

(7) Hust, J. G., "Status of Thermal Conductivity Standard Reference Materials at the National Bureau of Standards," *Thermal Conductivity 18*, Plenum Press, New York and London, Edited by T. Ashworth and David R. Smith, 1985, pp. 317–326.

(8) Tye, R.P., Coumou, K.G., Desjarlais, A.O. and Haines, D.M., "Historical Development of Large Heat Flow Meter Apparatus for Measurement of Thermal Resistance of Insulations," *ASTM STP 922*, ASTM, 1987, pp. 651–664.

(9) Bomberg, M., "A Workshop on Measurement Errors and Methods of Calibration of a Heat Flow Meter Apparatus," *Journal of Thermal Insulation,* Vol 18, October, 1994, pp. 100–114.

(10) Scott, J. A., and Bell, R. W., "Discussion of Heat Flow Meter Apparatus Calibration and Traceability Issues for Thermal Conductivity Measurements," *Journal of Thermal Insulation,* Vol 18, October, 1994, pp. 146–162.

(11) Albers, M.A., and Pellanne, C.M., "Experimental and Mathematical Study of the Effect of Thickness in Low-Density Glass-Fiber Insulation," *Thermal Conductivity 17,* Plenum Press, New York and London, J.G. Hust, Ed., 1983, pp. 471–482.

(12) Bomberg, M., Pelanne, C.M., and Newton, W.S., "Analysis of Uncertainties in Calibration of a Heat-Flow Meter Apparatus," *Thermal Conductivity 18,* Plenum Press, New York and London, T.

Ashworth and D.R. Smith, Eds., 1985, pp. 254–272.
(13) Hollingsworth, M., "Experimental Determination of the Thickness Effect in Glass Fiber Building Insulation," *ASTM STP 718,* ASTM 1980, pp. 255–271.
(14) Pelanne, C. M., "Discussion on Experiments to Separate the 'Effect of Thickness' from Systematic Equipment Errors in Thermal Transmission Measurements," *ASTM STP 718*, D. L. McElroy, R. P. Tye, Eds., ASTM, 1978, pp. 322–334.
(15) Rennex, B., "Error Analysis for the National Bureau of Standards 1016 mm Guarded Hot Plate," *NBSIR 83–2674*, Washington, DC, 1983.
(16) De Ponte, F. and Maccato, W., "The Calibration of Heat Flow Meters," *Thermal Insulation Performance, ASTM STP 718*, ASTM 1980, pp. 237–254.
(17) Bode, K-H., "Thermal Conductivity Measurements with the Plate Apparatus: Influence of the Guard Ring Width on the Accuracy of Measurement," *ASTM STP 879*, ASTM, 1985, pp. 29–48.
(18) Shirtliffe, C.J., "Establishing Steady-State Thermal Conditions in Flat Slab Specimens," *Heat Transmission Measurement in Thermal Insulations, ASTM STP 544*, ASTM, 1974, p. 13.
(19) Zarr, R. R., "Control Stability of a Heat-Flow-Meter-Apparatus," *Journal of Thermal Insulation and Building Envelopes*, Vol 18, October 1994, pp. 116–127.
(20) Eisenhart, C., "Realistic Evaluation of the Precision and Accuracy of Instrument Calibration Systems," *Journal of Research of the National Bureau of Standards*, Vol. 67C, No. 2, April–June 1963, pp. 161–187.
(21) ASTM, Manual on Presentation of Data and Control Chart Analysis, Manual 7, 6th Edition, 1991, Available from ASTM Headquarters, Request PCN:28-0070899-34.
(22) Hust, J.G. and Pelanne, C.M., "Round Robins on the Apparent Thermal Conductivity of Low-Density Glass Fiber Insulations Using Guarded Hot Plate and Heat-Flow-Meter Apparatus," *NBSIR 85–3026*, May 1985.
(23) Adams, R.D. and Hust, J.G., "A Round Robin on Apparent Thermal Conductivity of Several Loose-Fill Insulations," *Insulation Materials, Testing and Applications, ASTM STP 1030,* McElroy and Kimpflen, Eds., ASTM, June 1990, p. 263.
(24) McCaa, D.J., Smith, D.R., et al, "Interlaboratory Comparison of the Apparent Thermal Conductivity of a Fibrous Batt and Four Loose-Fill Insulations," *Insulation Materials: Testing and Applications*, 2nd Volume, ASTM STP 1116, ASTM 1991, pp. 534–557.
(25) Zarr, R. R., Lagergren, E. S., "Interlaboratory "Pilot Run" Study of Small Heat-Flow-Meter Apparatus for ASTM C518," *Journal of Testing and Evaluation, JTEVA*, Vol 27, No.6, November 1999, pp. 357-367.
(26) Horlick, J. and Berger, H.W., "NVLAP and the Thermal Insulation Proficiency Testing Program," *Journal of Thermal Insulations*, Vol 8, April 1985, pp. 278–297.
(27) Horlick, J., "National Voluntary Laboratory Accreditation Program Proficiency Testing for Thermal Insulation Materials, Laboratory Accreditation Program Round 9—August 1983," National Institute of Standards and Technology Publication NBSIR 84-2890, May 1980.
(28) Pelanne, C. M., and Bradley, C. B., "A Rapid Heat Flow Meter Thermal-Conductivity Apparatus," *Materials Research and Standards,* Vol 2, No 7, July, 1962, p. 549.
(29) DePonte, F., and Di Filipo, P., "Design Criteria for Guarded Hot Plate Apparatus," *Heat Transmission Measurements in Thermal Insulations, ASTM STP 544*, R. P., Tye, Ed., 1974, p. 97.
(30) DePonte, F., and Di Filipo, P., "Some Remarks on the Design of Isothermal Plates," *Quaderno No. 37, Istituto di Fisica Tecnia, Universita di Padova*, 1972.
(31) "Guide to the Expression of Uncertainty in Measurements," ISBN 92-67-10188-9, 1st Ed. ISO, Geneva, Switzerland, 1993.
(32) Lackey, J., Normandin, N., Marchand, R., and Kumaran, K., "Calibration of a Heat Flow Meter Apparatus," *Journal of Thermal Insulation and Building Envelopes*, Vol 18, October 1994, pp. 128–144.
(33) American National Standard for Expressing Uncertainty, U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997.
(34) Tye, R. P., and Baker, C. F., "Development of Experimental Data on Cellular Plastic Insulations Under Simulated Winter Conditions," Thermal Insulation: Materials and Systems, *ASTM STP 922*, F. J. Powell, S. M. Matthews, Eds., 1987, pp. 518–537.
(35) Smith S. A., Lynch J. J., Moore M. L., and Galbraith C. J., "A Round Robin Testing Program to Estimate the Precision of ASTM C518 for Measuring the k-Factor of Rigid Foam Product," *Journal of Thermal Insulation* , 14, January 1991, pp. 184–194.
(36) Graves R. S., McElroy D. L., Miller R. G., Yarborough D. W., and Zarr R. R., "Technical Note: A Comparison of Heat-Flow-Meter Tests for Four Laboratories," *Journal of Thermal Insulation*, 15, April 1992, pp. 354–358.
(37) Albers, M. A., "Calibration of Heat Flow Meters in Vacuum, Cryogenic, and High Temperature Conditions," *Journal of Thermal Insulation and Building Envelopes*, Vol 18, April 1995, pp. 399–410.