Designation: C 1114 – ~~98~~00

Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus[1]

This standard is issued under the fixed designation C 1114; 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.

1. Scope

1.1 This test method covers the determination of the steady-state thermal transmission properties of flat-slab specimens of thermal insulation using a thin heater of uniform power density having low lateral heat flow. A thin heater with low lateral thermal conductance can reduce unwanted lateral heat flow and avoid the need for active-edge guarding.

1.2 This primary test method of thermal-transmission measurement describes a principle, rather than a particular apparatus. The principle involves determination of the thermal flux across a specimen of known thickness and the temperatures of the hot and cold faces of the specimen.

1.3 Considerable latitude is given to the designer of the apparatus in this test method; since a variety of designs is possible, a procedure for qualifying an apparatus is given in 5.3.

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[1] This test method is under the jurisdiction of ASTM Committee C~~-~~16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

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1.4 The specimens must meet the following conditions if thermal resistance or thermal conductance of the specimen is to be determined by this test method[2]:

1.4.1 The portion of the specimen over the isothermal area of the heater must accurately represent the whole specimen.

1.4.2 The remainder of the specimen should not distort the heat flow in that part of the specimen defined in 1.4.1.

1.4.3 The specimen shall be thermally homogeneous such that the thermal conductivity is not a function of the position within the sample, but rather may be a function of direction, time, and temperature. The specimen shall be free of holes, of high-density volumes, and of thermal bridges between the test surfaces or the specimen edges.

1.4.4 Test Method C 177 describes tests that can help ascertain whether conditions of 1.4 are satisfied. For the purposes of this test method, differences in the measurements of less than 2 % may be considered insignificant, and the requirements fulfilled.

1.5 The specimens shall meet one of the following requirements, in addition to those of 1.4.

1.5.1 If homogeneous materials as defined in Terminology C 168 are tested, then the thermal resistivity and thermal conductivity can be determined by this test method.

1.5.2 If materials which are layered or otherwise thermally inhomogeneous are tested, thermal resistance and thermal conductance can be determined by this test method.

1.6 Two versions of thin-heater apparatus using the same principle of the standard are described in Annex A1 and Annex A2. They are similar in concept but differ in size and construction, and hence warrant separate descriptions for each design. This test method in no way limits the size of the thin-heater element. One of the units described uses a thin metal foil, while the other uses a metal screen as the heat source. The smaller, foil apparatus is designed to make rapid measurements of heat transmission through specimens as thin as 0.5 cm and as thick as 2 cm; however, an apparatus using a foil heater could be designed to measure much thicker materials, if desired. The larger, screen apparatus is designed to measure specimens with thicknesses between 3 and 15 cm, where the exact limits depend on the thermal resistance of the specimens. Both apparatuses use thermocouples for measuring temperature, but other temperature-sensing systems can be used.

1.7 This test method covers the theory and principles of the measurement technique. It does not provide details of construction other than those required to illustrate two devices which meet the prescribed requirements. Detailed information is available in References **(1-23)**[3] and the Adjunct.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 168 Terminology Relating to Thermal Insulating Materials[4]

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[4]

C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[4]

C 687 Practice for Determination of the Thermal Resistance of Loose-Fill Building Insulation[4]

C 1043 Practice for Guarded-Hot-Plate Design Using Circular Line-Heat Sources[4]

C 1044 Practice for Using the Guarded-Hot-Plate Apparatus in the One-Sided Mode to Measure Steady-State Heat Flux and Thermal Transmission Properties[4]

C 1045 Practice for Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements[4]

C 1058 Practice for Selecting Temperatures for Reporting and Evaluating Thermal Properties of Thermal Insulation[4]

NOTE 1—Consult Test Methods C 177, C 518, and Practice C 1045 for the correct application of this test method.

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[5]

2.2 *ASTM Adjuncts:*

Descriptions of Two Types of Thin-Heater Apparatus[6]

3. Terminology

3.1 Applicable terms and symbols are defined in Terminology C 168. Any terms or symbols not included in C 168 but used in this test method will be defined within the text.

4. Summary of Test Method

4.1 *Principles*:

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[2] Further discussion on the definition of these limitations may be found in Tye, R. P., "What Property Do We Measure?," *Heat Transmission Measurements in Thermal Insulations*, ASTM STP 544, ASTM, 1974, pp 5–12.

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

[4] *Annual Book of ASTM Standards*, Vol 04.06.

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

[6] Order PCN:12–311140–61 from ASTM Headquarters.

4.1.1 A thin-foil or metal-screen heating apparatus operates in accordance with the basic concept of a unidimensional, longitudinal heat-flow technique. The heater is made sufficiently thin so that lateral heat flow along the plane of the heater is insignificant, and so that there is no need for isolation and separate temperature control of a guard region, except possibly the control of ambient temperature.

4.1.2 The low mass of the thin heater apparatus minimizes drift error and allows the apparatus to reach steady-state in a significantly shorter time than a typical Test Method C 177 apparatus.

4.1.3 It should be noted that all quantities in this procedure are determined by direct measurement. There are no arbitrary factors requiring calibration by comparison with a standard: thus, the apparatus yields results on an absolute basis.

4.1.4 A properly designed heater will be sufficiently thin to reduce lateral heat flow from the central zone to an acceptably small level. The result is that within a central zone, one-dimensional, longitudinal flow of heat perpendicular to the heater is obtained through the specimen. Because the foil or screen heater is very thin, the need for a gap between the inner and outer heater regions to act respectively as hot-plate and guard, is unnecessary.

5. Significance and Use

5.1 Factors that may influence the thermal-transmission properties of a specimen of material are described in Practice C 1045 and the Precision and Bias section of Test Method C 177.

5.2 Because of the required test conditions prescribed by this test method, it shall be recognized that the thermal properties obtained will not necessarily apply without modification to all conditions of service. As an example, this test method normally provides that the thermal properties shall be obtained on specimens that do not contain 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.

5.3 When a new or modified design of apparatus is evolved, tests shall be made on at least two sets of differing material of known long-term thermal stability. Tests shall be made for each material at a minimum of two different mean temperatures within the operating range of each. Any differences in results should be carefully studied to determine the cause and then be removed by appropriate action. Only after a successful verification study on materials having known thermal properties traceable to a recognized national standards laboratory shall test results obtained with this apparatus be considered to conform with this test method. Periodic checks of apparatus performance are recommended.

5.4 The thermal transmission properties of many materials depend upon the prior thermal history. Care must be exercised when testing such specimens at a number of conditions so that tests are performed in a sequence that limits such effects on the results.

5.5 Typical uses for the thin-heater apparatus include the following:

5.5.1 Product development and quality control applications.

5.5.2 Measurement of thermal conductivity at desired mean temperatures.

5.5.3 Thermal properties of specimens that are moist or close to melting point or other critical temperature (see Note 2).

NOTE 2—Apparatus of the type covered by this test method apply to the study of thermal properties of specimens containing moisture because of the use of small temperature differences and the low thermal capacity of the heat source.

5.5.4 Determination of thermal properties of relatively high *R* value insulation samples with large apparatuses. In the case of the metal-screen heater apparatus, samples with thicknesses up to 15 cm can be measured.

6. Apparatus and Specimen Preparation

6.1 The simplicity of this test procedure may cause very important factors to be overlooked which may affect the results. To ensure accuracy of measurements, the user of this apparatus should know how to measure temperature and power as they relate to testing of thermal resistance. It is also necessary that the specimens be properly selected and prepared for evaluation.

6.2 Normally, test specimens are selected in pairs from the sample lot. The specimens selected should be uniform and homogeneous to ensure that test apparatus symmetry is maintained. Appropriate thermal modeling may allow tests of nonuniform specimens, such as small specimens positioned within larger ones, or composite or layered specimens.

6.3 Test specimens shall be prepared and conditioned in accordance with the appropriate material specification. The conditioning of the test specimens shall be reported.

6.3.1 The surfaces of the specimens shall be prepared to ensure uniform thermal contact with the heater and temperature-controlled plates. Further details may be found in the Specimen Preparation section of Test Method C 177.

6.3.2 When evaluating compressible specimens, provide means to maintain a definite, known test thickness. One method is to insert rigid equal-length spacers made of low thermal-conductivity material in the corners of specimens. An alternative method involves using mechanical arrangements to establish fixed and known spacing and parallelism between the heater and cold plates.

6.3.3 The maximum allowable distance between the heater and cold plates (specimen thickness) is limited by the specimen thermal resistance, the ambient temperature, and the ratio of measurement area to apparatus size. The isothermal area established in the center of the heater is influenced by these factors. The isothermal area must be large enough to establish the equilibrium heat flux (W/m^2) through a representative area of the specimen. References are presented which will help guide users in determining the maximum thickness that can be used for specimens in their apparatus.

6.4 The distance between the heater and the cold plates must be adjusted to confine the specimens with pressure sufficient to ensure good thermal contact between the specimens and the bounding surfaces. For rigid specimens, a pressure of 2.5 kPa is recommended. For compressible specimens, see 6.3.2.

7. Procedure

7.1 The testing procedure includes the following steps:
7.1.1 Specimen selection,
7.1.2 Specimen preparation and installation, and
7.1.3 Test execution.

7.2 *Specimen Selection*—Only those specimen selection factors important to the performance of the apparatus are considered here. Those factors dictated by the objectives related to obtaining derived thermal properties are described in Practice C 1045 and material specifications. For the two-sided mode of operation, the two specimens should be selected to be as similar in thickness and thermal characteristics as possible.

7.2.1 *Size*—The maximum specimen thickness that can be measured to a given accuracy is dependent on several parameters, including the size of the apparatus, thermal resistance of the specimen, and the accuracy desired. To maintain edge heat losses to below about 0.5 %, the recommended maximum thickness of the specimen is one third the ~~maximum~~ minimum linear dimension of the metered region, if different from the thin-heater area. For more specific quantitative information on this limitation see Refs. **(24), (25), (26)**, and **(27)**.

7.2.1.1 The specimen may be sized to extend beyond the metered area by a distance sufficient to ensure one-dimensional heat flow within the metered area.

7.2.2 *Homogeneity*— There are two potential problems in determining the heat flux through highly inhomogeneous specimens. One is related to the interpretation and application of the resulting data; it is discussed in Practice C 1045. The other is connected with the degradation in performance of the apparatus. If the specimen itself is highly inhomogeneous, that is, the heat flux density varies appreciably over the metered area, several errors can be significantly increased. The temperature distribution of the thin heater can deviate appreciably from isothermal conditions which, in turn, can cause large uncertainties in the average temperature difference across the specimen. The increased temperature variations of the thin heater can also lead to increased edge heat losses. The importance of measuring temperatures of the thin heater or specimen surface at numerous points is greatly increased under such conditions.

7.3 *Specimen Preparation and Installation*—The specimen shall be conditioned in accordance with the appropriate material specification. The following guidelines for specimen preparation apply when the material specification is incomplete or unavailable. In general, the surfaces of the specimen should be prepared to ensure uniform thermal contact with the thin heater and the cooling plates.

7.3.1 *Compressible Specimens*—Also, for compressible specimens the surfaces of the uncompressed specimens may be comparatively rough so long as these undulations essentially vanish under test compression. Under more extreme conditions, it may be necessary to smooth the specimen surfaces to achieve better specimen contact. If the apparent thermal conductivity of the contact void is greater than that of the specimen, the measured R value will be smaller than the R value 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 conductivity of compressible specimens, the temperature sensors are often mounted directly in the contacting surfaces. Spacers need to be used for the measurement of compressible specimens (see 6.3.2).

7.3.2 *Rigid and High-Conductance Specimens*—The measurement of conductivity of rigid specimens or high-conductance specimens requires more careful surface preparation. First, the surfaces should be made flat and parallel to the same degree as the contacting surfaces. If the specimen has a thermal resistance that is sufficiently high compared to the specimen-to-surface interfacial resistance, temperature sensors mounted in the surfaces may be adequate. However, if the interfacial resistance is too high, the use of other techniques that ensure good thermal contact and accurate temperature measurement will be necessary.

7.3.2.1 In some cases it is necessary to mount the temperature sensors directly on the specimen surfaces to avoid the effects of high interfacial thermal resistance that create heat flux nonuniformities. In any event, the user should always try to minimize the ratio of contact resistance to specimen resistance and to strive for a constant ratio over the entire surface.

7.3.2.2 Another potential solution (that must be used with caution) is to mount a compressible thin sheet (for example, a soft rubber) between the surfaces and specimen to improve the uniformity of the thermal contact. The temperature sensors should be mounted on the side of the sheet facing the specimen. If the thermal conductance of the thin sheet is known, temperature corrections can be applied to the measured temperatures to obtain the specimen surface temperatures. Clearly, the thermal resistance of the thin sheets should be small compared to the specimen thermal resistance, otherwise the temperature correction uncertainty will cause excessive errors in the specimen surface temperatures.

7.3.3 *Anisotropic Specimens*—The measurement of conductivity of highly anisotropic specimens may result in significantly larger errors than for isotropic specimens. For example, layered specimens that have a high ratio of lateral to axial conductance require special attention. For such specimens, it is recommended that a low-conductance gap be created in the specimen. Specimens whose axes of symmetry do not coincide with flat-slab geometry are not recommended for measurement by this test method because the results will be ambiguous due to increased measurement errors.

7.3.4 *Loose-Fill Specimens*—The determination of thermal properties for loose-fill specimens requires special handling, conditioning, and measurement techniques. The user is directed to Practice C 687 for details on specimen preparation and measurement of loose-fill.

7.4 *Test Execution*:

7.4.1 *Thermal Steady-State*—The time required to achieve thermal steady-state of the system varies considerably with the characteristics of the apparatus design, the specimen to be measured, and the test conditions. Generally, however, since this test method is applicable to low-conductance specimens, the time to thermal equilibrium is on the order of hours. Times to thermal equilibrium generally increase with thicker specimens, specimens with low thermal diffusivity, redistribution of moisture within test specimen, and increasing mass of the thin-heater. After achievement of the desired steady-state, three successive data acquisition runs shall be completed. These runs shall be conducted at intervals of no more than 30 min. Longer times (days) may be necessary for thermally massive systems. It is recommended that the lengths of the intervals be no less than the thermal time constant of the system (see Note 3). This combination of three runs shall be considered a valid test if each datum obtained for each measured variable differs from the mean by no more than the uncertainty of that variable as estimated to establish the values given in the report. If the data obtained change monotonically with time, thermal steady-state has not been achieved; further runs shall be conducted until this steady drift is no longer observed. Such a drift, even at low levels, may indicate that the specimen characteristics are changing or that the system is not at steady-state within its test capabilities. Serious errors may result if sufficient time for thermal equilibrium is not allowed. For further details see Refs. **(28), (29)**, and **(30)**.

NOTE 3—The thermal time constant of the system is the time required to come to within 1/e (37 %) of the fixed value after a step thermal disturbance of the system. This time is strongly dependent on the mode of operation. The two modes of operation generally used are: (*1*) constant power to the thin-heater, and (*2*) constant temperature control of the thin-heater. The thermal time constant for the latter mode is usually considerably shorter because it is not dependent on the mass of the thin-heater. The thermal time constant in the constant power mode is the time required to come to within 37 % of the final temperature. The thermal time constant in the constant temperature mode is the time required to come to within 37 % of the final power. The thermal time constant of a system can be approximated from a knowledge of the thermal diffusivities of the components of the system, but it is more readily determined experimentally.

7.4.2 *Final Checks*— Upon completion of the thermal measurements, recheck the specimen thickness before removal, then remove the specimen and examine the system components, such as temperature sensor mounting, for proper placement and operation. The specimen thickness spacers should be checked to ensure accuracy. Any significant changes in the physical appearance or characteristics of the specimen should be reported. The mass of the specimen should be redetermined to detect changes during the test procedure. If the specimen is rigid, its thickness should be checked for an irreversible change during the test.

8. Calculation

8.1 The primary data required for this test method include electrical power, surface temperatures, area, and thickness. Of these, only thickness is generally a directly measured quantity. The others are either calculated from other more fundamental measurements or are converted by an electrical device. The manner in which these variables can be obtained is discussed as follows:

8.2 *Heat Flow*—The heat flow to be reported is that which passes through the specimen. For the single-sided mode of operation this is equal to the power generated by the metered region heater corrected for any back heat flow that occurs in the back flow specimen. This is discussed in Practice C 1044. For the double-sided mode of operation, only one half the power generated by the heater flows through each specimen. The power, Q, is frequently determined from emf, E, and current, I, measurement, and is calculated as follows:

$$Q = E \cdot I \tag{1}$$

8.3 *Metered Area*— The metered area, A, is the total thin-heater area or some defined portion of that area.

8.4 *Temperature*— Again, the basic measurement here is voltage (for a thermocouple) or voltage and current for a resistive temperature sensor. These data are normally converted to temperatures through a formula based on a calibration curve or interpolation of a table. In some instances, the formula is packaged within an instrument that reads directly in temperature. In any event, the user should note that the total error contains components due to the measurement process and the calibration (including the error caused by the functional or tabular interpolation of the calibration).

8.5 *Density*—The specimen density is to be reported. The equation for density, ρ, is the following:

$$\rho = M/V \tag{2}$$

where:

M = mass of the specimen (kg), and

V = volume that the specimen occupies between the plates under test conditions.

To minimize the error caused by specimen inhomogeneity it is best to determine the density of the specimen within the metered volume. This requires cutting out the metered position of the specimen for the mass determination. The volume is determined from the metered area and the in-situ specimen thickness (L). In the case of compressible specimens, the surface spacing is used for specimen thickness.

8.6 *Thermal Transmission Properties*—The properties included are thermal resistance, thermal conductance, apparent thermal conductivity, and thermal resistivity as defined by Terminology C 168. These quantities shall be reported only in accordance with the requirements and restrictions of Practice C 1045. In addition to reporting the systematic and random uncertainty of these properties, the range of applicable conditions must be reported. These include mean temperature or temperature range, specimen thickness, density, and surface emittance.

8.6.1 Calculate the thermal conductance, C, for a given specimen as follows:

$$C = q/\Delta T \tag{3}$$

where:

q = rate of heat flux through the specimen per unit area, and Q/A,
ΔT = temperature difference $T_h - T_c$

NOTE 4—Thermal resistance, R, the reciprocal of thermal conductance, is calculated for a given specimen as follows:

$$R = \Delta T/q \tag{4}$$

8.6.2 Calculate the apparent thermal conductivity as follows:

$$\lambda = \frac{Q}{2} \times \frac{L}{\Delta TA} \text{(flat}-\text{slab geometry)} \tag{5}$$

where:

Q = rate of heat flow, W,
A = specimen area normal to heat flux direction, m^2,
L = specimen thickness, m,
ΔT = temperature difference, $T_h - T_c$.

NOTE 5—Heat flux, $Q/2A$, in Eq 3 can be written as Q/A with A defined as the total heat transfer area (for double-sided operation this area is twice the metering area).

9. Report

9.1 The Report section in Test Method C 177 applies to this test method.

9.2 If results are to be reported as having been obtained by this test method, then all pertinent requirements prescribed by this test method should be met. Where such conditions are not met, the sentence "All requirements of Test Method C 1114 have been met with the exception of ... " should be added with a complete list of the exceptions included.

9.3 Select evaluation temperatures using Practice C 1058, and specifically report any exceptions.

10. Precision and Bias

10.1 *Precision of a Thin-Foil Type Apparatus*:

10.1.1 Based on the separate parameters of one apparatus (see Annex A1) of this type, it is estimated that the maximum error is 3 % and the most probable error is 2 % at 300 K when ΔT exceeds 1.1 K (2°F).

10.1.2 Data for cork-rubber and polystyrene were compared to data on the same specimens obtained in an apparatus using the Northrup technique **(21)**. Fiberboard specimens were tested using both the thin-foil apparatus and a standard conductimeter **(22)**. All results were consistent with the estimated errors **(5, 9)**.

10.1.3 Data on calcium silicate from 300 to 550 K with ΔTs from 2 to 5 K were internally consistent to within 2 %. Two specimens tested in four different versions of this apparatus type yielded average results within 3 % of results obtained with Test Method C 518 **(20)**.

10.1.3.1 These four tests determinations gave 95 % repeatability limits (within laboratory) of 1.6 %, 6.5 %, 4.7 %, 2.9 %, and 3.1 % at mean temperatures of 300, 370, 420, 480, and 530 K, respectively. Since data are available from only one laboratory, it is not possible to give a reproducibility limit. The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E 177. The coefficients of variation among test results may be obtained by dividing the above repeatability limit values by 2.8.

10.1.4 At this time, data using NIST SRMs are not available.[7]

10.2 *Bias of Thin-Foil Type Apparatus*:

10.2.1 The bias of this test method using this type of apparatus is undetermined at this time.

10.3 *Precision of a Metal-Screen Type Apparatus*:

10.3.1 A determinate error analysis for one apparatus (Annex A2) of this type shows a maximum measurement uncertainty of 1.7 % and a most-probable error of 1.2 % for a specimen ΔT of 5 K **(17, 18)**.

10.3.2 One apparatus of this type was used in a round robin for Practice C 687 in which the measurement capability of the eleven participating laboratories could be characterized by an imprecision of 3 % and a negligible bias of the mean based on a fibrous-glass blanket reference sample.

10.3.3 Four test determinations were made by one laboratory on SRM 1450b at a mean temperature of 297 K. The 95 % repeatability limit (within laboratory) was 1.7 %. Since data are available from only one laboratory, it is not possible to give a

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[7] For information on Standard Reference Materials (SRMs), contact the National Institute of Standards and Technology, Gaithersburg, MD 20899.

reproducibility limit. The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E 177. The coefficient of variation among test results may be obtained by dividing the above limit value by 2.8. The practical interpretation of this precision statement is that repeat measurements by the one laboratory have a 95 % probability of falling within ±1.7 % of their mean value.

10.4 *Bias of Metal-Screen Type Apparatus*:

10.4.1 Data were obtained on specific specimens of NIST SRMs 1451 **(16)** and 1450b **(15)** using both this type of apparatus and the 1-m NIST Guarded Hot Plate C 1043. The results were within 0.6 and 0.9 % for SRM 1451 and SRM 1450b, respectively **(18)**, indicating that the bias is less than −1 %.

11. Keywords

11.1 heat flow; thermal conductivity; thermal resistivity; thermal transmission; thin-heater apparatus; unguarded hot plate

ANNEXES

(Mandatory Information)

A1. FOIL-HEATER APPARATUS

A1.1 *General*—The specific foil-heater apparatus described in this section illustrates a unit that meets the requirements of this test method.

A1.2 *Concept:*

A1.2.1 The thin-foil heater in this apparatus consists of a uniform strip of metal foil folded in half with a thin intervening layer of electrical insulation, as shown in Fig. A1.1. The ends of the foil are established as electrical equipotentials by attaching heavy, metal buss bars. The folded-foil configuration is sandwiched between two identical specimens of sample material. The specimen thickness normally does not exceed one tenth of the least dimension of the heater, excluding the thickness of the heater. Two heavy, isothermal cooling plates enclose the entire assembly.

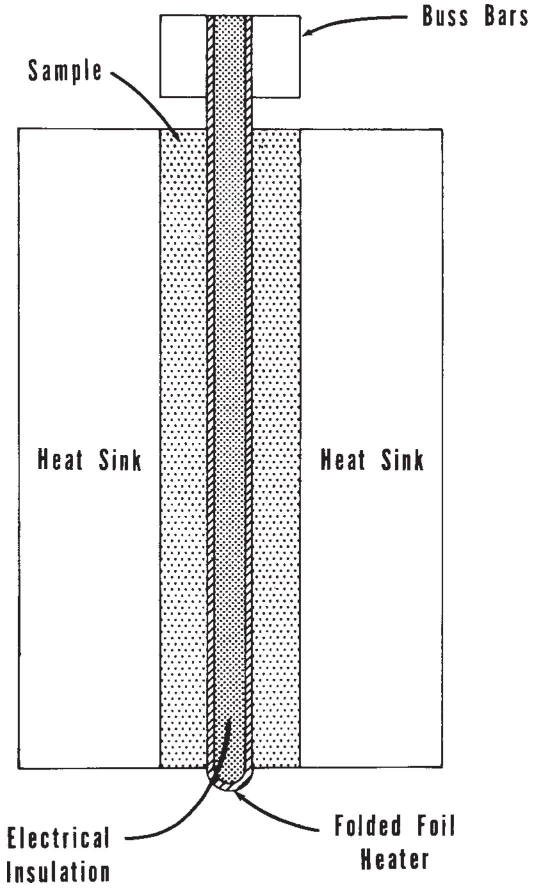


FIG. A1.1 Schematic of the Thin-Foil Heater

A1.2.2 The thin-foil heater is connected to a constant-current power supply using two buss bars. Assuming the temperatures of the heat-sink blocks are fixed, a steady-state is eventually reached such that the rate of heat generation in the heater equals the total rate of heat flow through the two specimens.

A1.2.3 Under steady-state conditions, the relevant thermal property of the central portions of the specimens is determined by measuring the temperature difference produced by the heater in relation to the specimen thickness and heat flow per unit area.

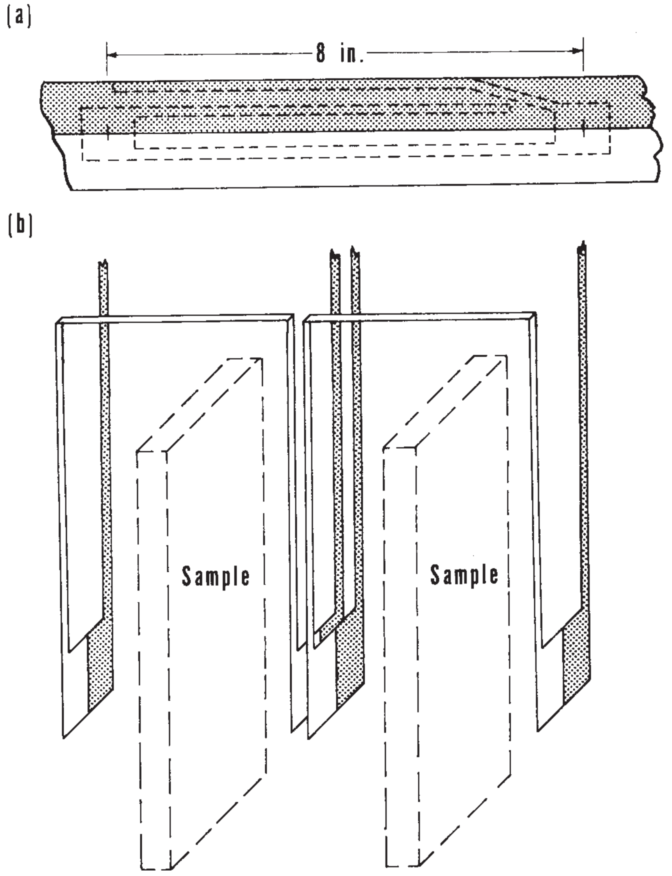
A1.2.4 To make a practical apparatus in accordance with these principles, a procedure must be established for determining q from knowledge of the parameters of the heater and power supply. There must be means for measuring the temperature difference, ΔT, using appropriate temperature sensors, and the length of the heat flow path, L, which, in this apparatus, is usually the specimen thickness.

A1.3 *Assembly:*

A1.3.1 The specific apparatus described here incorporates differential thermocouple systems for measuring the temperature difference between the two opposite faces of each of the two specimens. The differential thermocouples are cut from a strip of edge-welded copper-constantan foil, as shown in Fig. A1.2(a). Each specimen has its own differential couple, as shown in Fig. A1.2(b), with platelets on opposite sides of a given sample being connected by the continuous strip of constantan foil extending around the edge of the specimen. Copper leads attached to the foil provide connections to the external readout instrument.

A1.3.2 As explained in A1.3.3, the two inner platelets are laminated inside the heater. (Because of the symmetry of the apparatus, the two heater foils are at the same temperature when the steady-state condition is reached. Therefore, the space between these foils is isothermal, at least near the central area of the heater, and the thermocouple platelets inside the heater foils should be at the same temperature as the foils and the inside surfaces of the specimens.)

A1.3.3 The apparatus is shown in Fig. A1.3. The heater is fabricated from a 102 by 305-cm piece of 0.03-mm thick No. 321 stainless steel foil. The foil is uniform to within ±2 % (see A1.3.3.1). Two 102 by 152-mm sheets of 0.25-mm thick silicone-glass laminate are laminated together, enclosing two of the thermocouple platelets as described in A1.3.3.1 These platelets and their leads are electrically insulated from each other with 0.05-mm polyimide film. The centers of the platelets are located about 64 cm from the fold in the heater, and midway between the heater edges.



NOTE 1—Copper foil is shaded area; constantan foil is unshaded area.

(a) Layout for cutting Differential Thermocouple

(b) Relative Position of Platelets in Apparatus

FIG. A1.2 Details of Differential Thermocouple Configuration

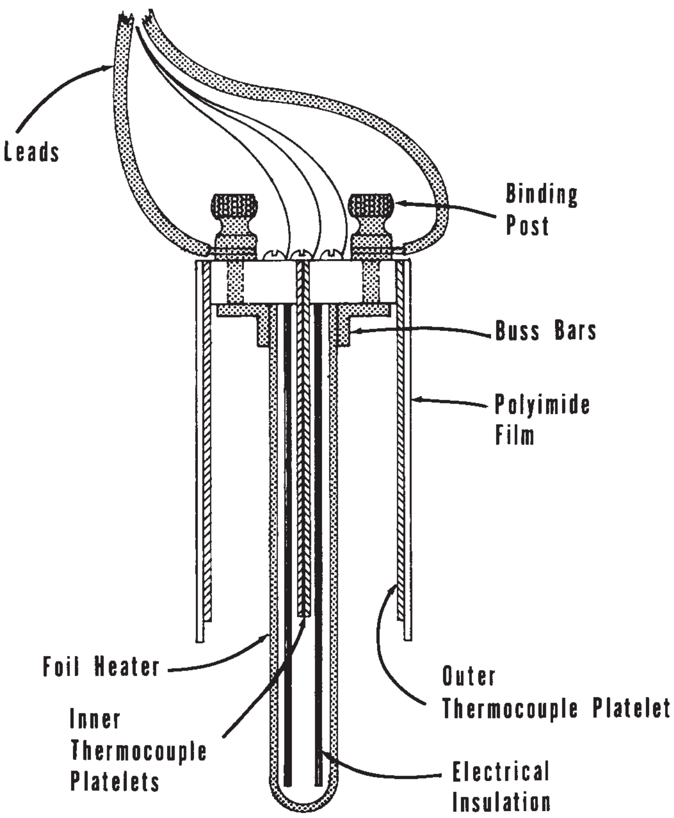


FIG. A1.3 Schematic of One Thin-Foil Heater Apparatus

A1.3.3.1 The foil thickness must be uniform **(5)** to produce a uniform heat flux. Precision metal foils whose thickness does not vary from the mean value by more than 0.005 mm are available from several commercial suppliers.

A1.3.4 The four leads from the two platelets extend from between the two silicone-glass sheets near the middle of one of the 102-mm edges. The heater is then folded over and bonded to the silicone-glass assembly such that the buss bars are at the same end of the silicone-glass as the leads from the thermocouple platelets. A25 by 102-mm mounting strip made of 0.6-mm thick silicone-glass laminate is fastened to the buss bars with binding posts and bolts and nuts. The thermocouple leads are extended through a slot in this mounting strip. The two outer thermocouple platelets are positioned so that their centers are about 64 mm from the folded end of the heater; the leads are then bonded to the side of the mounting strip. Their centers are aligned with the centers of the pair of platelets inside the heater. The two copper leads extending from the between-heater platelets are folded together and clamped under a nylon screw tapped into the mounting strip. A thermocouple-quality copper wire, also joined in this connection, extends to the readout instrument. The copper leads from the outer platelets are similarly connected to external wires using two other screws. Power leads are fastened to the binding posts. These are bound together with the thermocouple wires to form a cable approximately 910 mm in length. All bonding is done with pressure-sensitive silicone adhesive.

A1.3.5 Experience has shown that reinforcing the outer thermocouples with films may be necessary. The films are cut large enough to cover platelets, leads, and a portion of the side of the mounting strip. These films are mounted with adhesive to the outer surface of the foils so they do not interfere with the thermal contact between the thermocouple platelets and the sample. Note that the outer thermocouples, including the film covers, can be bent to accommodate variations in specimen thickness.

A1.3.6 After the specimens are placed between the heater and the other thermocouple platelets, the assembly is clamped between two 102 by 151-mm blocks of 25-mm thick aluminum. The clamping is done with spring clamps, or by an overall wrapping of tape. Note that the polyimide film on the outer platelets prevents electrical shorting by the aluminum heat-sink blocks.

A1.3.7 For the assembly described, the fractional uncertainty for the range from 300 to 550 K is 3 %, while the most probable uncertainty is 2 % **(20)**.

A2. METAL-SCREEN HEATER APPARATUS

A2.1 *General*—The specific metal-screen heater apparatus described in this section illustrates a unit that meets the requirements of this test method.

A2.2 *Concept:*

A2.2.1 The apparatus is designed to measure the heat transmission characteristics of large, flat specimens of thermal insulation. It uses an electrically powered Type V nickel-chromium alloy screen as a heat source. This screen is large enough and has sufficiently low lateral thermal conductance to produce one-dimensional heat flow in its central region without active edge guarding. Control of the ambient temperature to the mean test temperature enables edge guarding to extend the measurement range. The screen is instrumented with eleven 36-gauge Type E (Chromel P and Constantan[8]) thermocouples and is positioned horizontally between a pair of insulation specimens that are bounded by temperature-controlled copper plates. Metal-screen heaters have been made using alloys other than Nichrome.

A2.2.2 A constant-direct-current power supply heats the screen. Assuming that the copper plates are maintained at a constant temperature, a steady state is eventually reached, such that the rate of heat generation in the screen equals the total rate of heat flow through the two specimens.

A2.2.3 For information on the thermal property of central portions of the specimens, see A1.2.3.

A2.2.4 For relevant parameters, see A1.2.4.

A2.3 *Assembly:*

A2.3.1 The assembled apparatus, without perimeter insulation, is shown in Fig. A2.1. This figure shows a 1.1 by 1.6-m table

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[8] Widely available from commercial suppliers.

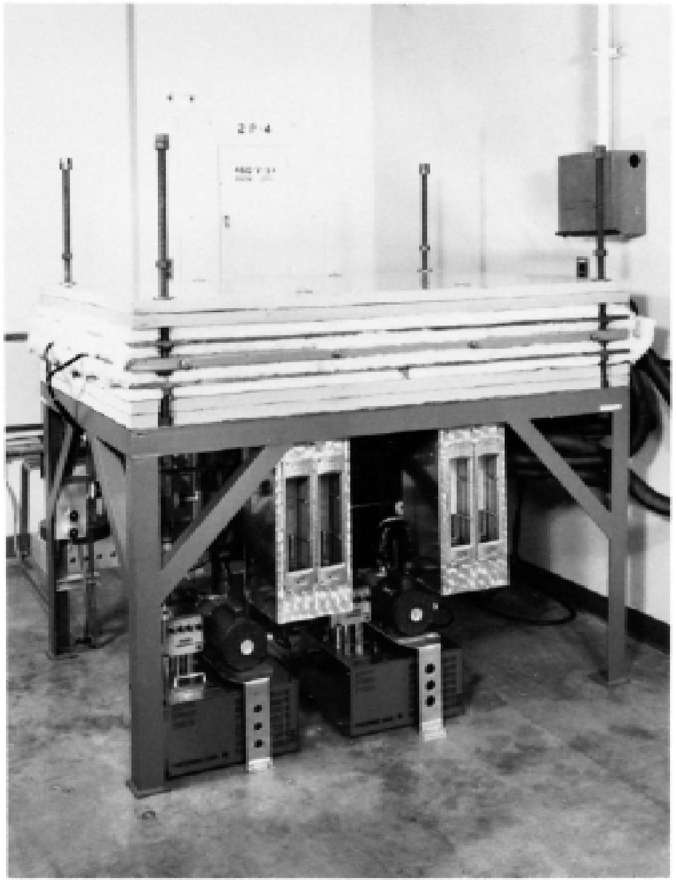


FIG. A2.1 Assembled Metal-Screen Heater Apparatus Without Perimeter Insulation

with four threaded corner posts for holding the top and bottom copper cold plates and the screen frame in their respective horizontal positions. This illustration shows the table top, the lower cold-plate insulation consisting of two insulating boards and a compressed, fiberglass batt, the lower cold plate, the lower sample, the screen-heater frame, the upper sample, the upper cold-plate, and the upper cold-plate insulation consisting of a compressed, fiberglass batt and two insulating boards. The upper and lower cold-plate insulation (0.11 m thick) provides an *R*-value of about 4.7 $K \cdot m^2/W$. The two independent fluid-circulating units that control the plate temperature are located below the table. With independent temperature controls, measurements can be made with heat flow up, heat flow down, or heat flow from the screen to each plate at the same temperature, similar to the apparatuses used for Test Method C 177 and Practice C 1044.

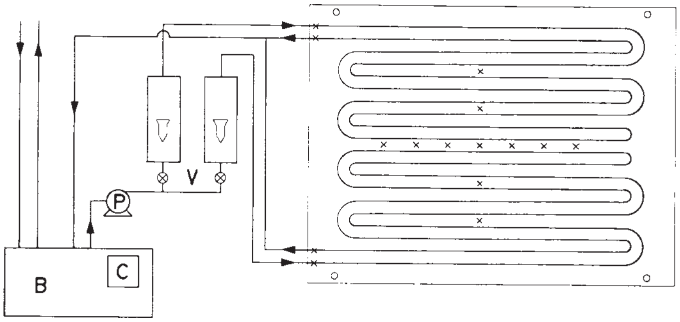
A2.3.2 Fig. A2.2 is a schematic drawing of the temperature-control plumbing for a cold plate. The solid bounding surfaces are fabricated from copper plate 12-mm thick, 1.14-m wide, and 1.75-m long. Four holes are provided for the positioning posts; 10-mm diameter copper tubing is soldered to the external surface of the copper plate for the circulating fluid. The copper tubing provides two counter-flow paths for water from the temperature-controlled water bath, with flow boosted by an external pump and balanced with two rotameters. The plate temperature profile and inlet/outlet temperatures are obtained using 15 Type E thermocouples, 0.12 mm in diameter, that are held to the plate surface with thermally conducting epoxy. The surfaces facing the sample are machined to a flatness of ±0.13 mm, and six table-support screws are adjusted to provide a flatness to this level. These surfaces are painted black to establish a total hemispherical emittance greater than 0.8 **(7, 17)**.

A2.3.3 Fig. A2.3 is a schematic drawing of the instrumented Nichrome metal-screen heater in its support frame. The screen is made from wire 0.25 mm in diameter, and woven as a 40 by 40-per-in. mesh with a thickness of 0.64 mm, width of 0.914 m, and length of 1.52 m. This screen is held in a frame with 14 electrically insulated tension springs with adjusting nuts. Distributed current-input leads join copper bars brazed to each end of the heater. Four voltage taps are welded to the edge of the heater and are centered on the screen with separations of 0.610 and 0.914 m. Eleven Type E thermocouples 0.12 mm in diameter are attached to the screen with thermally conducting epoxy on the 0° and 180° axis with 0.3-m spacing. The positions of spacers that maintain the sample thickness are also shown in Fig. A2.3.

A2.3.4 Forty-one Type E thermocouples, as used in this apparatus, join copper wires in a pair of ice-water reference baths. All thermal electromotive forces are measured with a potentiometer having a 1.6-v range and an accuracy of $\pm(0.001\ \% \times V + 2\ \mu V)$, or a data-acquisition scanner (with an uncertainty of ±1 μV in 30 000μ V). The electrical power to the screen heater is provided by a DC supply capable of providing 10 V at 100 A. A precision 0.01-ohm resistor in-series with the power leads is to measure current. The voltage taps with a spacing of 0.610 m on the screen edge define the metered area of 0.610 by 0.914 m.

A2.3.5 The sample thickness is fixed by eight low-conductivity tubular spacers 30-mm diameter positioned outside the 0.610-m voltage-tap spacing. Four such spacers are positioned on each side of the screen, and spacer tube lengths from 40 to 90 ± 0.010 mm can be used.

A2.3.6 For the assembly described, the fractional uncertainty in thermal conductivity for the range from 300 to 330 K is 1.7 %, while the most probable uncertainty is 1.2 % **(18)**.



Component	Illustration
Braun Water Bath	B
Controller	C
Booster Pump	P
Balancing Valves	V
Thermocouple	X

FIG. A2.2 Schematic of Temperature Control and Plumbing Systems for Each Cold Plate

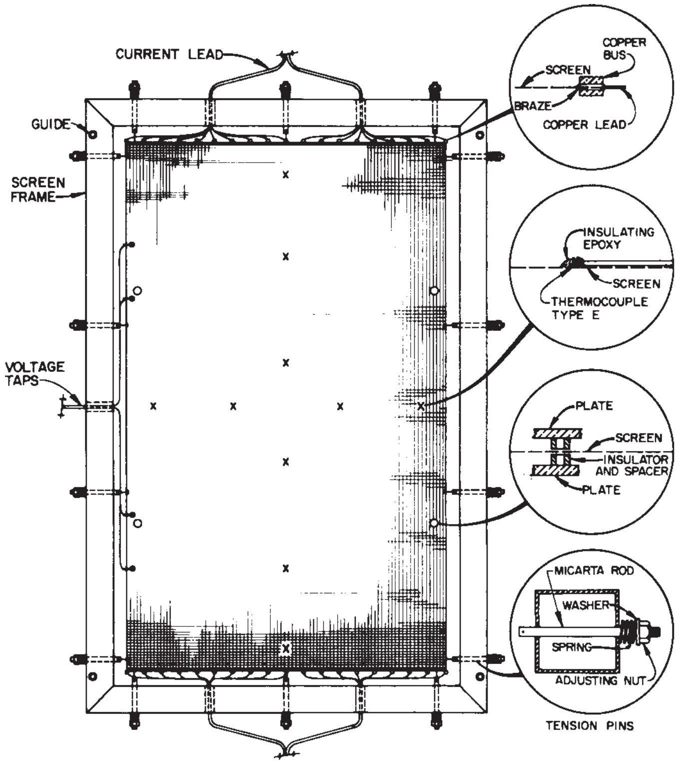


FIG. A2.3 Schematic Drawing of Instrumented Nichrome Metal-Screen Heater in Support Frame

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