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Standard Test Method for Steady-State Heat Transfer Properties of Pipe Insulation[1]

This standard is issued under the fixed designation C335/C335M; 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 the steady-state heat transfer properties of pipe insulations. Specimen types include rigid, flexible, and loose fill; homogeneous and nonhomogeneous; isotropic and nonisotropic; circular or non-circular cross section. Measurement of metallic reflective insulation and mass insulations with metal jackets or other elements of high axial conductance is included; however, additional precautions must be taken and specified special procedures must be followed.

1.2 The test apparatus for this purpose is a guarded-end or calibrated-end pipe apparatus. The guarded-end apparatus is a primary (or absolute) method. The guarded-end method is comparable, but not identical to ISO 8497. The ISO method does not use the calculation procedure in Practice C1045.

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 When appropriate, or as required by specifications or other test methods, the following thermal transfer properties for the specimen can be calculated from the measured data (see 3.2):

1.4.1 The pipe insulation lineal thermal resistance and conductance,

1.4.2 The pipe insulation lineal thermal transference,

1.4.3 The surface areal resistance and heat transfer coefficient,

1.4.4 The thermal resistivity and conductivity,

1.4.5 The areal thermal resistance and conductance, and

1.4.6 The areal thermal transference.

NOTE 1—In this test method the preferred resistance, conductance, and transference are the lineal values computed for a unit length of pipe. These must not be confused with the corresponding areal properties computed on a unit area basis which are more applicable to flat slab geometry. If these areal properties are computed, the area used in their computation must be reported.

[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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NOTE 2—Discussions of the appropriateness of these properties to particular specimens or materials may be found in Test Method C177, Test Method C518, and in the literature (**1**).[2]

1.5 This test method allows for operation over a wide range of temperatures. The upper and lower limit of the pipe surface temperature is determined by the maximum and minimum service temperature of the specimen or of the materials used in constructing the apparatus. In any case, the apparatus must be operated such that the temperature difference between the exposed surface and the ambient is sufficiently large enough to provide the precision of measurement desired. Normally the apparatus is operated in closely controlled still air ambient from 15 to 30°C, but other temperatures, other gases, and other velocities are acceptable. It is also acceptable to control the outer specimen surface temperature by the use of a heated or cooled outer sheath or blanket or by the use of an additional uniform layer of insulation.

1.6 The use any size or shape of test pipe is allowable provided that it matches the specimens to be tested. Normally the test method is used with circular pipes; however, its use is permitted with pipes or ducts of noncircular cross section (square, rectangular, hexagonal, etc.). One common size used for interlaboratory comparison is a pipe with a circular cross section of 88.9-mm diameter (standard nominal 80-mm [3-in.] pipe size), although several other sizes are reported in the literature (**2-4**).

1.7 The test method applies only to test pipes with a horizontal or vertical axis. For the horizontal axis, the literature includes using the guarded-end, the calibrated, and the calibrated-end cap methods. For the vertical axis, no experience has been found to support the use of the calibrated or calibrated-end methods. Therefore the method is restricted to using the guarded-end pipe apparatus for vertical axis measurements.

1.8 This test method covers two distinctly different types of pipe apparatus, the guarded-end and the calibrated or calculated-end types, which differ in the treatment of axial heat transfer at the end of the test section.

1.8.1 The guarded-end apparatus utilizes separately heated guard sections at each end, which are controlled at the same temperature as the test section to limit axial heat transfer. This type of apparatus is preferred for all types of specimens within the scope of this test method and must be used for specimens incorporating elements of high axial conductance.

1.8.2 The calibrated or calculated-end apparatus utilizes insulated end caps at each end of the test section to minimize axial heat transfer. Corrections based either on the calibration of the end caps under the conditions of test or on calculations using known material properties, are applied to the measured test section heat transfer. These apparatuses are not applicable for tests on specimens with elements of high axial conductance such as reflective insulations or metallic jackets. There is no known experience on using these apparatuses for measurements using a vertical axis.

1.9 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *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]

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
C302 Test Method for Density and Dimensions of Preformed Pipe-Covering-Type Thermal Insulation
C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
C680 Practice for Estimate of the Heat Gain or Loss and the Surface Temperatures of Insulated Flat, Cylindrical, and Spherical Systems by Use of Computer Programs
C870 Practice for Conditioning of Thermal Insulating Materials
C1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions

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

[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.

C1058 Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation
E230 Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples

2.2 *ISO Standards:*

ISO 8497 Thermal Insulation-Dermination of Steady State Thermal Transmission Properties of Thermal Insulation for Circular Pipes

~~2.3 *ASTM Adjuncts:*[4]~~
~~Guarded-end Apparatus~~
~~Calibrated-end Apparatus~~

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology C168.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *areal thermal conductance, C*—the steady-state time rate of heat flow per unit area of a specified surface (Note 3) divided by the difference between the average pipe surface temperature and the average insulation outer surface temperature. It is the reciprocal of the areal thermal resistance, *R*.

$$C = \frac{Q}{A\left(t_o - t_2\right)} = \frac{1}{R} \tag{1}$$

where the surface of the area, *A*, must be specified (usually the pipe surface or sometimes the insulation outer surface).

NOTE 3—The value of *C*, the areal thermal conductance, is arbitrary since it depends upon an arbitrary choice of the area, *A*. For a homogeneous material for which the thermal conductivity is defined as in 3.2.7 (Eq 8), the areal conductance, *C*, is given as follows:

$$C = \frac{2\pi L \lambda_p}{A \ln(r_2/r_o)} \tag{2}$$

If the area is specially chosen to be the "log mean area," equal to $2\pi L\ (r_2 - r_o)/\mathrm{l}\ n(r_2/r_o)$, then $C = \lambda_p/(r_2 - r_o)$. Since $(r_2 - r_o)$ is equal to the insulation thickness measured from the pipe surface, this is analogous to the relation between conductance and conductivity for flat slab geometry. Similar relations exist for the areal thermal resistance defined in 3.2.2. Since these areal coefficients are arbitrary, and since the area used is often not stated, thus leading to possible confusion, it is recommended that these areal coefficients not be used unless specifically requested.

3.2.2 *areal thermal resistance, R*—the average temperature difference between the pipe surface and the insulation outer surface required to produce a steady-state unit rate of heat flow per unit area of a specified surface (Note 3). It is the reciprocal of the areal thermal conductance, *C*.

$$R = \frac{A\left(t_o - t_2\right)}{Q} = \frac{1}{C} \tag{3}$$

where the surface of the area, *A*, must be specified (usually the pipe surface or sometimes the insulation outer surface).

3.2.3 *areal thermal transference, T_r*—the time rate of heat flow per unit surface area of the insulation divided by the difference between the average pipe surface temperature and the average air ambient temperature.

$$T_r = \frac{Q}{2\pi r^2 L\left(t_o - t_a\right)} \tag{4}$$

3.2.4 *pipe insulation lineal thermal conductance, C_L*—the steady-state time rate of heat flow per unit pipe insulation length divided by the difference between the average pipe surface temperature and the average insulation outer surface temperature. It is the reciprocal of the pipe insulation lineal thermal resistance, R_L.

$$C_L = \frac{Q}{L\left(t_o - t_2\right)} = \frac{1}{R_L} \tag{5}$$

3.2.5 *pipe insulation lineal thermal resistance, R_L*—the average temperature difference between the pipe surface and the insulation outer surface required to produce a steady-state unit time rate of heat flow per unit of pipe insulation length. It is the reciprocal of the pipe insulation lineal thermal conductance, C_L.

$$R_L = \frac{L\left(t_o - t_2\right)}{Q} = \frac{1}{C_L} \tag{6}$$

3.2.6 *pipe insulation lineal thermal transference,* T_{r_p}—the steady-state time rate of heat flow per unit pipe insulation length divided by the difference between the average pipe surface temperature and the average air ambient temperature. It is a measure of the heat transferred through the insulation to the ambient environment.

$$T_{r_p} = \frac{Q}{L(t_o - t_a)} \quad (7)$$

3.2.7 *pipe insulation thermal conductivity,*λ_p—of homogeneous material, the ratio of the steady-state time rate of heat flow per unit area to the average temperature gradient (temperature difference per unit distance of heat flow path). It includes the effect of the fit upon the test pipe and is the reciprocal of the pipe insulation thermal resistivity, r_L. For pipe insulation of circular cross section, the pipe insulation thermal conductivity is:

$$\lambda_p = \frac{Q \ 1n \left(r_2/r_o\right)}{L2\pi(t_o - t_2)} = \frac{1}{r_L} \quad (8)$$

3.2.8 *pipe insulation thermal resistivity,* r_L—of homogeneous material, the ratio of the average temperature gradient (temperature difference per unit distance of heat flow path) to the steady-state time rate of heat flow per unit area. It includes the effect of the fit upon the test pipe and is the reciprocal of the pipe insulation thermal conductivity, λ_p. For pipe insulation of circular cross section, the pipe insulation thermal resistivity is calculated as follows:

$$r_L = \frac{2\pi L(t_o - t_2)}{Q \ 1n \left(r_2/r_o\right)} = \frac{1}{\lambda_p} \quad (9)$$

3.2.9 *surface areal heat transfer coefficient,* h_2—the ratio of the steady-state time rate of heat flow per unit surface area to the average temperature difference between the surface and the ambient surroundings. The inverse of the surface heat transfer coefficient is the surface resistance. For circular cross sections:

$$h_2 = \frac{Q}{2\pi r^2 L(t_2 - t_a)} \quad (10)$$

3.3 *Symbols:* see 1.3:

C_L = pipe insulation lineal thermal conductance, W/m·K [Btu · in⁄F · hr · ft^2],
R_L = pipe insulation lineal thermal resistance, K·m/W [Btu · in⁄F · hr · ft^2],
T_{r_p} = pipe insulation lineal thermal transference, W/m·K [Btu · in⁄F · hr · ft^2],
λ_p = pipe insulation thermal conductivity, W/m·K [Btu · in⁄F · hr · ft^2],
r_L = pipe insulation thermal resistivity, K·m/W [F · hr · ft^2],
h_2 = surface areal heat transfer coefficient of insulation outer surface, W/m^2·K [Btu · in⁄F · hr · ft^2],
C = areal thermal conductance, W/m^2·K [Btu · in⁄F · hr · ft^2],
R = areal thermal resistance, K·m^2/W [F · hr · ft^2],
T_r = areal thermal transference, W/m^2·K [Btu · in⁄F · hr · ft^2],
Q = time rate of heat flow to the test section of length L, W [Btu/hr],
t_o = temperature of pipe surface, K [F],
t_1 = temperature of insulation inside surface, K [F],
t_2 = temperature of insulation outside surface, K [F],
t_a = temperature of ambient air or gas, K [F],
r_o = outer radius of circular pipe, m [ft],
r_1 = inner radius of circular insulation, m [ft],
r_2 = outer radius of circular insulation, m ft],
L = length of test section (see 8.1.1), m [ft], and
A = area of specified surface, m^2 [ft^2].

4. Significance and Use

4.1 As determined by this test method, the pipe insulation lineal thermal resistance or conductance (and, when applicable, the thermal resistivity or conductivity) are means of comparing insulations which include the effects of the insulation and its fit upon the pipe, circumferential and longitudinal jointing, and variations in construction, but do not include the effects of the outer surface resistance or heat transfer coefficient. They are thus appropriate when the insulation outer-surface temperature and the pipe temperature are known or specified. However, since the thermal properties determined by this test method include the effects of fit and jointing, they are not true material properties. Therefore, properties determined by this test method are somewhat different from those obtained on apparently similar material in flat form using the guarded hot plate, Test Method C177, or the heat flow meter apparatus, Test Method C518.

4.2 The pipe insulation lineal thermal transference incorporates both the effect of the insulation and its fit upon the pipe and also the effect of the surface heat-transfer coefficient. It is appropriate when the ambient conditions and the pipe temperature are known or specified and the thermal effects of the surface are to be included.

4.3 Because of the test condition requirements prescribed in this test method, recognize that the thermal transfer properties obtained will not necessarily be the value pertaining under all service conditions. As an example, this test method provides that the thermal properties shall be obtained by tests on dry or conditioned specimens, while such conditions are not necessarily realized in service. The results obtained are strictly applicable only for the conditions of test and for the product construction tested, and must not be applied without proper adjustment when the material is used at other conditions, such as mean temperatures that differ appreciably from those of the test. With these qualifications in mind, the following apply:

4.3.1 For horizontal or vertical pipes of the same size and temperature, operating in the same ambient environment, values obtained by this test method can be used for the direct comparison of several specimens, for comparison to specification values, and for engineering data for estimating heat loss of actual applications of specimens identical to those tested (including any jackets or surface treatments). When appropriate, correct for the effect of end joints and other recurring irregularities (4.4).

4.3.2 When applying the results to insulation sizes different from those used in the test, an appropriate mathematical analysis is required. For homogeneous materials, this consists of the use of the thermal conductivity or resistivity values (corrected for any changes in mean temperature) plus the use of the surface heat transfer coefficient when the ambient temperature is considered (for example, see Practice C680). For nonhomogeneous and reflective insulation materials, a more detailed mathematical model is required which properly accounts for the individual modes of heat transfer (conduction, convection, radiation) and the variation of each mode with changing pipe size, insulation thickness, and temperature.

4.4 It is difficult to measure the thermal performance of reflective insulation that incorporate air cavities, since the geometry and orientation of the air cavities can affect convective heat transfer. While it is always desirable to test full-length pipe sections, this is not always possible due to size limitations of existing pipe insulation testers. If insulation sections are tested less than full length, internal convective heat transfer are usually altered, which would affect the measured performance. Therefore, it must be recognized that the measured thermal performance of less than full-length insulation sections is not necessarily representative of full-length sections.

4.5 The design of the guarded-end pipe apparatus is based upon negligible axial heat flow in the specimen, the test pipe, heaters, and other thermal conductive paths between the metering and guard sections. Some nonhomogeneous and reflective insulation are usually modified at the end over the guard gap in order to prevent axial heat flow. Avoid these modifications where possible, but for some nonhomogeneous insulation designs, they provide the only means to satisfy the negligible heat flow assumption across the guard gaps. Therefore, thermal performance measured on insulation specimens with modified ends are not necessarily representative of the performance of standard insulation sections.

4.6 It is acceptable to use this test method to determine the effect of end joints or other isolated irregularities by comparing tests of two specimens, one of which is uniform throughout its length and the other which contains the joint or other irregularity within the test section. The difference in heat loss between these two tests, corrected for the uniform area covered by the joint or other irregularity, is the extra heat loss introduced. Care must be taken that the tests are performed under the same conditions of pipe and ambient temperature and that sufficient length exists between the joint or irregularity and the test section ends to prevent appreciable end loss.

4.7 For satisfactory results in conformance with this test method, the principles governing construction and use of apparatus described in this test method must be followed. If the results are to be reported as having been obtained by this test method, then all the pertinent requirements prescribed in this test method shall be met or any exceptions shall be described in the report.

4.8 It is not practical in a test method of this type to establish details of construction and procedure to cover all contingencies that might offer difficulties to a person without technical knowledge concerning the theory of heat flow, temperature measurements, and general testing practices. Standardization of this test method does not reduce the need for such technical knowledge. It is

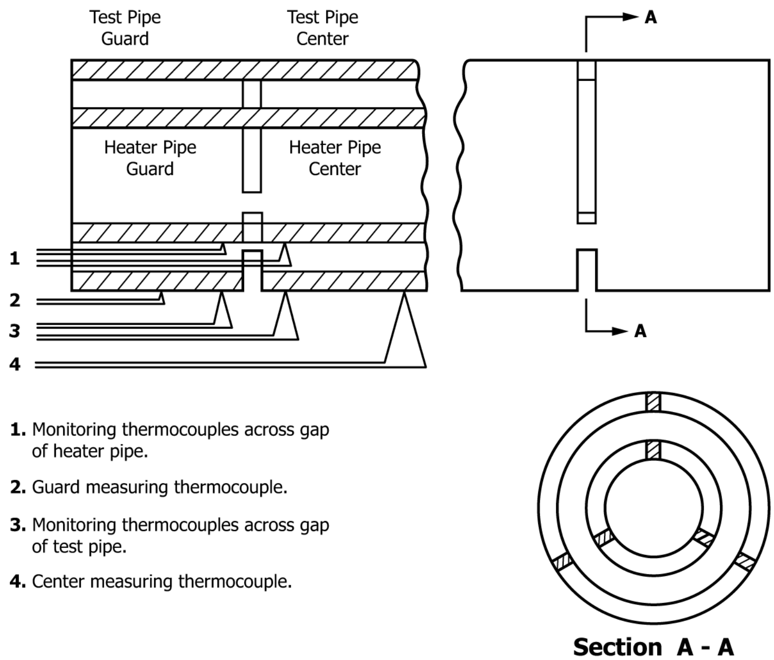

FIG. 1 Guarded-End Apparatus

recognized also that it would be unwise to restrict the further development of improved or new methods or procedures by research workers because of standardization of this test method.

NOTE 4—When testing at ambient temperatures below normal room temperatures, theoretical analysis shows that the experimental heat flow direction is unimportant for a perfectly homogenous material. However, if the properties of the insulation vary in the radical direction, the experimental heat flow direction will significantly affect the measured thermal conductivity. Exercise great care when using data from a radial heat flow outward experiment for a radial heat flow inward application.

5. Apparatus

5.1 The apparatus shall consist of the heated test pipe and instrumentation for measuring the pipe and insulation surface temperatures, the average ambient air temperature, and the average power dissipated in the test section heater. The pipe shall be uniformly heated by an internal electric heater (Notes 5 and 6). In large apparatus, give some consideration on providing internal circulating fans or to filling the pipe with a heat transfer fluid to achieve uniform temperatures. The guarded end design also requires, a short section of pipe at each end of the test section, with its own separately controlled heater (see 5.3 and Fig. 1). The calibrated or calculated-end design requires suitable insulated caps at each end (see 5.4 and Fig. 2). An essential requirement of the test is an enclosure or room equipped to control the temperature of the air surrounding the apparatus. The apparatus shall conform to the principles and limitations prescribed in the following sections, but it is not intended in this test method to include detailed requirements for the construction or operation of any particular apparatus.

NOTE 5—Experiments have been reported that use an electrically heated cylindrical screen rather than an internally heated pipe (**5**). An extension of the heated screen technique has been reported (**6**) for testing below normal temperatures using the radial heat flow inward, similar to some insulation system applications. While these designs and the accompanying analysis are not included in this test method, their findings are pertinent to this standard.

NOTE 6—The most commonly used heater consists of electrical resistance wire or ribbon on the surface or in the grooves of a tubular ceramic core that is internal to the test pipe. If the heater fits snugly inside the test pipe, the contact must be uniform to achieve uniform test pipe temperatures. If the heater core is smaller than the inside diameter of the pipe, then fill the gap with a material such as sand to provide uniform heat transfer. In this standard the combination of heater winding and heater pipe will be called either a "heater" or a "heater pipe."

5.2 *Apparatus Pipe,* no restriction is placed on the cross section size or shape, but the length of the test section must be sufficient to ensure that the total measured heat flow is large enough, when compared to end losses and to the accuracy of the power measurement, to achieve the desired test accuracy (see 5.3 and 8.4). A test section length of approximately 0.5 m [24 in.] has proven satisfactory for an apparatus with a circular cross-section of 88.9 mm (nominal 80-mm, [nominal 3-in.] pipe size) that is often used for inter-laboratory comparisons. Do not assume that this length is satisfactory for all sizes of apparatus and for all test conditions. Estimates of the required length must be made from an appropriate error analysis. As a convenience, it is recommended that the apparatus be constructed to accept an integral number of standard lengths of insulation.

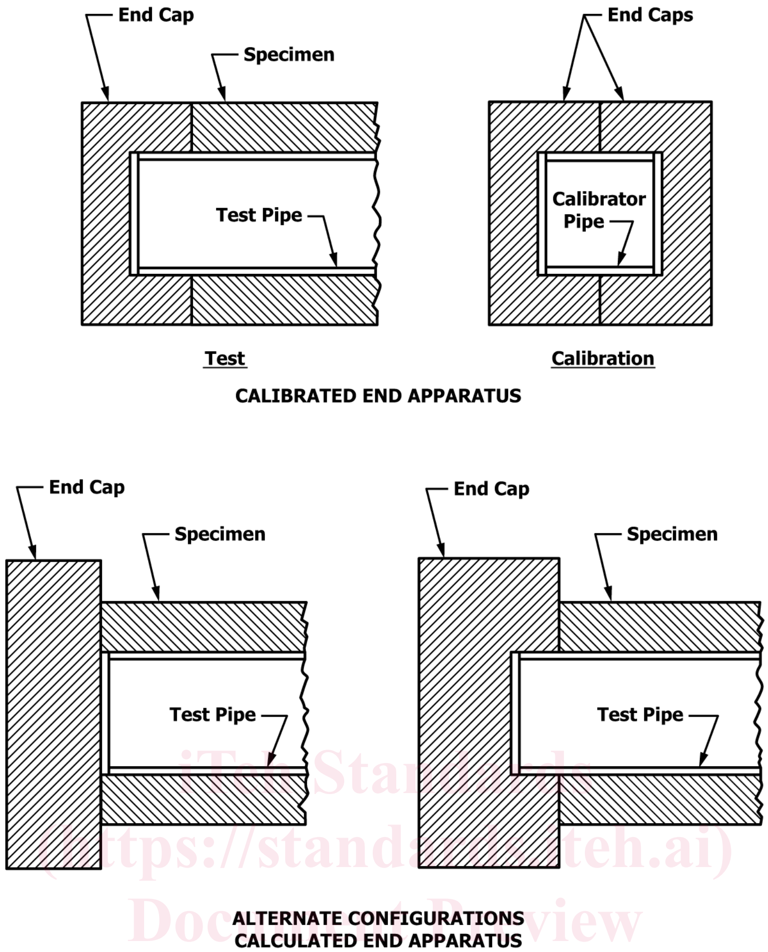

FIG. 2 Calibrated or Calculated-End Apparatus

5.3 *Guarded-End Apparatus* (Fig. 1), uses separately heated pipe sections at each end of the test section to accomplish the purposes of minimizing axial heat flow in the apparatus, of aiding in achieving uniform temperatures in the test section, and of extending these temperatures beyond the test section length so that all heat flow in the test section is in the radial direction. Both test and guard section heaters shall be designed to achieve uniform temperatures over the length of each section. This typically requires the use of auxiliary heaters at the outside ends of single guards or the use of double guards.

5.3.1 The length of the guard section (or the combined length of double guards) shall be sufficient to limit at each end of the test section the combined axial heat flow in both apparatus and specimen to less than 1% of the test section measured heat flow. A guard section length of approximately 200 mm [4 in.] has been found satisfactory for apparatus of 88.9 mm (nominal 80-mm [nominal 3-in.] pipe size) when testing specimens that are essentially homogeneous, are only moderately nonisotropic, and are of a thickness not greater than the pipe diameter. Longer guard sections are usually required when testing thicker specimens or when the specimen possesses a high axial conductance.

5.3.2 A gap shall be provided between the guards and the test section, and between each guard section if double-guarded, in both the heater pipe and the test pipe (except for small bridges necessary for structural support). It is highly desirable that all support bridges of high conductance be limited to the test pipe since any bridges in heater pipes or internal support members make it difficult or impossible to achieve uniform surface temperatures while at the same time minimizing end losses in the apparatus. Internal barriers shall be installed at each gap to minimize convection and radiation heat transfer between sections.

5.3.3 Thermocouples of wire as small as possible but not larger than 0.64 mm [0.025 in. (22 Awg)] and meeting the requirements of 5.11, shall be installed in the test pipe surface on both sides of each gap, and not more than 25 mm [1 in.] from the gap, for the purpose of monitoring the temperature difference across each gap. It is acceptable to connect the thermocouples in series and use as a differential thermopile. Similar thermocouples shall also be installed on any heater pipes or support members that provide a highly conductive path from test section to guard sections.