



# Standard Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulation<sup>1</sup>

This standard is issued under the fixed designation C 335; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers the measurement of the steady-state heat transfer properties of pipe insulations installed on a horizontal test pipe operating at temperatures above ambient. Specimens may be rigid, flexible, or loose fill, may be homogeneous or nonhomogeneous, isotropic or nonisotropic, and of 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 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):

1.2.1 The pipe insulation lineal thermal resistance and conductance,

1.2.2 The pipe insulation lineal thermal transference,

1.2.3 The surface areal resistance and heat transfer coefficient,

1.2.4 The thermal resistivity and conductivity,

1.2.5 The areal thermal resistance and conductance, and

1.2.6 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.

NOTE 2—Discussions of the appropriateness of these properties to particular specimens or materials may be found in Test Method C 177, Test Method C 518, and in the literature (1).<sup>2</sup>

1.3 This test method allows for operation over a wide range of temperatures. The upper limit of the pipe surface tempera-

ture is determined by the maximum service temperature of the specimen or of the materials used in constructing the apparatus. The lower limit is determined by the restriction that it be sufficiently greater than the temperature of the specimen outer surface to provide the precision of measurement desired. Normally the apparatus is operated in closely controlled still air ambient from 15 to 30°C, but this may be extended to other temperatures, other gases, and other velocities. The outer specimen surface temperature may also be fixed by the use of a heated or cooled outer sheath or blanket or by the use of an additional uniform layer of insulation.

1.4 The test pipe may be of any size or shape 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).

1.5 The test method applies only to test pipes with a horizontal axis. Other orientations, such as vertical, require special precautions, which are being considered for a separate method.

1.6 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.

1.6.1 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 may be used for all types of specimens within the scope of this test method and must be used for specimens incorporating elements of high axial conductance, such as reflective insulations or metallic jackets.

1.6.2 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 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

<sup>1</sup> 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.

Current edition approved December 1, 2003. Published January 2004. Originally approved in 1954. Last previous edition approved in 2003 as C 335 – 03.

<sup>2</sup> The boldface numbers in parentheses refer to the references at the end of this test method.

such as reflective insulations or metallic jackets whose effect may not be adequately covered by calibration or calculation.

1.7 SI units are standard for this test method. Conversion factors to other units are given in Table 1. The units used must accompany all numerical values.

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:*<sup>3</sup>
  - C 168 Terminology Relating to Thermal Insulation
  - C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
  - C 302 Test Method for Density and Dimensions of Preformed Pipe-Covering-Type Thermal Insulation
  - C 518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
  - C 680 Practice for Estimate of Heat Gain or Loss, and Surface Temperature of Insulated Flat, Cylindrical, and Spherical Systems by the Use of a Computer Program
  - C 870 Practice for Conditioning of Thermal Insulating Materials

<sup>3</sup> 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.

- C 1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions
- E 230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

**3. Terminology**

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology C 168.

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*.

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

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 may be 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  $2L(r_2 - r_o) / \ln(r_2/r_o)$ , 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

**TABLE 1 Conversion Factors (International Table)**

NOTE—For thermal conductance per unit length or thermal transference per unit length, use the inverse of the table for thermal resistance per unit length. For thermal resistivity, use the inverse of the table for thermal conductivity. For thermal conductance (per unit area) or thermal transference (per unit area), use the inverse of the table for thermal resistance (per unit area).

Thermal Resistance per Unit Length <sup>A</sup>						
	K·m·W <sup>-1(B)</sup>	K·cm·W <sup>-1</sup>	K·cm·s·cal <sup>-1</sup>	K·m·h·kg·cal <sup>-1</sup>	°F·ft·h·Btu <sup>-1</sup>	
1 K·m·W <sup>-1</sup> =	1.000	100.0	418.7	1.163	1.731	
1 K·cm·W <sup>-1</sup> =	1.000 × 10 <sup>-2</sup>	1.000	4.187	1.163 × 10 <sup>-2</sup>	1.731 × 10 <sup>-2</sup>	
1 K·cm·s·cal <sup>-1</sup> =	2.388 × 10 <sup>-3</sup>	0.2388	1.000	2.778 × 10 <sup>-3</sup>	4.134 × 10 <sup>-3</sup>	
1 K·m·h·kg·cal <sup>-1</sup> =	0.8598	85.98	360.0	1.000	1.488	
1 °F·ft·h·Btu <sup>-1</sup> =	0.5778	57.78	241.9	0.6720	1.000	
Thermal Conductivity <sup>A</sup>						
	W·m <sup>-1</sup> ·K <sup>-1(B)</sup>	W·cm <sup>-1</sup> ·K <sup>-1</sup>	cal·s <sup>-1</sup> ·cm <sup>-1</sup> ·K <sup>-1</sup>	kg·cal·h <sup>-1</sup> ·m <sup>-1</sup> ·K <sup>-1</sup>	Btu·h <sup>-1</sup> ·ft <sup>-1</sup> ·°F <sup>-1</sup>	Btu·in. <sup>-1</sup> ·h <sup>-1</sup> ·ft <sup>-2</sup> ·°F <sup>-1</sup>
1 W·m <sup>-1</sup> ·K <sup>-1</sup> =	1.000	1.000 × 10 <sup>-2</sup>	2.388 × 10 <sup>-3</sup>	0.8598	0.5778	6.933
1 W·cm <sup>-1</sup> ·K <sup>-1</sup> =	100.0	1.000	0.2388	85.98	57.78	693.3
1 cal·s <sup>-1</sup> ·cm <sup>-1</sup> ·K <sup>-1</sup> =	418.7	4.187	1.000	360.0	241.9	2903.
1 kg·cal·h <sup>-1</sup> ·m <sup>-1</sup> ·K <sup>-1</sup> =	1.163	1.163 × 10 <sup>-2</sup>	2.778 × 10 <sup>-3</sup>	1.000	0.6720	8.064
1 Btu·h <sup>-1</sup> ·ft <sup>-1</sup> ·°F <sup>-1</sup> =	1.731	1.731 × 10 <sup>-2</sup>	4.134 × 10 <sup>-3</sup>	1.488	1.000	12.00
1 Btu·in. <sup>-1</sup> ·h <sup>-1</sup> ·ft <sup>-2</sup> ·°F <sup>-1</sup> =	0.1442	1.442 × 10 <sup>-3</sup>	3.445 × 10 <sup>-4</sup>	0.1240	8.333 × 10 <sup>-2</sup>	1.000
Thermal Resistance per Unit Area <sup>A</sup>						
	K·m <sup>2</sup> ·W <sup>-1(B)</sup>	K·cm <sup>2</sup> ·W <sup>-1</sup>	K·cm <sup>2</sup> ·s·cal <sup>-1</sup>	K·m <sup>2</sup> ·h·kg·cal <sup>-1</sup>	°F·ft <sup>2</sup> ·h·Btu <sup>-1</sup>	
1 K·m <sup>2</sup> ·W <sup>-1</sup> =	1.000	1.000 × 10 <sup>4</sup>	4.187 × 10 <sup>4</sup>	1.163	5.678	
1 K·cm <sup>2</sup> ·W <sup>-1</sup> =	1.000 × 10 <sup>-4</sup>	1.000	4.187	1.163 × 10 <sup>-4</sup>	5.678 × 10 <sup>-4</sup>	
1 K·cm <sup>2</sup> ·s·cal <sup>-1</sup> =	2.388 × 10 <sup>-5</sup>	0.2388	1.000	2.778 × 10 <sup>-5</sup>	1.356 × 10 <sup>-4</sup>	
1 K·m <sup>2</sup> ·h·kg·cal <sup>-1</sup> =	0.8598	8.594 × 10 <sup>3</sup>	3.600 × 10 <sup>4</sup>	1.000	4.882	
1 °F·ft <sup>2</sup> ·h·Btu <sup>-1</sup> =	0.1761	1.761 × 10 <sup>3</sup>	7.373 × 10 <sup>3</sup>	0.2048	1.000	

<sup>A</sup> Units are given in terms of (1) the absolute joule per second or watt, (2) the calorie (International Table) = 4.1868 J, or the British thermal unit (International Table) = 1055.06 J.

<sup>B</sup> This is the SI (International System of Units) unit.

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,  $C$ .

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

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.

$$T_r = \frac{Q}{2\pi r_2 L(t_o - t_a)} \quad (4)$$

3.2.4 *pipe insulation lineal thermal conductance,  $C_p$* —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 insulation outer surface temperature. It is the reciprocal of the pipe insulation lineal thermal resistance,  $R_p$ .

$$C_p = \frac{Q}{L(t_o - t_2)} = \frac{1}{R_p} \quad (5)$$

3.2.5 *pipe insulation lineal thermal resistance,  $R_p$* —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,  $C_p$ .

$$R_p = \frac{L(t_o - t_2)}{Q} = \frac{1}{C_p} \quad (6)$$

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,  $\lambda_p$* —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,  $r_p$ . For pipe insulation of circular cross section, the pipe insulation thermal conductivity is:

$$\lambda_p = \frac{Q \ln(r_2/r_o)}{L2\pi(t_o - t_2)} = \frac{1}{r_p} \quad (8)$$

3.2.8 *pipe insulation thermal resistivity,  $r_p$* —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,  $\lambda_p$ . For pipe insulation of circular cross section, the pipe insulation thermal resistivity is calculated as follows:

$$r_p = \frac{2\pi L(t_o - t_2)}{Q \ln(r_2/r_o)} = \frac{1}{\lambda_p} \quad (9)$$

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: Symbols* see 1.7:

$C_p$	= pipe insulation lineal thermal conductance, W/m·K,
$R_p$	= pipe insulation lineal thermal resistance, K·m/W,
$T_{r_p}$	= pipe insulation lineal thermal transference, W/m·K,
$\lambda_p$	= pipe insulation thermal conductivity, W/m·K,
$r_p$	= pipe insulation thermal resistivity, K·m/W,
$h_2$	= surface areal heat transfer coefficient of insulation outer surface, W/m <sup>2</sup> ·K,
$C$	= areal thermal conductance, W/m <sup>2</sup> ·K,
$R$	= areal thermal resistance, K·m <sup>2</sup> /W,
$T_r$	= areal thermal transference, W/m <sup>2</sup> ·K,
$Q$	= time rate of heat flow to the test section of length $L$ , W,
$t_o$	= temperature of pipe surface, K,
$t_1$	= temperature of insulation inside surface, K,
$t_2$	= temperature of insulation outside surface, K,
$t_a$	= temperature of ambient air or gas, K,
$r_o$	= outer radius of circular pipe, m,
$r_1$	= inner radius of circular insulation, m,
$r_2$	= outer radius of circular insulation, m,
$L$	= length of test section (see 9.1.1), m, and
$A$	= area of specified surface, m <sup>2</sup> .

#### 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 may be somewhat different from those obtained on apparently similar material in flat form using the guarded hot plate, Test Method C 177, or the heat flow meter apparatus, Test Method C 518.

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, it should be recognized 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 a condition may not be 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 pipes of the same size and temperature, operating in the same ambient environment, values obtained by this test method may be used for the intercomparison 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). For such use, it may be necessary to 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 may consist 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 C 680). 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 This test method may be used 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.

4.5 For satisfactory results in conformance with this test method, the principles governing construction and use of apparatus described in this test method should 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.

4.6 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 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 insulation's properties vary in the radial direction, the experimental heat flow direction will significantly affect the measured thermal conductivity. Therefore great care should be exercised 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 it may be advantageous to provide internal circulating fans or to fill the pipe with a heat transfer fluid to achieve uniform temperatures. The guarded end design also requires, at each end of the test section, a short section of pipe with its own separately controlled heater (see 5.3 and Fig. 1) while 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.<sup>4</sup>

NOTE 5—Experiments have been reported that use an electrically heated cylindrical screen rather than an internally heated pipe (5). 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 an insulated electrical resistance wire or ribbon on the surface or in the grooves of a separate pipe, internal to the test pipe. This heater pipe may either be a snug fit inside the test pipe, in which case the contact must be uniform to achieve uniform test pipe temperatures, or the heater pipe may be smaller so that heat is transferred across a uniform air gap. 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 9.4). A test section length of approximately 0.5 m has proven satisfactory for an apparatus with a circular

<sup>4</sup> Documents showing details of both guarded-end and calibrated-end apparatus complying with the requirements of this method are available from ASTM for a nominal fee. Order Adjunct: ADJC033501 for the Guarded-End Apparatus and Adjunct: ADJC033502 for the Calibrated-End Cap Apparatus.



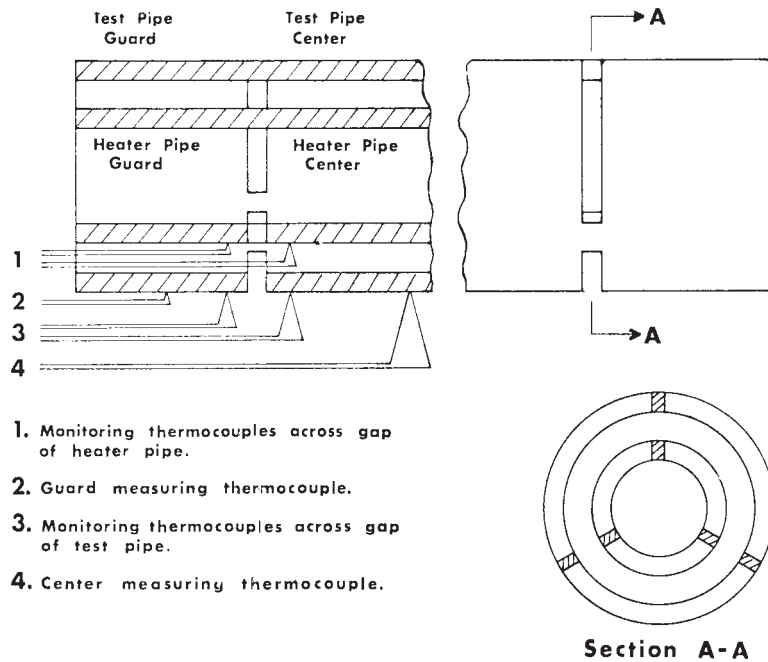


FIG. 1 Guarded-End Apparatus

cross-section of 88.9 mm (standard 80-mm, (3-in.) pipe size) that is often used for inter-laboratory comparisons. However, this length may not be satisfactory for all sizes of apparatus or for all test conditions, and 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.

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 may require 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 has been found satisfactory for apparatus of 88.9 mm (standard nominal 80-mm (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 may be 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 (which may be connected as differential thermopiles), of wire as small as possible but not larger than 0.64 mm (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 from the gap, for the purpose of monitoring the temperature difference across each gap. 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.

5.4 *Calibrated or Calculated-End Apparatus* (Fig. 2), uses insulated caps at each end of the test section to minimize axial heat flow. The measured test section heat loss is then corrected for the end cap loss, that may be determined either by direct calibration under the conditions of test (the calibrated-end apparatus) or by calculation, using known material properties (the calculated-end apparatus). Internal electric heaters shall be provided to heat the test section uniformly over its length. It may be necessary to provide supplementary internal heaters at each end to compensate for the end heat loss. The power to such heaters must be included in the measured test section power.

5.4.1 For the calibrated-end apparatus, the end caps shall be of the same cross-section as the test specimen and have approximately the same thermal transfer properties. Each end cap shall have a cavity of minimum depth equal to one half the test pipe diameter (or one half the major cross-section diagonal of noncircular pipes) and of a size and shape to accept the end of the test pipe. The calibrator pipe shall consist of a short section of the same pipe used to construct the test pipe of a length equal to the combined cavity depth of the two end caps.

It shall be fitted with internal heaters similar to those used in the end sections of the test pipe including any supplementary end heaters. A minimum of four thermocouples spaced 90° apart shall be provided in the surface of the calibrator pipe to measure its temperature. They shall meet the requirements of 5.5.1 and be of a wire size as small as possible but in no case larger than 0.64 mm diameter (22 Awg).

for each 150 mm of length of the test section, whichever is greater, shall be located to sense equally the temperature of all areas of the test section surface. They shall be applied either by peening the individual wires into small holes drilled into the pipe surface not more than 3 mm apart or by joining the wires by a welded bead and cementing them into grooves so that the bead is tangent to the outer surface of the pipe, but does not

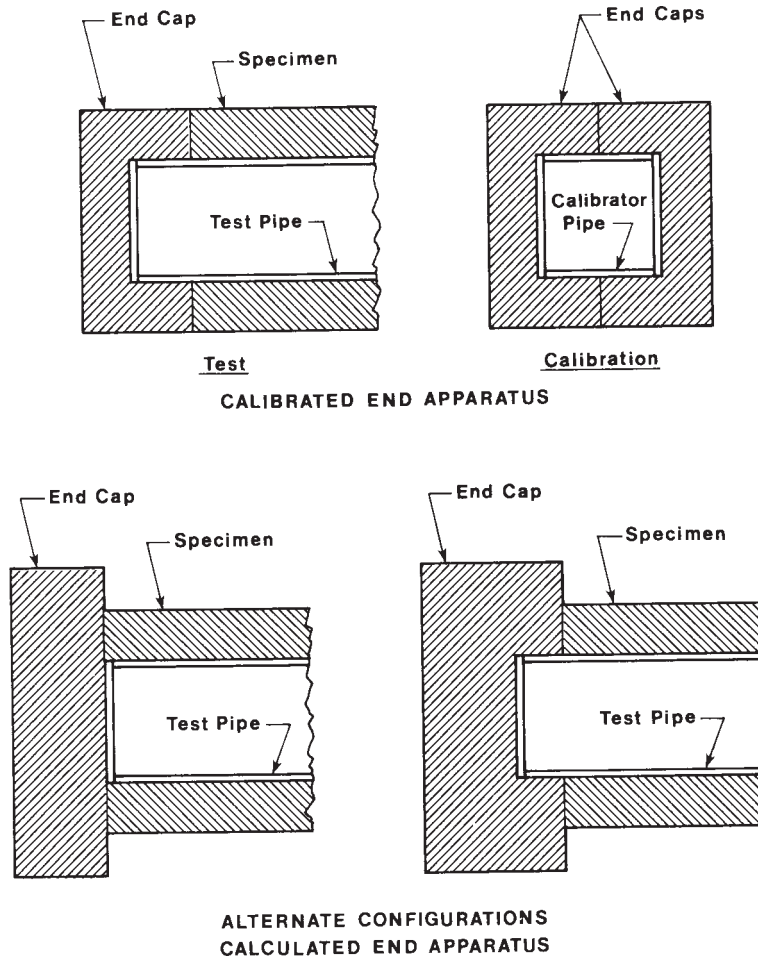


FIG. 2 Calibrated or Calculated-End Apparatus

5.4.2 For the calculated-end apparatus, the end caps shall be as large or larger than the test specimen. They shall be made of homogeneous insulation material of low conductivity and may or may not have a cavity for the test pipe end. The thermal conductivity of the end cap material shall be determined by Test Method C 177 or Test Method C 518 over the temperature range of contemplated use. If the material is not isotropic, the thermal conductivity must be determined in different directions as needed.

5.5 *Thermocouples*, for measuring the surface temperature of the test pipe shall meet the requirements of 5.5.1 and be of a wire size as small as possible, but in no case larger than 0.64 mm (22 Awg) in diameter.<sup>5</sup> At least four thermocouples, or one

project above the surface. For direct averaging, the thermocouples may be connected in parallel, provided their junctions are electrically isolated and the total resistances are essentially equal.

5.5.1 Thermocouples used for this method shall be made of special grade wire as specified in Tables E 230 or shall be individually calibrated to the same tolerance. Generally, thermocouples made from wire taken from the same spool will be found to agree with each other within the required tolerance and thus only one calibration will be required for each spool of wire.

5.6 *Temperature-Measuring System*, excluding the sensor, with an accuracy equivalent to  $\pm 0.1$  K. A d-c potentiometer or digital microvoltmeter is normally used for thermocouple readout.

5.7 *Power Supplies*, for operating the test section heater should be closely regulated and may be either a-c or d-c. Power

<sup>5</sup> Any temperature-measuring sensor can be used, but thermocouples are used predominantly.

supplies for guard heaters, if used, need not be regulated if automatic controllers are used.

5.8 *Power-Measuring System*, capable of measuring the average power to the test section heater with an accuracy of  $\pm 0.5\%$  shall be provided. If power input is steady, this may consist of a calibrated wattmeter or a voltage-measuring system for voltage and amperage (using a standard resistance). If power input is variable or fluctuating, an integrating type of power measurement, using an integrating period long enough to assure a reliable determination of average power, is required. In all cases, care must be taken that the measured power is only that dissipated in the test section. This requires that corrections be applied for power dissipated in leads, dropping resistors, or uncompensated wattmeters.

5.9 For a given set of observations as defined in 10.2.2 the ambient air temperature shall be maintained within  $\pm 1\%$  of the smallest temperature difference between the test pipe and the ambient or to  $\pm 1^\circ\text{C}$ , whichever is greater. The apparatus shall be located in a region of essentially still air and shall not be close to other objects that would alter the pattern of natural convection around the heated specimen. All surfaces or objects that could exchange radiation with the specimen shall have a total hemispherical emittance of at least 0.85 and shall be at approximately the same temperature as the ambient air. Optional equipment may be provided to use gases other than air and to simulate wind effects by establishing forced air velocities of the direction and magnitude desired.

5.10 An optional temperature-controlled jacket should be provided to control the outer surface of the specimen to a temperature different than that of the ambient air. An alternative procedure for raising the outer surface temperature of a specimen is to surround it with an additional layer of thermal insulation. In either case the thermocouples specified in 6.5 for the measurement of the specimen outer surface temperature must be installed prior to placement of the jacket or additional insulation layer. Moreover, the emittance of the inner surface of the jacket or added insulation (facing the specimen) must be greater than 0.8 in order not to reduce any radiation transfer within the specimen. In such cases it is not possible to measure directly the thermal transference for the specimen.

## 6. Test Specimen

6.1 Specimens may be rigid, semi-rigid, or flexible (blanket-type), or loose-fill, suitably contained. Specimens shall be uniform in size and shape throughout their length (except for any intentional irregularities that occur well within the test section) and shall be designed for use on pipes of the same size and shape as the available test apparatus.

6.2 If test results are to be considered as representative of a type of product or of a particular production lot, etc., or of a material (in the case of homogeneous materials), then appropriate sampling plans must be followed. In the absence of such plans, the test results can be considered to represent only the specimens tested.

6.3 The intended purpose of the test must be considered in determining details of the specimen and its applications to the test pipe (Note 7). Some considerations are:

- 6.3.1 The means of securing the specimen to the test pipe.
- 6.3.2 The use of sealants or other materials in the joints.

6.3.3 Whether jackets, covers, bands, reflective sheaths, etc., are included.

6.3.4 For the testing of reflective insulation, it is recommended that at least two insulation sections be mounted within the central test section. While the use of full length specimens within the central test section is preferred, this may not be practical within the limits of existing apparatus.

NOTE 7—Unless other purpose is intended, the specimen should be secured to the test pipe in accordance with normal application practice and may include jackets and other features when desired.

6.4 After the specimen is mounted on the test pipe, measurements of the outside dimensions needed to describe the shape shall be made to within  $\pm 0.5\%$  (both before and after testing). For circular shapes, measurements should be made using a flexible steel tape to obtain the circumference which is divided by  $2\pi$  to obtain the radius  $r_2$ . The test section length shall be divided into at least four equal parts, and dimension measurements shall be taken at the center of each, except that any irregularity being investigated shall be avoided. Additional measurements shall be taken to describe the irregularities. For guarded-end apparatuses, additional measurements at the center of each guard section are also required. Specimens intended to be of uniform cross section dimensions throughout their length should be rejected if any individual dimension measurement (test section or guard) differs from the average of the test section measurements by more than 5%.

6.5 Thermocouples for the measurement of the average outside surface temperature,  $t_2$ , shall be attached to the insulation surface in accordance with the following:

6.5.1 The test section length shall be divided into at least four equal parts and surface thermocouples shall be longitudinally located at the center of each. Large apparatuses will require a greater number of thermocouples. For circular shapes, the thermocouples shall also be circumferentially equally spaced to form helical patterns with an integral number of complete revolutions and with the angular spacing between adjacent locations from 45 to 90°. For non-circular shapes, the thermocouples shall be spaced around in much the same manner but located to obtain an area-weighted average. Any of the above specified locations shall, whenever possible, be offset a distance equal to the specimen thickness from any joint or other irregularity, and additional thermocouples shall be used as necessary to record the surface temperature. In such situations the individual temperatures and locations shall be reported (see 12.1.6).

6.5.2 Thermocouples shall be made of wire not larger than 0.40 mm (26 Awg) and shall meet the requirements of 5.5.1. They shall be fastened to the surface by any means that will hold the junction and the required length of adjacent wire in intimate thermal contact with the surface but does not alter the radiation emittance characteristics of the adjacent surface.

6.5.2.1 For nonmetallic surfaces, a minimum of 100 mm of adjacent wire shall be held in contact with the surface. One satisfactory method of fastening is to use masking tape either adhered to the specimen surface or wrapped around the specimen and adhered to itself.

6.5.2.2 For metallic surfaces, a minimum of 10 mm of adjacent lead wire shall be held in contact with the surface.

Acceptable means of fastening thermocouple junctions are by peening, welding, soldering or brazing, or by use of metallic tape of the same emittance as the surface. Capacitive discharge welding is especially recommended. Small thin strips of metal similar to the surface metal may be welded to the surface to hold the lead wire in contact with the surface.

6.5.3 The average surface temperature is calculated by averaging the individual readings of the surface thermocouples. If desired, the average may be read directly by connecting the thermocouples in parallel, provided that the junctions are electrically isolated and the total electrical resistances are essentially equal.

6.6 Thermocouples meeting the requirements of 5.5.1 shall be installed on elements of high axial heat conductance such as metallic jackets or accessible liners (specimens with such elements must be tested on a guarded-end apparatus) in order to measure axial temperature gradients needed to compute axial heat transfer. These thermocouples shall be installed at both top and bottom locations, and shall be located an equal distance of approximately 45 mm on each side of the gap between the test section and each guard.

## 7. Preparation of Apparatus

7.1 For the evaluation of reflective insulation, air exchange must not occur between the test and guard sections.

7.1.1 Install a fibrous insulation seal, not more than 25 mm wide, between the hot pipe and specimen inner casing to prevent air exchange within this annular space. This seal must be installed in the guard region adjacent to the guard gap and not in the central test section.

## 8. Conditioning

8.1 In general, specimens shall be dried or otherwise conditioned to stable conditions immediately prior to test unless it has been shown that such procedures are unnecessary to achieve reproducible results for the material being tested. Conditioning procedures of the materials specification should be followed when applicable; otherwise, the normal procedure is to dry to constant weight at a temperature of 102 to 120°C, unless the specimen is adversely affected, in which case drying in a desiccator from 55 to 60°C is recommended (see Practice C 870). Weight changes due to conditioning may be determined when desired. Specimen density may be determined by Test Method C 302.

8.2 During the experimentation, operate the apparatus in a controlled room or enclosure so that the ambient temperature does not vary during a test by more than  $\pm 1^\circ\text{C}$  or  $\pm 1\%$  of the difference between the test pipe and the ambient ( $t_o - t_a$ ), whichever is greater. Run the test in essentially still air (or other desired gas) unless appreciable velocity is needed to attain uniform temperatures or when the effect of air velocity is to be included as part of the test conditions. Measure any forced velocity and report its magnitude and direction.

## 9. Procedure

9.1 Measure the test section length,  $L$ , and the specimen outside circumference or other dimensions needed to describe the shape. Normally dimensions used in this method shall be

those measured at ambient temperatures of 10 to 35°C. If properties based upon actual dimensions at operating temperature are desired, the dimensions may be obtained by calculation from those measured at ambient temperature using previously measured or known coefficients of thermal expansion, or they may be determined by direct measurement at operating temperature. Any properties based upon dimensions at operating temperature must be so identified.

9.1.1 For guarded-end pipes, the test length,  $L$ , is the distance between the centerlines of the gaps at the ends of the test section. For calibrated or calculated-end pipes, the test length,  $L$ , is the distance between the end caps.

9.1.2 Take outside dimensions of the specimen at locations described in 6.4.

9.2 Adjust the temperature of the test pipe (or the test section of a guarded-end apparatus) to the desired temperature.

9.3 When using the guarded-end method, adjust the temperature of each guard so that the temperature difference across the gap between the test section and the guard (measured on the surface of the test pipe) is zero or not greater than the amount that will introduce an error of 1% in the measured heat flow. Ideally, the axial temperature gradient across the gaps between the test and guard sections of both the outer test pipe and the internal heater pipe and along any internal support members should be zero to eliminate all axial heat flow within the pipe. In some designs, it is impossible to balance both surface and internal elements at the same time, and it will be necessary to correct for internal apparatus axial losses. When the only support bridges are in the outer test pipe, it is sufficient to bring the test pipe surface gap balance (between test section and guards) to zero and no corrections are needed. When the apparatus uses internal support bridges, it is necessary to use the readings of the internal thermocouples specified in 5.3, along with the known dimensions and properties of the support bridges, to estimate the internal axial losses that must be added to (or subtracted from) the measured power input to the test section. In either case it is often desirable to run two tests, one with the temperature of the guards slightly higher than the test section and one with it slightly lower. Interpolation between these gives an accurate value for the zero balance heat flow along the internal bridges and for the test section power input and provides information on the maximum allowable imbalance that still meets the 1% criterion. One criterion which has often been used is that the allowable imbalance is no greater than 0.5% of the temperature drop through the specimen, ( $t_2 - t_1$ ). This may not hold under all conditions.

9.3.1 When evaluating reflective insulation, measure the temperature gradients along the interior and exterior casings with thermocouples detailed in 6.6. The axial heat conduction along the inner and outer casings should be computed from the average gradients for that casing. Using the average of the four gradients, the total axial heat conduction for all internal liners should be computed. The total axial heat flow for each end of the test section should not exceed  $\pm 1\%$  of the heat input to the heater in the test section.

9.4 Conduct the test as follows:

9.4.1 After steady-state conditions have been attained, determine:



9.4.1.1 The average temperature of the pipe test section,  $t_o$ ,

9.4.1.2 The test section to guard balances (for guarded-end apparatuses),

9.4.1.3 The average temperature of the specimen outer surface,  $t_2$ ,

9.4.1.4 The average ambient air temperature,  $t_a$ , and, if forced air is used, the air velocity, and

9.4.1.5 The average electrical power to the test section heater measured over a minimum 30-min period.

9.4.2 Continue the observations until at least three successive sets of observations of minimum 30-min duration give thermal transfer properties not changing monotonically and not differing by more than 1%. More stringent requirements may be necessary in some cases.

## 10. End Cap Corrections

10.1 Corrections are required for the heat loss through the end caps of calibrated or calculated-end apparatuses, but are not required for the guarded-end apparatus. These corrections, in watts, are obtained either by calibration or calculation of the end cap heat loss and are to be subtracted from the power measured during specimen tests under the same conditions.

10.2 Calibrated-end apparatuses require calibration of the end caps over a range of temperatures that cover the conditions of intended use. It is convenient to run at least three or four calibrations at approximately equally spaced pipe temperatures and to plot a curve of electrical power versus temperature difference between the pipe and the ambient air. Obtain separate calibration curves for each ambient temperature. If the test apparatus is to be used at only one set of conditions, then it may be convenient to interpolate between two tests run in the same ambient but with the calibrator pipe slightly above and slightly below the desired temperature. The procedure for end cap calibration is as follows:

10.2.1 Assemble the end caps to the calibrator pipe and seal the crack with glass fiber or other suitable sealant. Connect the power and thermocouple leads.

10.2.2 Adjust the power input to the heater to achieve the desired temperature. After steady-state conditions are attained, make the necessary observations to determine the following:

10.2.2.1 The temperature of the calibrator pipe,

10.2.2.2 The temperature of the ambient air, and

10.2.2.3 The average electrical power over a minimum 30-min period.

10.2.3 Continue the observations until at least three successive sets of measurements of minimum 30-min duration give heat transfer properties not changing monotonically or more than 1%. More stringent requirements may be necessary in some cases.

10.3 Calculated-end apparatuses require detailed mathematical calculation (such as a finite element analysis) of the heat loss under the conditions of test using known thermal properties of the end cap materials. Material thermal properties should be determined on flat specimens taken from the same lot of material used to construct the end caps, or may be taken from data obtained on other similar material if estimates show that the expected error in corrected test heat loss due to any uncertainty in materials properties is well within the allowable test uncertainty. Measurements of material thermal properties

may be made either by the guarded hot plate, Test Method C 177, or by the heat flow meter, Test Method C 518, and must be taken in all pertinent directions if the material is not isotropic.

## 11. Calculation

11.1 Calculate the corrected test section power input,  $Q$ , from the measured power input as follows:

11.1.1 For guarded-end apparatus with no internal support bridges—no correction needed.

11.1.2 For guarded-end apparatus with internal support bridges, follow the procedure described in 9.3 using measured support gradients, dimensions, and material properties.

11.1.3 For calibrated-end apparatus, use the calibration corrections developed in 10.2.

11.1.4 For calculated-end apparatus, use the corrections developed in 10.3.

11.2 Calculate the heat transfer properties for each of the three or more observations required in 9.4.2 or in 10.2.2 and average the values of those differing by no more than 1% for reporting in 12.1.8. For pipes of circular cross section, make calculations for those properties desired as follows:

11.2.1 Calculate the pipe insulation lineal thermal conductance,  $C_p$ , by means of Eq 5 (see 3.2.4).

11.2.2 Calculate the pipe insulation lineal thermal resistance,  $R_p$ , by means of Eq 6 (see 3.2.5).

11.2.3 Calculate the pipe insulation lineal thermal transference,  $T_{rp}$ , by means of Eq 7 (see 3.2.6).

11.2.4 Calculate the surface areal heat transfer coefficient,  $h_2$ , by means of Eq 10 (see 3.2.9).

11.2.5 When applicable, calculate the pipe insulation thermal conductivity,  $\lambda_p$ , from Eq 8 (see 3.2.7). The thermal conductivity for a large temperature difference is not, in general, the same as that for a small temperature difference at the same mean temperature. When conductivities are measured at three or more mean temperatures, a correction can be made to account for the large temperature difference. The guidelines in Practice C 1045 should be used to make the correction.

11.2.6 When applicable, calculate the pipe insulation thermal resistivity,  $r_p$ , from Eq 9 (see 3.2.8).

11.2.7 When applicable, calculate the areal thermal resistance, conductance and transference from Eq 2-4 (see 3.2.1-3.2.3).

## 12. Report

12.1 The report shall describe the test specimens, the sampling and test procedures, the test apparatus, and the results. Whenever numerical values are reported, both SI and inch-pound units shall be stated. The appropriate items of those listed below shall be included:

12.1.1 Sample description and other identification including the trade and manufacturer's name, the generic type of material, the date of manufacture, the procurement date and source, the nominal size and shape, and when desired, the nominal weight and density. Also include observations of specimen condition including any unusual details both before and after test.

12.1.2 Measured dimensions and, when obtained, the measured weight and density both before and after test. If dimensions are at temperatures other than ambient, the temperature and the means of obtaining the dimensions must be reported.

12.1.3 Description of the application and means of securing the sample to the test pipe including the number, type, and location of any bands or fasteners, the type of jacket or cover if used, and the type and location of any sealants used.

12.1.4 Description of any conditioning or drying procedures followed and, when obtained, the weight, density, or dimensional changes due to conditioning or drying.

12.1.5 Average temperature of the pipe test section,  $t_o$ .

12.1.6 Average temperature of the specimen outside surface,  $t_2$ , and for irregular specimens, the readings and positions of thermocouples used to describe uneven surface temperatures (see 6.5.1).

12.1.7 The type of ambient gas, its average temperature,  $t_a$ , and when forced, the velocity (both magnitude and direction) or details of other means of controlling outer temperature such as extra insulation or temperature-controlled sheath or blankets.

12.1.8 The corrected test section power input,  $Q$ .

12.1.9 The desired thermal transfer properties, including any or all of the following when applicable and the corresponding mean temperature,  $(t_o + t_2)/2$ . These shall be the averages calculated in 9.4:

12.1.9.1 Pipe insulation lineal thermal conductance,  $C_p$ ,

12.1.9.2 Pipe insulation lineal thermal resistance,  $R_p$ ,

12.1.9.3 Pipe insulation lineal thermal transference,  $T_r$ ,

12.1.9.4 Pipe insulation thermal conductivity,  $\lambda_p$ , or the corrected pipe insulation thermal conductivity when available,

12.1.9.5 Pipe insulation thermal resistivity,  $r_p$ ,

12.1.9.6 Insulation surface areal heat transfer coefficient,  $h_2$ ,

12.1.9.7 Areal thermal conductance,  $C$ , with the surface referenced,

12.1.9.8 Areal thermal resistance,  $R$ , with the surface referenced,

12.1.9.9 Areal thermal transference  $T_r$ , with the surface referenced, and

12.1.10 When more than one measurement is made, report if measurements started at the lowest mean temperature and progressed to the maximum test temperature, or started at the highest reported temperature and progressed to the lowest temperature.

12.1.11 Estimates of error of the test results.

12.1.12 Any exceptions made in the test method.

12.1.13 Outlines of, or references to, any special calculations used.

12.2 Graphical representations of results obtained over a temperature range are useful and should be included when applicable. Recommended plots are:

12.2.1 Pipe insulation lineal thermal conductance or resistance, and when applicable, thermal conductivity or resistivity versus mean temperature,  $(t_o + t_2)/2$ .

12.2.2 Pipe insulation lineal thermal transference versus overall temperature difference,  $(t_o - t_a)$ .

### 13. Precision and Bias <sup>6</sup>

13.1 Three interlaboratory round-robin comparison programs have been conducted by ASTM Subcommittee C16.30 to determine the reproducibility of this test method.

13.1.1 Tests performed at several laboratories on a single sample of glass fiber insulation in the range, of mean temperatures from 60 to 160°C and reported in Hollingsworth (6), shows that the measured heat transfer properties should not vary by more than  $\pm 3\%$  of the average.

13.1.2 Tests performed at three laboratories on similar samples of reflective insulation over the hot surface temperature range of 149 to 482°C shows that the heat-transfer properties of reflective insulation materials should not vary by more than  $\pm 7\%$  of the average.

13.1.3 Tests were performed at seven different laboratories using guarded-end horizontal pipe test apparatus on similar samples of preformed mineral fiber pipe insulation. The hot surface temperature range was 46 to 670°C. The maximum deviation from the average was + 10 % and – 9 % (7).

13.1.4 Tests performed at seven different laboratories using the horizontal guarded-end apparatus and at one laboratory using an unguarded cylindrical screen test apparatus on two samples of calcium silicate insulation in the range of mean temperatures from 35 to 390°C did not vary by more than 6.3 % of the average (8).

13.2 The behavior of this test method outside the reported conditions is unproven, and additional comparisons at higher temperatures are recommended when suitable high-temperature standards are developed.

### 14. Keywords

14.1 apparent thermal conductivity; experimental design; radial heat transfer; steady state heat transfer; thermal resistance

<sup>6</sup> Supporting data for these round robins have been filed at ASTM Headquarters. Request RR: C16-1003, RR: C16-1004, and RR: C16-1019.

## REFERENCES

- (1) ASTM Subcommittee C16.30, "What Property Do We Measure?," *Heat Transmission Measurements in Thermal Insulations, ASTM STP 544*, 1974, pp. 5–12.
- (2) Kimball, L. R., "Thermal Conductance of Pipe Insulation—A Large Scale Test Apparatus," *Heat Transmission Measurements in Thermal Insulations, ASTM STP 544*, 1974, pp. 135–146.
- (3) Svedberg, R. C., Steffen, R. J., Rupp, A. M., and Sadler, J. W., "Evaluation of High-Temperature Pipe Insulations Using a 16-inch Diameter Pipe Test Apparatus," *Thermal Transmission Measurements in Thermal Insulations, ASTM STP 660*, 1978, pp. 374–405.
- (4) Electric Power Research Institute Project 1730-1, "Control of Containment Air Temperature: An Industry Survey and Insulation Test," 1982.
- (5) Jury, S. H., McElroy, D. L., and Moore, J. P., "Pipe Insulation Testers," *Thermal Transmission Measurements in Thermal Insulations, ASTM STP 660*, 1978, pp. 310–326.
- (6) Hollingsworth, Marion, Jr., "An Interlaboratory Comparison of the ASTM C335 Pipe Insulation Test," *Thermal Transmission Measurements in Thermal Insulations, ASTM STP 660*, 1978, pp. 50–59.
- (7) Smith, David R., "Interlaboratory Comparison of the Capabilities of Guarded-End Horizontal Test Pipe Apparatus in Measuring Apparent Thermal Conductivity of Mineral-Wool-Fiber Pipe Insulation," Report to Be Published, National Institute of Standards and Technology, Boulder, CO.
- (8) Whitaker, T. E., Graves, R. S., McElroy, D. L., and Smith, D. R., "Interlaboratory Comparison of the Horizontal Pipe Insulation Test Apparatus up to 350°C," Submitted to 22nd International Thermal Conductivity Conference, Arizona State University, Tempe, AZ.

*ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.*

*This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.*

*This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org).*