Designation: C 1033 – 85 (Reapproved 1994)$^{\epsilon 1}$

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

This standard is issued under the fixed designation C 1033; 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.

ϵ^1 NOTE—Keywords were added editorially in March 1994.

1. Scope

1.1 This test method covers the measurement of the steady-state heat transfer properties of pipe insulations for pipes operating at temperatures above the ambient environment from approximately 40°C to the maximum insulation design temperature. Specimens may be rigid, flexible, or loose-fill, may be homogeneous or nonhomogeneous, isotropic or nonisotropic, and of circular or noncircular cross section. Measurement of metallic reflective insulations is included in this test method; however, additional precautions must be taken when these materials are being evaluated.

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 thermal resistance and conductance,

1.2.2 The thermal transference,

1.2.3 The surface resistance and heat transfer coefficient, and

1.2.4 The apparent thermal resistivity and conductivity.

1.3 This test method applies only for testing of insulations on vertical pipes, and the results will only apply for insulations installed vertically (see Note 1).

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 an 88.9-mm outside diameter (standard nominal 80-mm, 3-in. pipe size).

1.5 This test method covers only the guarded-end type of pipe apparatus. No experience has been gathered with the calibrated or calculated-end pipe apparatus; therefore, this type of tester is not included as part of this specification.

1.6 The values stated in SI units are to be regarded as the standard. Conversion factors to other units are given in Table 1. The units used must accompany all numerical values.

NOTE 1—Measurement of insulations installed horizontally is covered in Test Method C 335 and Test Method C 691.

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.[2]

1.7 *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[3]

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[3]

C 302 Test Method for Density of Preformed Pipe-Covering-Type Thermal Insulation[3]

C 335 Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulations[3]

C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[3]

C 680 Practice for Determination of Heat Gain or Loss and the Surface Temperatures of Insulated Pipe and Equipment Systems by the Use of a Computer Program[3]

C 691 Test Method for Steady-State Thermal Transmission Properties of Nonhomogeneous Pipe Insulation Installed Horizontally[4]

C 870 Practice for Conditioning of Thermal Insulating Materials[3]

E 230 Temperature Electromotive Force (EMF) Tables for

[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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[2] ASTM Subcommittee C16.30, "What Property Do We Measure," *Heat Transmission Measurements in Thermal Insulations, ASTM STP 544*, ASTM, 1974, pp. 5–12.

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

[4] Discontinued—See 1986 *Annual Book of ASTM Standards*, Vol 04.06.

TABLE 1 Conversion Factors (International Table)

NOTE 1—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[A]					
	$K{\cdot}m{\cdot}W^{-1}$[B]	$K{\cdot}cm{\cdot}W^{-1}$	$K{\cdot}cm{\cdot}s{\cdot}cal^{-1}$	$K{\cdot}m{\cdot}h{\cdot}kg\text{-}cal^{-1}$	$°F{\cdot}ft{\cdot}h{\cdot}Btu^{-1}$
$1\ K{\cdot}m{\cdot}W^{-1}$ =	1.000	100.0	418.7	1.163	1.731
$1\ K{\cdot}cm{\cdot}W^{-1}$ =	1.000×10^{-2}	1.000	4.187	1.163×10^{-2}	1.731×10^{-2}
$1\ K{\cdot}cm{\cdot}s{\cdot}cal^{-1}$ =	2.388×10^{-3}	0.2388	1.000	2.778×10^{-3}	4.134×10^{-3}
$1\ K{\cdot}m{\cdot}h{\cdot}kg\text{-}cal^{-1}$ =	0.8598	85.98	360.0	1.000	1.488
$1°F{\cdot}ft{\cdot}h{\cdot}Btu^{-1}$ =	0.5778	57.78	241.9	0.6720	1.000

Thermal Conductivity[A]						
	$W{\cdot}m^{-1}{\cdot}K^{-1}$[B]	$W{\cdot}cm^{-1}{\cdot}K^{-1}$	$cal{\cdot}s^{-1}{\cdot}cm^{-1}{\cdot}K^{-1}$	$kg\text{-}cal{\cdot}h^{-1}{\cdot}m^{-1}{\cdot}K^{-1}$	$Btu{\cdot}h^{-1}{\cdot}ft^{-1}{\cdot}°F^{-1}$	$Btu{\cdot}in.{\cdot}h^{-1}{\cdot}ft^{-2}{\cdot}°F^{-1}$
$1\ W{\cdot}m^{-1}{\cdot}K^{-1}$=	1.000	1.000×10^{-2}	2.388×10^{3}	0.8598	0.5778	6.933
$1\ W{\cdot}cm^{-1}{\cdot}K^{-1}$=	100.0	1.000	0.2388	85.98	57.78	693.3
$1\ cal{\cdot}s^{-1}{\cdot}K^{-1}$=	418.7	4.187	1.000	360.0	241.9	2903.
$1\ kg{\cdot}cal{\cdot}h^{-1}{\cdot}K^{-1}$=	1.163	1.163×10^{-2}	2.778×10^{-3}	1.000	0.6720	8.064
$1\ Btu{\cdot}h^{-1}{\cdot}ft^{-1}{\cdot}°F^{-1}$=	1.731	1.731×10^{-2}	4.134×10^{-3}	1.488	1.000	12.00
$1\ Btu{\cdot}in.{\cdot}h^{-1}{\cdot}ft^{-2}{\cdot}°F^{-1}$=	0.1442	1.442×10^{-3}	3.445×10^{-4}	0.1240	8.333×10^{-2}	1.000

Thermal Resistance per Unit Area[A]					
	$K{\cdot}m^2{\cdot}W^{-1}$[B]	$K{\cdot}cm^2{\cdot}W^{-1}$	$K{\cdot}cm^2{\cdot}s{\cdot}cal^{-1}$	$K{\cdot}m^2{\cdot}h{\cdot}kg\text{-}cal^{-1}$	$°F{\cdot}ft^2{\cdot}h{\cdot}Btu^{-1}$
$1\ K{\cdot}m^2{\cdot}W^{-1}$ =	1.000	1.000×10^{4}	4.187×10^{4}	1.163	5.678
$1\ K{\cdot}cm^2{\cdot}W^{-1}$ =	1.000×10^{-4}	1.000	4.187	1.163×10^{-4}	5.678×10^{-4}
$1\ K{\cdot}cm^2{\cdot}s{\cdot}cal^{-1}$ =	2.388×10^{-5}	0.2388	1.000	2.778×10^{-5}	1.356×10^{-4}
$1\ K{\cdot}m^2{\cdot}h{\cdot}kg\text{-}cal^{-1}$ =	0.8598	8.594×10^{3}	3.600×10^{4}	1.000	4.882
$1°F{\cdot}ft^2{\cdot}h{\cdot}Btu^{-1}$ =	0.1761	1.761×10^{3}	7.373×10^{3}	0.2048	1.000

[A] 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.
[B] This is the SI (International System of Units) unit.

Standardized Thermocouples[5]

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 *pipe insulation thermal conductance, C*—the steady-state time rate of heat flow per unit pipe area 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 thermal resistance, *R*.

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

3.2.2 *pipe insulation thermal resistance, R*—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 area. It is the reciprocal of the pipe insulation thermal conductance, *C*.

$$R = \frac{A_o(t_o - t_2)}{Q} = \frac{1}{C} \tag{2}$$

3.2.3 *pipe insulation thermal transference, T_r*—the steady-state time rate of heat flow per unit pipe area 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.

$$T_r = \frac{Q}{A_o(t_o - t_a)} \tag{3}$$

3.2.4 *surface 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:

$$h_2 = \frac{Q}{A_2(t_2 - t_a)} \tag{4}$$

3.2.5 *pipe insulation apparent thermal conductivity, λ—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 apparent thermal resistivity, *r*. For pipe insulation of circular cross section, the pipe insulation apparent thermal conductivity is:

$$\lambda = \frac{Q\,1n(r_2/r_o)}{L2\pi(t_o - t_2)} = \frac{1}{r} \tag{5}$$

3.2.6 *pipe insulation apparent thermal resistivity, r—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

[5] *Annual Book of ASTM Standards*, Vol 14.03.

includes the 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 apparent thermal conductivity, λ. For pipe insulation of circular cross section, the pipe insulation apparent thermal resistivity is:

$$r = \frac{2\pi L(t_o - t_2)}{Q \ln(r_2/r_o)} = \frac{1}{\lambda} \quad (6)$$

3.3 *Symbols:* (see 1.6):

C = pipe insulation thermal conductance, $W/m^2 \cdot K$,
R = pipe insulation thermal resistance, $K \cdot m^2/W$,
T_r = pipe insulation thermal transference, $W/m^2 \cdot K$,
λ = pipe insulation apparent thermal conductivity, $W/m \cdot K$,
r = pipe insulation apparent thermal resistivity, $K \cdot m/W$,
h_2 = surface heat transfer coefficient of insulation outer surface, $W/m^2 \cdot K$,
Q = time rate of heat flow in test section, 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,
A_o = area of pipe test section surface, m^2, and
A_2 = area of external surface of specimen test section, m.

4. Significance and Use

4.1 As determined by this test method, the pipe thermal resistance or conductance (and, where applicable, the apparent thermal resistivity or conductivity) are means of comparing insulations that include the effects of the insulation and its fit upon the pipe 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. The pipe 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.

4.2 The thermal properties determined by this test method are not true material properties since they include the effects of the fit upon the pipe (including the air space resistances), orientation, and the effect of any longitudinal and circumferential joints. Therefore, properties determined by this test method may be somewhat different than that 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, or similar material in pipe form using Test Method C 335.

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, the 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 vertical 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 estimating heat loss of actual applications of specimens identical to those tested (including any jackets, joints, or surface treatments). For such use, it may be necessary to correct for the effect of end joints and other recurring irregularities (see 4.6).

4.3.2 When applying the results to insulation sizes and thicknesses 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, temperature, and orientation.

4.4 It is difficult to measure the thermal performance of reflective insulations which 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 may be altered, which would affect the measured performance. Therefore, it must be recognized that the measured thermal performance of less than full length insulation sections may not represent that of full length sections.

4.5 The design of the guarded-end pipe apparatus is based upon negligible heat flow across the guard gaps in both the insulation specimen and the test pipe. Some nonhomogeneous and reflective insulations may have to be modified at the end over the guard gap in order to prevent axial heat flow. While these modifications are not desirable and should be avoided, 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 may not represent the performance of standard insulation sections.

4.6 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

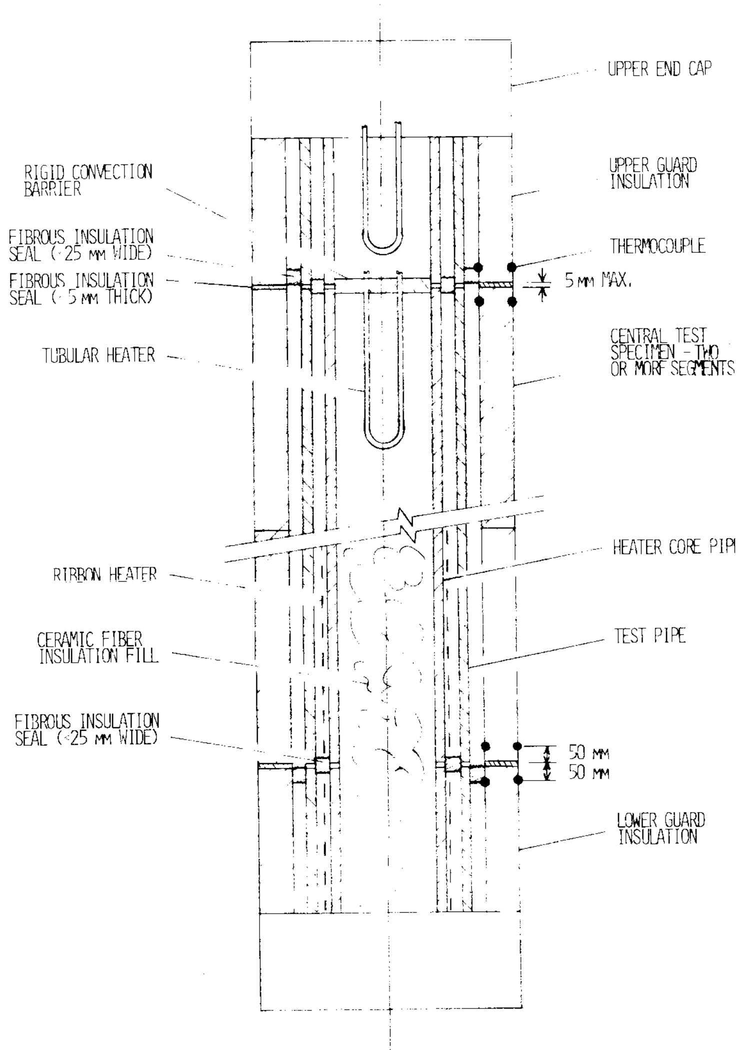

FIG. 1 Cross Section of Vertical Hot Pipe Illustrating Convection Seals and Packing Required to Isolate and Eliminate Internal Convection

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 To assure satisfactory results in the use of this test method, the principles governing the size, 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 of the pertinent requirements prescribed in this method shall be met or all exceptions shall be noted and detailed 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. Standardization of this test method does not reduce the need for technical knowledge. It is recognized also that it would be unwise to restrict the further development of improved or new test methods or procedures by research workers because of standardization of this test method.

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 (see Notes 3 and 4). In a 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 a separately controlled heater (see 5.3 and Fig. 1). 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.[6]

NOTE 3—Experiments have been reported that use an electrically heated cylindrical screen rather than an internally heated pipe (see the

[6] Documents showing details of a guarded-end apparatus complying with the requirements of this test method are available from ASTM, 1916 Race St., Philadelphia, PA 19103, at a nominal charge. Request Adjunct No. 12-303350-00.

literature[7]). While these designs and the accompanying analysis are not included in this test method, their findings are pertinent to this standard.

NOTE 4—The most commonly used heater consists of an insulated electrical resistance wire or ribbon on the surface or in 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 test method the combination of heater winding and heater pipe will be called either a "heater" or a "heater pipe."

5.2 *Length of Test Section*—No restriction is placed on the cross-section size or shape of the apparatus pipe, but the length of the test section must be sufficient to ensure that the total measured heat flow is large enough, 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 having an outer diameter of 88.9 mm (standard 80 mm, 3 in. pipe size) that is often used for interlaboratory 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. Several other sizes are reported in the literature.[8,9,10] 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*, (see 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 *Length of Guard Section*—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 (see 9.4). A guard section length of approximately 200 mm has been found satisfactory for apparatus of 88.9 mm (standard nominal 88.9-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 specimens possess a high axial conductance. 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).

5.3.2 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. 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 5.10, 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 *Thermocouples*, for measuring the surface temperature of the test pipe and the ambient air shall meet the requirements of 5.10 and be of a wire size as small as possible, but in no case larger than 0.64 mm (22 Awg) in diameter.

5.4.1 Thermocouples used for this test 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 samespool 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.

5.4.2 For surface temperature measurement, at least four thermocouples, or one 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 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.

5.4.3 For ambient air temperature measurement, at least three equally spaced thermocouples shall be used.

5.5 *Temperature-Measuring System*, excluding the sensor, with an accuracy of ±0.1 K. A dc potentiometer or digital microvoltmeter is normally used for thermocouple readout.

5.6 *Power Supplies*, for operating the test section heatermay be either ac or dc. Power supplies for guard heaters, if used, need not be regulated if automatic controllers are used.

5.7 *Power-Measuring System*, capable of measuring the average power to the test section heater with an accuracy of ±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

[7] Jury, S. H., McElroy, D. L., and Moore, J. D., "Pipe Insulation Testers," *Thermal Transmission Measurements of Insulation, ASTM STP 660*, ASTM, 1978, pp. 310–326.

[8] Kimball, L. R., "Thermal Conductance of Pipe Insulation—A Large Scale Test Apparatus," *Heat Transmission Measurements in Thermal Insulations, ASTM STP 544*, ASTM, 1974, pp. 135–146.

[9] 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*, ASTM, 1978, pp. 374–405.

[10] Electric Power Research Institute Project 1730-1, "Control of Containment Air Temperature: An Industry Survey and Insulation Test," 1982.

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.

5.8 *Temperature-Controlled Enclosure or Room*, capable of maintaining the ambient air temperature to within ±1 % of the smallest temperature difference between the test pipe and the ambient or to ±1°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.

5.9 *Optional Temperature-Controlled Jacket*, 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 6.4 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, flexible (blanket-type), or loose-fill, suitably contained. The specimen used for a test must be sufficiently uniform in structure to represent the material from which it is taken.

6.2 The intended purpose of the test must be considered in determining details of the specimen and its applications to the test pipe. Some considerations are:

6.2.1 The means of securing the specimen to the test pipe.

6.2.2 The use of sealants or other materials in the joints.

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

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

6.3 After the specimen is mounted on the test pipe, measurements of the outside dimensions needed to describe the shape shall be made to within± 0.5 % (both before and after testing). Measurements should be made using a flexible steel tape to obtain the circumference which is divided by 2π 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.

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

6.4.1 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. 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°. 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 11.1.6).

6.4.2 Thermocouples shall be made of wire not larger than 0.40 mm (26 Awg) and shall meet the requirements of 5.10. 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.

6.4.2.1 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.

6.4.2.2 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. The method of attachment should not alter the radiative characteristics of the insulation jacket in the immediate vicinity of the junction.

6.4.3 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 resistances are essentially equal.

6.5 Thermocouples meeting the requirements of 5.4.1 shall be installed on elements of high axial heat conductance such as metallic jackets or liners 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 Place a thin (5 mm maximum) fibrous insulation sheet between the butt joint at the guard gaps only in order to block this air exchange within the test specimen. Butt joints within the central test section must not be modified.

7.1.2 The guard to the central test section air exchange must also be prevented in the annular space between the hot pipe and insulation inner surface. Install a fibrous insulation seal, no more than 25 mm wide, 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, 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.

9. Procedure

9.1 Measure the test section length, L, and the specimen outside circumference or other dimensions needed to describe the shape.

9.1.1 The test length, L, is the distance between the centerlines at the gaps at the ends of the test section.

9.1.2 Take outside dimensions of the specimen at locations described in 6.3.

9.2 Operate the apparatus in a controlled room or enclosure so that the ambient temperature does not vary during a test by more than ± 1°C or ±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 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.

9.3 Adjust the temperature of the test pipe to the desired temperature.

9.4 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 5.3.2, 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.

9.5 Conduct the test as follows:

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

9.5.1.1 The average temperature of the pipe test section, t_o,

9.5.1.2 The test section to guard balances,

9.5.1.3 The average temperature of the specimen outer surface, t_2,

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

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

9.5.2 For specimens with elements of high axial conductance, also measure the thermocouples specified in 6.5 to determine axial gradients. Using the average of the gradients and known dimensions and thermal conductance properties of the highly conductive elements, calculate the estimated total axial heat conduction. Reject any tests where the specimen axial heat flow at either end is estimated to be more than 2 % of the average heat input to the test section.

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

10. Calculation

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

10.1.1 For pipe apparatus with no internal support bridges, no correction is needed.

10.1.2 For pipe apparatus with internal support bridges, follow the procedure described in 9.4 using measured support gradients, dimensions and material properties.

10.2 Calculate the heat transfer properties for each of the three or more observations required in 9.5.3 and average the values of those differing by no more than 1 % for reporting in 11.1.9. Make calculations for those properties desired as follows:

10.2.1 Calculate the pipe insulation thermal conductance, C, by means of Eq 1 (see 3.2.1).

10.2.2 Calculate the pipe insulation thermal resistance, R, by means of Eq 2 (see 3.2.2).

10.2.3 Calculate the pipe insulation thermal transference, T_r, by means of Eq 3 (see 3.2.3).

10.2.4 Calculate the surface heat transfer coefficient, h_2, by means of Eq 4 (see 3.2.4).

10.2.5 When applicable, calculate the pipe insulation apparent thermal conductivity, λ, from Eq 5 (see 3.2.5).

10.2.6 When applicable, calculate the pipe insulation apparent thermal resistivity, r, from Eq 6 (see 3.2.6).

11. Report

11.1 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:

11.1.1 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, and 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.

11.1.2 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.

11.1.3 Description of the application and means of securing 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.

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

11.1.5 Average temperature of the pipe test section, t_o.

11.1.6 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 6.4.1).

11.1.7 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.

11.1.8 The corrected test section power input, Q.

11.1.9 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 accordance with 10.2.

11.1.9.1 Pipe insulation thermal conductance, C.

11.1.9.2 Pipe insulation thermal resistance, R.

11.1.9.3 Pipe insulation thermal transference, T_r.

11.1.9.4 Pipe insulation apparent thermal conductivity, λ.

11.1.9.5 Pipe insulation apparent thermal resistivity, r.

11.1.9.6 Insulation surface heat transference coefficient, h_2.

11.1.10 Estimates of error of the test results.

11.1.11 Any exceptions made in the test method.

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

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

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

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

12. Precision and Bias

12.1 Precision and bias statements based on interlaboratory tests are not yet available for portions of this test method.

12.1.1 The precision and bias of this test method of measuring heat transfer properties of homogeneous insulations are as specified in Test Method C 335.

12.1.2 For nonhomogeneous and reflective insulations, the precision is expected to be comparable to that obtainable with the horizontal pipe test method, Test Method C 691. The bias is expected to be somewhat poorer than Test Method C 691 due to the difficulty in maintaining proper guarding of the central test specimens in the vertical orientation.

12.2 For cases not discussed in 12.1.1 or 12.1.2, the precision and bias must be estimated by an error analysis.

12.2.1 Prescribed precision and bias are not mandated by this test method. However, it is required that the user assess and report the precision and bias of the data.

12.3 The precision and bias data to be reported for this test method shall include uncertainties for the following parameters:

12.3.1 Heat flow, δQ,

12.3.2 Pipe surface area, δA,

12.3.3 Temperature difference, $\delta(t_o - t_2)$, $\delta(t_o - t_a)$ and $\delta(t_2 - t_a)$, and

12.3.4 Specimen radii, δr_2 and δr_o.

12.3.5 Both systematic and random errors shall be considered when determining the uncertainty of each parameter.

12.4 Error components of each parameter shall at least include the following considerations:

12.4.1 *Heat Flow*—Edge heat loss, gap heat loss, and power measurement.

12.4.2 *Geometry*—Measuring instrument uncertainty, specimen nonuniformity and thermal expansion.

12.4.3 *Temperature Difference*—Calibration, instrumentation error, sensor mounting and location, and thermal disturbance caused by the sensor.

12.4.4 For guidelines to establish the uncertainty in the measured parameters, refer to Test Method C 177.

12.5 The precision and bias of a derived parameter shall be determined by a standard error propagation formula.

12.5.1 As an example, the total uncertainty in the pipe insulation thermal transference, δT_r, would be the following:

$$(\delta T_r/T_r)^2 = (\delta Q/Q)^2 + (\delta A/A)^2 + [\delta(t_o - t_a)/(t_o - t_a)]^2 \quad (7)$$

12.6 One test pipe designed in accordance with this test method has reported a bias of ±5 %.[9]

13. Keywords

13.1 experimental design; heat flux; radical heat transfer; steady state heat transfer; thermal testing