Standard Practice for Determination of Thermal Resistance of Attic Insulation Systems Under Simulated Winter Conditions[1]

This standard is issued under the fixed designation C 1373; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice presents a laboratory procedure to determine the thermal resistance of attic insulation systems under simulated steady-state winter conditions. The practice applies only to attic insulation systems that face an open attic air space.

1.2 The thermal resistance of the insulation is inferred from calculations based on measurements on a ceiling system consisting of components consistent with the system being studied. For example, such a system might consist of a gypsum board or plywood ceiling, wood ceiling joists, and attic insulation with its top exposed to an open air space. The temperature applied to the gypsum board or plywood shall be in the range of 18 to 24°C (64 to 75°F). The air temperature above the insulation shall correspond to winter conditions and may range from –46°C to 10°C (–51 to 50°F). The gypsum board or plywood ceiling shall be sealed to prevent direct airflow between the warm and cold sides of the system.

1.3 This practice applies to a wide variety of loose-fill or blanket thermal insulation products including fibrous glass, rock/slag wool, or cellulosic fiber materials; granular types including vermiculite and perlite; pelletized products; and any other insulation material that may be installed pneumatically or poured in place. The practice considers the effects on heat transfer of structures, specifically the ceiling joists, substrate, for example, gypsum board, air films, and possible facings, films, or other materials that may be used in conjunction with the insulation.

1.4 This practice measures the thermal resistance of the attic/ceiling system in which the insulation material has been preconditioned according to the material Specifications C 549, C 665, C 739, and C 764.

1.5 The specimen preparation techniques outlined in this standard do not cover the characterization of loose-fill materials intended for enclosed applications.

1.6 This practice may be used to characterize material behavior under controlled steady-state laboratory conditions intended to simulate actual temperature conditions of use. The practice does not simulate forced air flow conditions.

1.7 All values shall be reported in both SI and inch-pound units unless specified otherwise by the client.

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

2. Referenced Documents

2.1 *ASTM Standards:*

C 167 Test Methods for Thickness and Density of Blanket or Batt Thermal Insulations[2]

C 168 Terminology Relating to Thermal Insulating Materials[2]

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus[2]

C 236 Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box[2]

C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[2]

C 520 Test Methods for Density of Granular Loose-Fill Insulations[2]

C 549 Specification for Perlite Loose Fill Insulation[2]

C 665 Specification for Mineral-Fiber Blanket Thermal Insulation for Light Frame Construction and Manufactured Housing[2]

C 687 Practice for Determination of Thermal Resistance of Loose-Fill Building Insulation[2]

C 739 Specification for Cellulosic Fiber (Wood Base) Loose-Fill Thermal Insulation[2]

C 764 Specification for Mineral Fiber Loose-Fill Thermal Insulation[2]

C 976 Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box[2]

C 1045 Practice for Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements[2]

C 1058 Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation[2]

C 1114 Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus[2]

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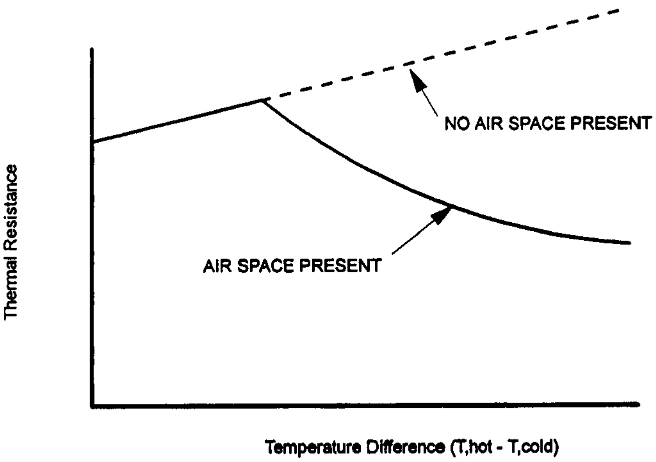
[1] This practice is under the jurisdiction of ASTM Committee C-16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurements.

Current edition approved Nov. 10, 1998. Published May 1999.

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



NOTE 1—A constant hot-side temperature (*T*, hot) is used for both tests and the temperature difference increases as the cold side temperature (*T*, cold) is decreased. See 5.1.6 for requirements on size of air space.

FIG. 1 Schematic of Thermal Resistance for a Permeable Attic Insulation Under Simulated Winter Conditions (Heat Flow Up)

C 1363 Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus[2]

3. Terminology

3.1 *Definitions*— Unless otherwise stated, the definitions listed in Terminology C 168 are applicable herein.

4. Significance and Use

4.1 The thermal resistance of a ceiling system is used to characterize its steady-state thermal performance.

4.2 The thermal resistance of insulation is related to the density and thickness of the insulation. Test data on thermal resistance are obtained at a thickness and density representative of the end use applications. In addition, the thermal resistance of the insulation system will be different from that of the thermal insulation alone because of the system construction and materials.

4.3 This practice is needed because the in-service thermal resistance of some permeable attic insulations under winter conditions may be different, lower or higher *R*, than that measured at or close to simulated room temperature conditions utilizing small-scale tests in which the insulation is sandwiched between two isothermal impermeable plates that have a temperature difference (ΔT) of 20 to 30°C (36 to 54°F). When such insulation is installed in an attic, on top of a ceiling composed of normal building materials such as gypsum board or plywood, with an open top surface exposed to the attic air space, the thermal resistance under winter conditions with heat flow up and large temperature differences may be significantly less because of additional heat transfer by natural convection. Fig. 1 illustrates the difference between results from small scale tests and tests under the conditions of this practice. See Ref **(1-12)** for discussions of this phenomenon.[3]

4.4 In normal use, the thickness of insulation products may range from 75 mm (3 in.) to 500 mm (20 in.). Installed densities will depend upon the product type, the installed thickness, the installation equipment used, the installation technique, and the geometry of the insulated space.

4.5 The onset of natural convection under winter conditions may be a function of specimen thickness. For purposes of this practice, the tests shall be carried out at thicknesses at which the product is used.

4.6 Since this practice simulates winter conditions, the heat flow direction shall be vertically upwards.

4.7 Specimens shall be prepared in a manner consistent with the intended installation procedure. Products for pneumatic installation shall be pneumatically-applied (blown), and products for pour-in-place installation shall be poured into place. See 5.2.

5. Equipment

5.1 Thermal test apparatus used for this practice shall meet the following requirements:

5.1.1 *Conformance to Standards*—The apparatus shall conform to all requirements of the ASTM thermal test method used, except as required by 5.1.2-5.1.6.

5.1.2 *Size*—The apparatus shall be capable of testing specimens at the thickness intended for product use. Length and width of the metering area shall be at least twice the spacing of the wood joists or four times the specimen thickness, whichever is greater (see Fig. 2).

5.1.3 *Temperature*— The apparatus shall be capable of testing with the hot side surface maintained between 18 and 24°C (64 and 75°F), and with the cold side air temperature maintained near the winter condition for the particular climate being simulated, which may range from –46 to 10°C (–51 to 50°F). In the absence of specified temperatures, the ambient temperatures listed in Table 2 of C 1058 on Temperatures for Thermal Transmittance Evaluations may be used.

NOTE 1—Only those with a hot ambient of 24°C (75°F) are applicable.

5.1.4 *Humidity*—The absolute humidity on both sides of the test apparatus shall be maintained low enough to prevent condensation within the specimen. See 6.9.6 of Test Method C 1363 for humidity requirements for the hot box methods, 6.6 of Test Method C 177 for the guarded hot plate method, and 7.10 of Test Method C 518 for the heat flow meter apparatus.

5.1.5 *Orientation and Direction of Heat Flow*—The thermal test specimen shall be oriented horizontally with heat flow up.

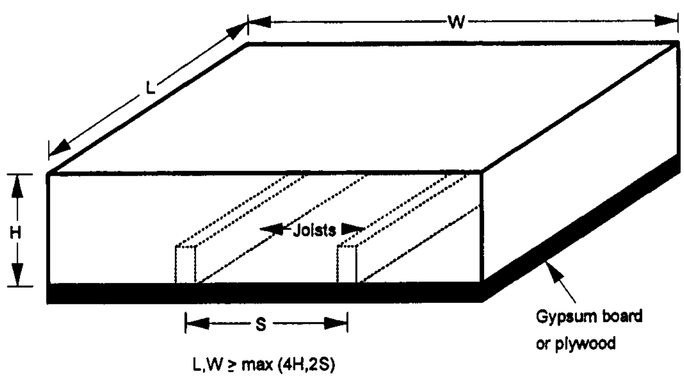


FIG. 2 Requirements on Dimensions of Test Specimen Metering Area

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

5.1.6 *Thermal Test Specimen and Holder*—The test assembly shall be sized to match the test apparatus and shall be made of construction materials representative of the intended application. The substrate on which the insulation rests shall be representative of the intended application, typically gypsum board. The substrate shall be sealed to prevent direct airflow between the warm and cold sides of the system. Wood joists also shall be included. The test assembly shall be constructed such that the top of the insulation is open to an air space having a minimum thickness of 150 mm (6 in.). Test Methods C 236, C 976, and C 1363 are preferred because of their ability to accommodate a large air space. Other apparatuses that can simulate in-service conditions also may be used, (for example, modifications of Test Methods C 177, C 518, or C 1114 with Practice C 1045). In all cases, the size requirements given in 5.1.2 shall be met. Fig. 3 shows a schematic of an attic test module that has been used for these types of tests. Other configurations without the roof structure are acceptable as long as the minimum150 mm (6 in.) air space is maintained.

5.2 *Specimen Preparation Equipment*:

5.2.1 *Blowing Apparatus*—A blowing apparatus is required when pneumatically-applied specimens are to be tested. Choose the combination of hopper, blower, hose size and length that is representative of common use for the application of the material to be tested. The following machine specifications have been developed for use with mineral fiber and cellulosic materials.

5.2.1.1 A commercial blowing machine with a design capacity for delivering the subject material at a rate recommended by the insulation manufacturer shall be used. The machine should utilize 46 m (150 ft) of flexible, internally corrugated blowing hose with an appropriate sized diameter as specified by the machine manufacturer. At least 30 m (100 ft) of the hose should be elevated between 3 and 6 m (10 and 20 ft) above the blowing machine to simulate typical installation configuration. The hose should have no more than eight 90° bends and no bends may be less than 1.2 m (4 ft) radius. It is good practice to clean the hose periodically by mechanically agitating it with the blower operating. This practice should dislodge any pieces of old insulation that might be caught in the hose.

6. Sampling

6.1 A sample of material shall be selected from a lot according to sampling plans given in the material specifications, regulations, or other appropriate documents when applicable. In the absence of such directions, material from at least two randomly chosen packages shall be combined in equal portions (mass) so as to combine materials as uniformly as practicable.

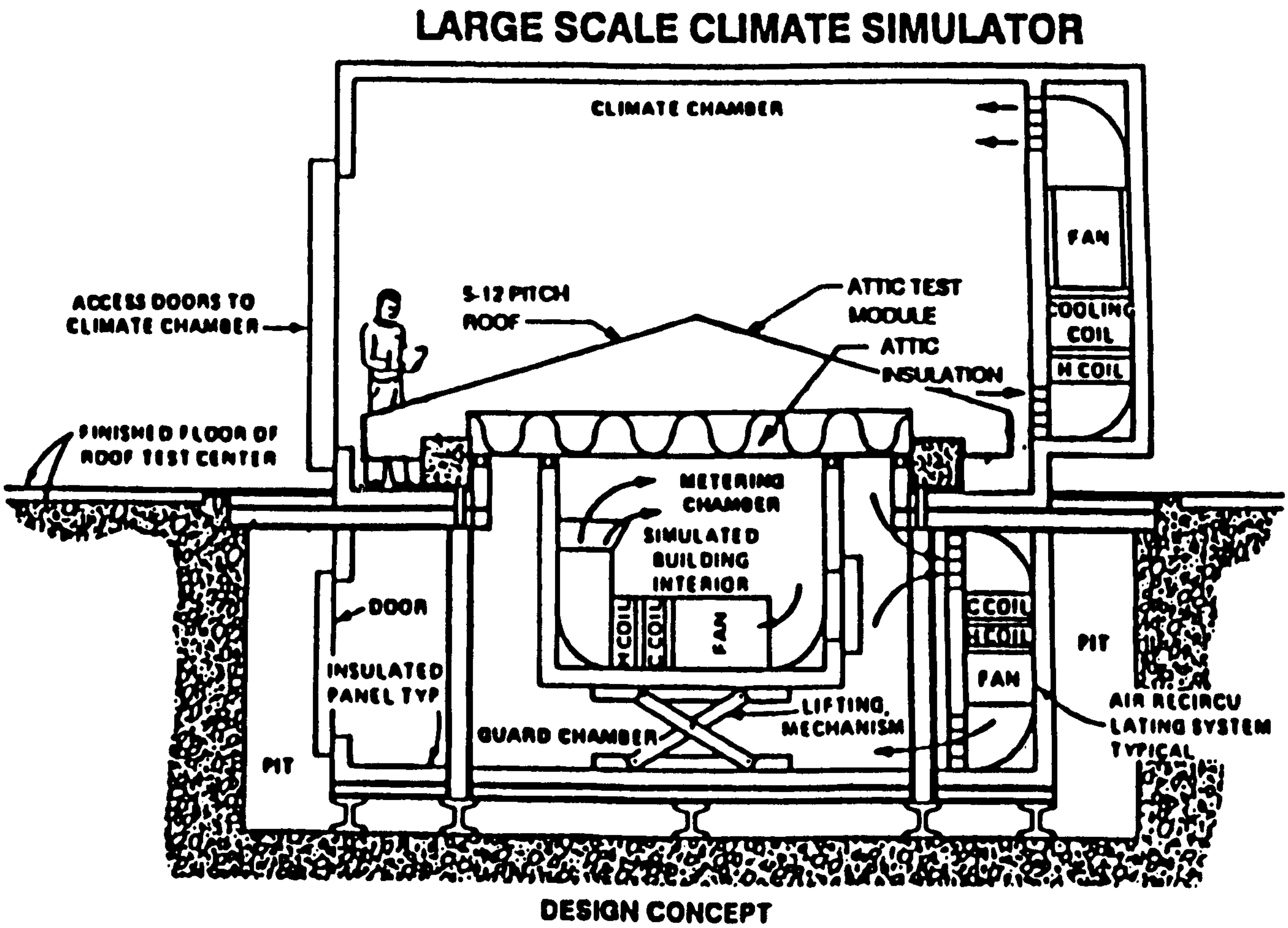


FIG. 3 Schematic of Attic Test Module and Large Scale Climate Simulator Used for Tests on Attic Insulation Under Simulated Winter Conditions

6.2 The insulation material should be preconditioned to a moisture content in equilibrium with the laboratory conditions prior to the specimen installation. Preconditioning of materials not only ensures controlled installation conditions but may reduce the time required to condition the prepared specimen prior to thermal testing. For conditioning requirements, see the applicable materials Specifications C 520, C 549, C 665, C 739, and C 764.

7. Specimen Preparation

7.1 *General Instructions*:

7.1.1 All specimens shall be prepared to a thickness and unit area mass that are given for the label *R*-value specification of interest for the material under test.

7.1.2 Specimens shall be prepared in a manner consistent with the intended installation procedure. All materials shall be installed carefully using the manufacturer's recommended installation practice. Batts shall be cut, as required, to fit the available specimen holder. Products for pneumatic installation shall be pneumatically-applied (blown), and products for pour-in-place installation shall be poured into the specimen holder. See 7.2.2 for the density of pneumatically-installed insulation. Other materials should be installed at the density suggested by the manufacturer.

7.1.3 The specimen holder shall represent typical attic frame construction, wherever possible. This requires, as a minimum, horizontal members representing the bottom chord of a truss system or rafter framing and an air-tight gypsum board or plywood bottom. The specimen holder shall be clean and free of insulation residue prior to installation of the sample insulation.

NOTE 2—For commonly available loose-fill insulation, state and federal energy codes, ASTM material specifications and the Federal Trade Commission have identified those materials that shall apply a correction for settling when determining thermal performance. It is beyond the scope of this practice to outline the procedures for this determination.

NOTE 3—Many factors can influence the characteristics of the loose-fill insulation. These include blowing rate, machine adjustments, the size and length of the hose, and the angle and dimensions of the hose outlet in relation to the specimen holder. Trained operators are required to duplicate field-installed conditioning.

NOTE 4—For these tests, the specimen shall be blown close to the labeled density. Some operators may wish to establish a target mass of insulation required to fill the test frame to the desired thickness and density as a control during the specimen preparation process. By weighing the initial material and that remaining after blowing is complete, the operator can estimate the material in the test frame. Other operators may wish to eliminate these extra steps. The reported test density, however, is obtained from the metering area density measurement conducted after the thermal test.

7.2 *Specimen Preparation–Pneumatic-Application*:

7.2.1 The procedure described in this section is intended for all products, which normally are installed pneumatically. For materials exhibiting post installation settling, a supplemental instruction set is provided in 7.3 to correct the test specimen blown density to accommodate for in-situ settling after installation.

7.2.2 *Installed Density*—The thermal resistances of loose-fill insulations are specified using densities selected by manufacturers to represent the product settled densities. Generally, it is necessary to know the product thermal resistance at a representative density. Some bag labels utilize multiple densities to reflect the fact that greater thickness installations usually result in higher installed densities. The use of multiple densities can be detected from the bag label by calculating the label density for several different *R*-value levels. Label densities for a given *R*-value can be calculated from the bag label by dividing the minimum mass/unit area by the minimum thickness. If the calculated densities are significantly different, the multiple density label has been used. When applicable specifications or codes do not specify the density to be used for comparison purposes, the recommended practice is to use the *R*-30 label density ($R(SI) - 5.3\ m^2 \cdot K/W$). If the density is not available from the bag label, a density for test purposes can be established by the procedures outlined in Test Method C 520 or Specification C 739.

7.2.3 Calculate the target mass of insulation required to fill the sample frame to the target thickness and density from the equation:

$$m = \rho\,[\,(L_{ins} \times A\,) - V_{joist}\,] \quad (1)$$

where:

m = target mass of insulation, kg (lb),
ρ = target density, kg/m^3 (lb/ft^3),
L_{ins} = target insulation thickness, m (ft),
A = area within sample frame, m^2 (ft^2), and
V_{joist} = volume of joists within frame area, m^3 (ft^3).

7.2.4 Assemble the blowing machine, hose and hose length combination as appropriate for the material being prepared.

7.2.5 Set the blowing machine adjustments and select the feed rates in accordance with the insulation manufacturer's recommendations. If the insulation manufacturer does not provide this information, consult the machine manufacturer for recommended settings.

7.2.6 Place the required amount of insulation material (7.2.3) into the blowing machine hopper. If the hopper is too small to hold the entire amount required, fill the hopper to capacity with the premixed insulation (see 6.1). Additional material is added as required during the blowing process until the total amount of needed insulation is blown.

7.2.7 Turn on the blowing machine with the hose outlet directed away from the center of the specimen metering area and toward the far end of the specimen holder. The hose outlet orientation may be varied, side to side, as needed to cover uniformly the entire area of the specimen holder, but shall remain approximately horizontal.

NOTE 5—Since the insulation material has been premeasured, some means of limiting the loose-fill trajectory to within the sample frame is required. A screen tent arrangement has been found effective in performing this operation.

7.2.8 Blow insulation into the specimen holder from the far end to approximately the middle line of the holder. Then move the hose to the opposite end of the specimen holder and blow the remainder of the holder with insulation. The direction from which the insulation is blown may be alternated several times during the blowing period in order to provide as nearly uniform coverage of the specimen holder as possible while obtaining the desired thickness and mass.

NOTE 6—A new specimen shall be prepared if the intent is to test at label thickness and density, but the specimen exceeds the upper mass without reaching the target thickness or exceeds the upper thickness limit without meeting the target mass.

NOTE 7—Care should be observed when handling or moving the filled specimen holder so as not to disturb the test specimen any more than is absolutely necessary. Any vibration or impact can change the pack structure of the blown specimen and change its thermal properties.

7.2.9 Use a rake or piece of stiff wire to level the top surface of the specimen taking care not to disturb the subsurface material.

7.3 *Pneumatic Application—Settled Density Correction*:

7.3.1 The procedure listed below is required for those materials where the specimen preparation shall be modified to accommodate a correction for settling after installation. See Note 2 following 7.1.3.

7.3.2 Prepare the insulation specimen as directed in 7.2.

7.3.3 Using the mass of the insulation material in the specimen holder, determine the required test thickness that provides the final product settled density.

7.3.4 Uniformly compress the insulation material using a large flat board or paddle to establish the targeted test thickness determined in 7.3.3.

7.4 *Pouring Application*—For products intended to be poured in place:

7.4.1 Calculate the mass of insulation required to fill the frame to the label thickness and density.

7.4.2 Pour an amount of insulation calculated in 7.4.1 into the sample holder following pouring instructions given in appropriate specifications or Test Method C 520.

7.4.3 Use a rake or piece of stiff wire to level the top surface of the specimen taking care not to disturb the subsurface material.

7.5 *Installation of Other Insulations*—Install the insulation following the manufacturer's instructions as required to fill the specimen frame to the required unit area mass and thickness.

8. Test Procedure

8.1 If the specimen holder is not already built into the apparatus, transfer the specimen and holder in its horizontal position to the thermal test apparatus, being careful not to disturb the specimen.

8.2 Conduct the test(s) in accordance with all requirements of the appropriate thermal test method, with the following exceptions (see also Section 5):

8.2.1 Certain methods require contact of both surfaces of the test specimen with isothermal plates; for this practice, a layer of still or slowly moving air (0.25 m/s [50 ft/min] or less) is required over the top surface of the insulation so that the top surface of the insulation is not in contact with an isothermal plate. Provision, however, shall be made to measure the temperature of the top surface of the insulation. For useful techniques, see Ref **(12)**. The insulation shall not be compressed, unless compression is a usual part of the installation procedure in the application of the product, in which case the usual procedure for compression shall be followed.

8.2.2 The average atmospheric pressure during the test shall be measured. The atmospheric pressure is necessary since theory predicts that the temperature difference at which natural convection commences is inversely proportional to the square of the atmospheric pressure (through the dependence of the density of air on pressure). See Ref **(4)** for a discussion of the factors that affect the onset of natural convection.

8.2.3 For some materials, the thermal resistance will vary significantly with changes in the temperature difference applied across the specimen. Because of this, tests shall be conducted at three or more different temperature differences. These may be specified by the client, or they may be at even increments of temperature difference, or they may be selected from the conditions listed in Table 2 of C 1058. A plot of *R*-value versus temperature difference shall be prepared to assist interested parties in determining the need for additional data.

8.3 Prior to the start and after completion of the thermal testing series, measure the thickness of the insulation in the metered area to the nearest millimetre using a pin gage (see Test Methods C 167 for a description of pin gages. A smaller diameter pin and careful insertion may be required to avoid compressing the insulation.) Prior to the test, the thickness shall be measured in at least five locations to allow estimation of the average thickness and density prior to testing. At the completion of testing and prior to removal of the insulation, the thickness shall be measured as required to get a true average thickness for the tested material. The number of individual measurements is at least one measurement for each 0.37 m^2 (4 ft^2) of insulation area or a total of five, whichever is greater. The measurements shall be made at locations of the full thickness of the insulation, for example, they shall not be made at joist locations. Any gaps, unusual settling or other observations of the insulation conditions shall be observed and recorded. The times and dates of the thickness determinations also shall be recorded.

8.4 Cut, remove, and weigh to the nearest 0.5 %, the insulation within the metering area for the density determination. Measurements of mass should be made as soon as possible after removal and also after the material has been conditioned to a moisture content in equilibrium with the laboratory conditions. If the metering area is smaller than the entire test area, a thin walled die cutter, deep enough to accommodate various material thicknesses, or other suitable means shall be used to isolate the material in the metering area. Some means of alignment shall be available so that the perimeter of the die cutter lines up with the perimeter of the metering area. The die cutter shall be designed to fit over joists and other obstructions that might be present (see Practice C 687 for details for pneumatically applied or poured insulations.)

9. Calculations

9.1 *Density*—Calculate the test density from the metering area, the mass of the insulation (from 8.4), and the test thickness (from 8.3) according to the following formula:

$$\rho_{meter} = \frac{m_{meter}}{[\,(L_{ins} \times A_{meter}) - V_{joist}\,]} \tag{2}$$

where:

ρ_{meter} = test density of insulation, kg/m ^{3} (lb/ft^3),
m_{meter} = mass of insulation within metering area, kg (lb),

$\bar{L}_{ins}$ = average insulation thickness within metering area, m (ft),
A_{meter} = metering area, m^2 (ft^2), and
V_{joist} = volume of joists within metering area, m^3 (ft^3).

9.2 *Thermal Resistance*:

9.2.1 Calculate the surface-to-surface thermal resistance of the test system, for example, the combination of insulation, gypsum board, and wood joists, following the procedures recommended for the test method being used. See 5.1.6 for preferred and allowable test methods.

9.2.2 Using an average of series-parallel and parallel-path calculations, calculate the thermal resistance of the insulation material, as specified in Annex A1. This calculation is necessary since the system characteristics of each apparatus can vary considerably. See Annex A1 for calculation example.

10. Report

10.1 Report the following information and that required by the test method, including references to applicable specifications and test methods:

10.1.1 The name, address, and other identification of the test laboratory and the date of the report.

10.1.2 The name and other identification of the material or product tested and the date of the test.

10.1.3 The source of the material or product, the date obtained, and the method of sampling.

10.1.4 The method and details of the specimen preparation. For example, the following would be included for loose-fill insulation: blowing machine, machine settings used, blow time, and any preconditioning.

10.1.5 The method and conditions of specimen conditioning.

10.1.6 The ASTM thermal test method used for the test results reported.

10.1.7 The details of the thermal apparatus and specimen holder, including the metering area and the number and placement of thermocouples. Other details of the specimen holder should include the type, grade, dimensions, and density of the materials of which it is constructed, and the method of sealing to prevent direct air flow through it. If a roof structure is included, it should be described similarly, and its slope should be given.

10.1.8 The temperatures measured at the bottom of the ceiling and the corresponding temperatures at the top of the insulation system and the measured heat flow.

10.1.9 The test thickness and the density of the specimen.

10.1.10 The thermal resistance of the ceiling/insulation system, the calculated thermal resistance of the insulation, and the method used for calculating the resistance of the insulation.

10.1.11 An estimate of the precision and bias of the test results. Refer to the appropriate test method.

10.1.12 The average atmospheric pressure during the test.

10.1.13 Any other pertinent observations or remarks.

NOTE 8—Unless otherwise specified, all values of dimensions, conditions, and properties given in 10.1.7 through 10.1.12 shall be reported in both SI and inch-pound units.

11. Precision and Bias

11.1 The precision and bias of the test results obtained using this practice include the effects of: adherence to the test procedures, performance characteristics of the test apparatus, variability of the material or product, and sampling and specimen preparation. The influence of the material or product variability and the test imprecision are interactive. The characteristics of the specimen can affect the test accuracy while characteristics of the test apparatus, for example, the test area size, will affect the apparent variability of the material or product. Larger areas are expected to provide better accuracy when specimens are thick and variable in character.

11.2 As a minimum requirement for this practice, estimates shall be made of the precision and bias of the test apparatus used. Guidance on estimates of these values is given in Test Methods C 177, C 518, C 236, C 976, and C 1114.

11.3 Estimates of the precision and bias of the results, as representative of the materials or product, must be based on sufficient experiments to determine the variability and the effect of sampling and specimen preparation upon it.

11.4 The precision of this practice is not known because interlaboratory data are not available. This practice may not be suitable for use in specification or in case of disputed results as long as these data are not available.

12. Keywords

12.1 attic insulation; convection; thermal resistance; winter conditions

ANNEX

(Mandatory Information)

A1. CALCULATIONS

A1.1 This annex gives an example of the calculation of the thermal resistance of the insulation as required by 9.2.2. As an example of the parallel-path and series-parallel calculations to determine the thermal resistance of the insulation material, assume that the ceiling consists of 12.7 mm (0.5 in.) gypsum board, wood joists 38.1 mm by 88.9 mm (1.5 in. by 3.5 in.) and spaced 609.6 mm (24 in.) apart, and loose-fill insulation at a thickness of 323.8 mm (12.75 in.). Also, assume that at some particular temperature difference, the measured surface-to-surface *R*-value of the assembly is *R(SI)*-3.52 $m^2 \cdot K/W$ (*R*-20 $h \cdot ft^2 \cdot °F/Btu$).

A1.2 From the ASHRAE Handbook—Fundamentals **(13)**, the estimated *R*-value of the gypsum board is *R(SI)*–0.079 $m^2 \cdot K/W$ (*R*–0.45 $h \cdot ft^2 \cdot °F/Btu$), that of the wood joists is *R(SI)*–0.771 $m^2 \cdot K/W$ (*R*–4.38 $h \cdot ft^2 \cdot °F/Btu$), and that of the film resistance at either the bottom of the gypsum board or the top of the insulation is *R(SI)*–0.107 $m^2 \cdot K/W$ (*R*–0.61 $h \cdot ft^2 \cdot °F/Btu$),

NOTE A1.1—Actual tested *R*–values for these components shall be used if they are available; otherwise, the values shall be obtained from the ASHRAE Handbook—Fundamentals **(13)**.

A1.3 For the parallel-path calculation, the air-to-air R-value of the assembly, the surface-to-surface *R*-value of the assembly, and the *R*-value of the insulation are related by:

$$\frac{A_{total}}{R_{air-air}} = \frac{A_{total}}{R_{surface-surface} + R_{films}} = \frac{A_{insulation\ path}}{R_{insulation\ path}} + \frac{A_{joist\ path}}{R_{joist\ path}} \tag{A1.1}$$

where:

$A_{insulation\ path}$ = the area perpendicular to the heat flow occupied by the space between the joists,
$A_{joist\ path}$ = the area perpendicular to the heat flow occupied by the joists,
A_{total} = is the sum of $A_{insulation\ path}$ and $A_{joist\ path}$,
$R_{air-air}$ = the air-to-air *R*-value of the assembly,
$R_{surface-surface}$ = the surface-to-surface *R*-value of the assembly
R_{films} = the sum of the film resistances on both sides of the assembly, and
$R_{insulation\ path}$ and $R_{joist\ path}$ = quantities given in Eqs A1.2, A1.3 and A1.4:

$$R_{insulation\ path} = R_{insulation} + R_{gypsum\ board} + R_{films} \tag{A1.2}$$

$$R_{joist\ path} = R_{insulation,\ joist} + R_{joist} + R_{gypsum\ board} + R_{films} \tag{A1.3}$$

$$R_{insulation,\ joist} = R_{insulation} \cdot \frac{\text{thickness of insulation at joists}}{\text{total thickness of insulation}} \tag{A1.4}$$

where:

$R_{insulation}$ = total *R*-value of the insulation,
$R_{gypsum\ board}$ = *R*-value of the gypsum board or other substrate,
R_{joist} = *R* -value of the ceiling joists, and
$R_{insulation,\ joist}$ = *R*-value of the part of the insulation that covers the joists.

Using these relationships for the above example, the surface-to-surface *R*-value and the insulation *R*-value are related by:

$$\frac{609.6}{3.52 + 2 \times 0.107} = \frac{571.5}{R_{insulation} + 0.079 + 2 \times 0.107} + \frac{38.1}{R_{insulation} \times \frac{323.85 - 88.9}{323.85} + 0.771 + 0.079 + 2 \times 0.107} \tag{A1.5}$$

Eq A1.5 may be solved (either by rearranging into a quadratic form or by a trial and error or iterative procedure) to give:

$$R\,(SI)_{insulation,\ parallel} = 3.45\ m^2 \cdot K/W\ (19.62\ h \cdot ft^2 \cdot °F/Btu) \tag{A1.6}$$

A1.4 Using the series-parallel method, the surface-to-surface *R*-value of the assembly and the *R*-value of the insulation are related by:

$$R_{surface-surface} = R_{gypsum\ board} + R_{insulation,\ joist} + \frac{A_{total}}{\frac{A_{insulation\ path}}{R_{insulation} - R_{insulation,\ joist}} + \frac{A_{joist\ path}}{R_{joist}}} \tag{A1.7}$$

For the example under consideration, Eq A1.7 becomes:

$$3.52 = 0.079 + R_{insulation} \times \frac{323.85 - 88.9}{323.85} + \frac{609.6}{\frac{571.5}{R_{insulation} \times \frac{88.9}{323.85}} + \frac{38.1}{0.771}} \tag{A1.8}$$

Eq A1.8 may be solved by trial and error to give:

$$R\,(SI)_{insulation,\ series-parallel} = 3.46\ m^2 \cdot K/W\ (19.63\ h \cdot ft^2 \cdot °F/Btu) \tag{A1.9}$$

A1.5 The *R*-value of the insulation is found by averaging the results of Eq A1.6 and Eq A1.9 to give a value of *R(SI)* of 3.46 $m^2 \cdot K/W$ (19.6 $h \cdot ft^2 \cdot °F/Btu$).

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