Designation: C 1484 – 01

Standard Specification for Vacuum Insulation Panels[1]

This standard is issued under the fixed designation C 1484; 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 specification covers the general requirements for Vacuum Insulation Panels (VIP). These panels have been used wherever high thermal resistance is desired in confined space applications, such as transportation, equipment, and appliances.

1.2 Vacuum panels typically exhibit an edge effect due to differences between core and barrier thermal properties. This specification applies to composite panels whose center-of-panel apparent thermal resistivities (sec. 3.2.4) typically range from 87 to 870 m·K/W (12.5 to 125 hr·ft^2·°F/Btu·in) at 24°C (75°F) mean, and whose intended service temperature boundaries range from –70 to 480°C (–94 to 900°F).

1.3 The specification applies to panels encompassing evacuated space with: some means of preventing panel collapse due to atmospheric pressure, some means of reducing radiation heat transfer, and some means of reducing the mean free path of the remaining gas molecules.

1.4 *Limitations*

1.4.1 The specification is intended for evacuated planar composites; it does not apply to non-planar evacuated self-supporting structures, such as containers or bottles with evacuated walls. The complexity of describing the performance of the planar products is considered sufficiently challenging for this initial specification, although other shapes will be considered at a future time.

1.4.2 The specification describes the thermal performance considerations in the use of these insulations. Because this market is still developing, discrete classes of products have not yet been defined and standard performance values are not yet available.

1.5 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.6 *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 specifications and determine the applicability of regulatory limitations prior to use.* For specific safety considerations see Annex A1.

2. Referenced Documents

2.1 *ASTM Standards:*

C 165 Test Method for Measuring Compressive Properties of 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 203 Test Methods for Breaking Load and Flexural Properties of Block-Type Thermal Insulation[2]

C 480 Test Method for Flexure Creep of Sandwich Constructions[3]

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

C 740 Practice for Use of Evacuated Reflective Insulation in Cryogenic Service[2]

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

C 1055 Guide for Heated System Surface Conditions that Produce Contact Burn Injuries[2]

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

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

C 1136 Specification for Flexible, Low Permeance Vapor Retarders for Thermal Insulation[2]

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

D 999 Methods for Vibration Testing of Shipping Containers[4]

D 1434 Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting[5]

D 2221 Test Method for Creep Properties of Package Cushioning Materials[4]

[1] This specification is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.22 on Organic and Nonhomogeneous Inorganic Thermal Insulations.

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

[3] *Annual Book of ASTM Standards*, Vol 15.03.

[4] *Annual Book of ASTM Standards*, Vol 15.09.

[5] *Annual Book of ASTM Standards*, Vol 08.01.

D 2126 Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging[5]
D 3103 Test Method for Thermal Insulation Quality of Packages[4]
D 3763 Test Method for High Speed Puncture Properties of Plastics Using Load and Displacement Sensors[6]
D 4169 Practice for Performance Testing of Shipping Containers and Systems[4]
E 493 Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode[6]
F 88 Test Method for Seal Strength of Flexible Barrier Materials[4]

2.2 *Other Standards:*

ISO 8318 Packaging - Complete, Filled Transport Packages - Vibration Tests Using a Sinusoidal Variable Frequency[7]
IEC68-2-6, Part 2, Test F, Vibration, Basic Environmental Testing Procedures[8]
TAPPI T803 Puncture Test of Containerboard[9]

3. Terminology

3.1 *Definitions*—Terminology C 168 applies to terms used in this specification.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *adsorbent*—a component of some VIP designs, comprising a chemical or physical scavenger for gas molecules.

3.2.2 *barrier*—the material used to separate the evacuated volume from the environment.

3.2.3 *center-of-panel*—a small area located at the center of the largest planar surface of the panel, equidistant from each pair of opposite edges of that surface.

3.2.4 *center-of-panel apparent thermal resistivity*—the thermal performance of vacuum panels includes an edge effect due to some heat flow through the barrier material and this shunting of heat around the panel becomes more prevalent with greater barrier thermal conductivity, as shown in Fig. 1. For panels larger than a minimum size (as described in 11.4.1 and Appendix X1), the center-of-panel apparent thermal resistivity is the intrinsic core thermal resistivity of the VIP. This center-of-panel measurement is used for quality control, compliance verification, and to calculate the effective thermal performance of a panel. The effective thermal performance of a panel will vary with the size and shape of the panel.

3.2.4.1 *Discussion*—Thermal resistivity, the inverse of thermal conductivity, is used when discussing the center-of-panel thermal behavior and this value is independent of the panel thickness.

3.2.5 *core*—the material placed within the evacuated volume. This material may perform any or all of the following functions: prevent panel collapse due to atmospheric pressure, reduce radiation heat transfer, and reduce the mean free path of the remaining gas molecules. The thermal conductivity of the core, or λ_{core}, is defined as the thermal conductivity of the core material under the same vacuum that would occur within a panel, but without the barrier material. This is the thermal conductivity that would be measured in the center of an infinitely large panel.

[6] *Annual Book of ASTM Standards*, Vol 03.03.

[7] International Organization for Standardization, Case Postale 56, Geneva CH-1211, Switzerland.

[8] International Electrotechnical Commission, 3 Rue De Varembe; PO Box 131, Geneva CH-1211, Switzerland.

[9] TAPPI, 15 Technology Parkway S., Norcross, GA 30092.

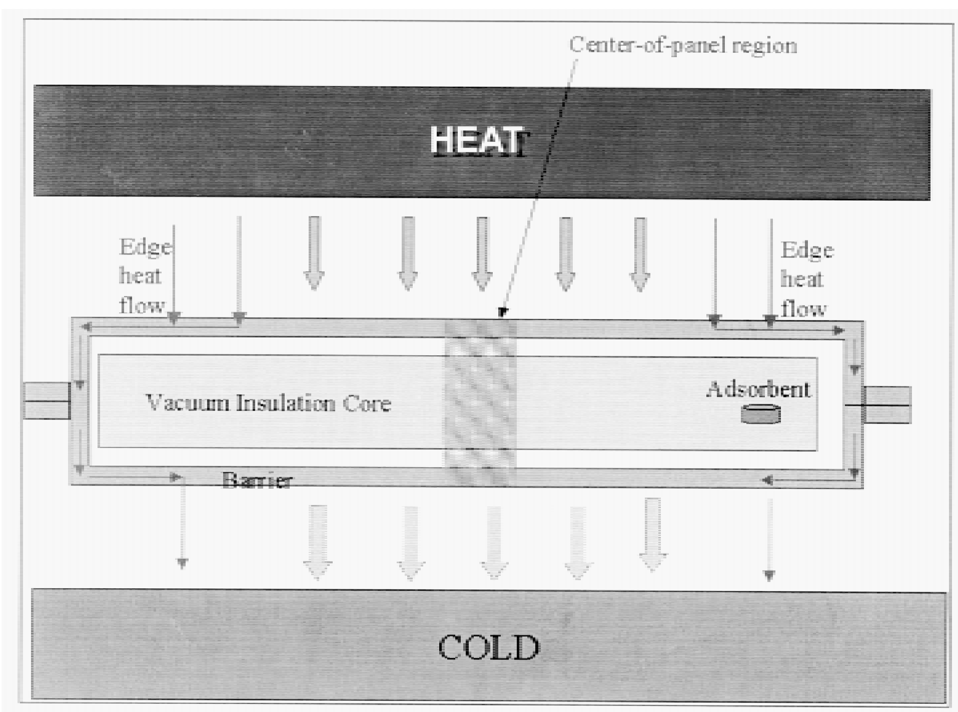


FIG. 1 Side View of a Vacuum Insulation Panel Showing Edge Heat Flow and the Center-of-Panel Region

3.2.6 *effective thermal resistance (Effective R-value)*—this value reflects the total panel resistance to heat flow, considering heat flow through the evacuated region and through the barrier material. Depending on the thermal conductivity of the barrier material and the size of the panel, the effective thermal resistance may be significantly less than the product of the center-of-panel apparent thermal resistivity and the panel thickness. The effective thermal resistance is based on the edge-to-edge area covered by the VIP, that is, the entire VIP. Note that the effective thermal resistance will also vary with the panel mean temperature.

3.2.6.1 *Discussion*—Thermal resistance, the inverse of thermal conductance, is used when discussing the effective thermal performance of the panel. This value includes the effect of the actual panel dimensions, including the panel thickness.

3.2.7 *effective thermal resistance after puncture*—this value represents the effective thermal resistance of the panel in the event of a total barrier failure (complete loss of vacuum). The edge effect is still present after a puncture.

3.2.8 *evacuated or vacuum insulations*—insulation systems whose gas phase thermal conductivity portion of the overall apparent thermal conductivity has been significantly reduced by reduction of the internal gas pressure. The level of vacuum will depend on properties of the composite panel materials, and the desired effective thermal conductivity.[10]

3.2.9 *seal*—any joint between two pieces of barrier material.

3.2.10 *service life*—the thermal resistance of a VIP may degrade with time due to residual outgassing of VIP materials and gas diffusion through the barrier and seals. Both of these processes are affected by the VIP's service environment, most importantly by the service temperature and humidity in the surrounding air. The service life is the period of time over which the center-of-panel thermal conductivity meets the definition of a superinsulator. A standard-condition service life is defined as that period of time over which the center-of-panel thermal conductivity meets the definition of a superinsulator under standard conditions of 24°C (75°F) and 50 % relative humidity. This standard-condition service life must be reported by the manufacturer, along with their basis for determining this value. The basis may be either actual, based on measured panel performance, or a combination of measured performance data and a predictive calculation model as described in Appendix X2. The user must recognise that the service life in hotter or more humid conditions may be shorter; conversely drier or colder environmental conditions can extend the life of the panel.

3.2.11 *superinsulation*—insulation systems whose center-of-panel thermal resistivity exceeds 87 m · K/W (12.5 h·ft^2·°F/BTU · in.) measured at 24°C (75°F) mean.

3.3 *Symbols and Units*—The symbols used in this test method have the following significance:

3.3.1 A = area, m^2.

3.3.2 B = outgassing coefficient of panel barrier, Pa·l/(h$^{(1-\beta)}$).

3.3.3 C = outgassing coefficient of panel filler, Pa·l/(h$^{(1-\alpha)}$).

3.3.4 d_o = density of the gas at standard temperature and pressure, kg/m^3.

3.3.5 g = outgassing rate, Pa·l/h.

3.3.6 G = adsorbent capacity, Pa·m^3.

3.3.7 k = gas permeation rate, m^3/h.

3.3.8 M = molecular weight, kg/mole.

3.3.9 P = pressure, Pa.

3.3.10 p = gas permeance, m/h·Pa.

3.3.11 q = heat flux, W/m^2.

3.3.12 Q = heat flow, W.

3.3.13 R = ideal gas constant, 8.315 J/g-mole · K.

3.3.14 T = temperature, K.

3.3.15 V = internal VIP free volume, m^3.

3.3.16 Z_{edge} = ratio of simplified heat flow through barrier material to simplified heat flow through VIP core.

3.3.17 α = outgassing exponent of filler.

3.3.18 β = outgassing exponent of barrier.

3.3.19 λ = thermal conductivity.

3.3.20 τ = time, h.

3.3.21 *Subscripts*:

3.3.21.1 a = ambient.

3.3.21.2 e = environmental.

3.3.21.3 f = flange.

3.3.21.4 i = refers to a specific gas, that is, P_i is the partial pressure of the ith gas.

3.3.21.5 $init$ = initial.

3.3.21.6 s = surface.

4. Ordering Information

4.1 Orders shall include the following information:

4.1.1 Title, designation, and year of issue of this specification,

4.1.2 Product name,

4.1.3 Panel size and effective R-value required,

4.1.4 Service environmental parameters: maximum temperature, average temperature, maximum relative humidity, average relative humidity,

4.1.5 Required service life,

4.1.6 Tolerance if other than specified,

4.1.7 Quantity of material,

4.1.8 Special requirements for inspection or testing, or both,

4.1.9 If packaging is other than specified,

4.1.10 If marking is other than specified,

4.1.11 Special installation instructions if applicable,

4.1.12 Required compressive resistance,

4.1.13 Required effective thermal resistance after puncture,

4.1.14 Any required fire characteristics,

4.1.15 Required creep characteristics,

4.1.16 Required seal strength, and

4.1.17 Required dimensional stability at service environmental conditions.

5. Materials and Manufacture

5.1 *Panel Composite Design*—The panel shall consist of a gas barrier layer(s), as described in 5.2, and an evacuated core material or system as described in 5.3. See Fig. 1. An engineered quantity of gas adsorbent may be included. It is not

[10] For further discussion on heat flow mechanisms in evacuated insulations, see Practice C 740 on Evacuated Reflective Insulation in Cryogenic Service.

necessary that the panel design be symmetrical, depending upon end-use requirements.

5.2 *Panel Barrier Composition*—The barrier may consist of one or more layers of materials whose primary functions are to control gas diffusion to the core, and to provide mechanical protection. The barrier may be metallic, organic, inorganic or a combination thereof depending on the level of vacuum required, the desired service life, and the intended service temperature regimes. Barrier materials are selected to prevent outgassing, or at least to give off only those gases or vapors which can be conveniently adsorbed.

5.3 *Panel Core Composition*—The core shall comprise a system of cells, microspheres, powders, fibers, aerogels, or laminates, whose chemical composition may be organic, inorganic, metallic, or both. The reticular nature of the core may include subsystems such as honeycomb or integral wall systems. The function of the core composition or system is typically twofold: it reduces the radiative, solid, and gaseous heat transfer contributions to overall heat transfer, and it can provide a structural complement to the barriers. Core systems or densities may therefore vary for different anticipated end-uses and service temperature regimes.

6. Physical and Mechanical Properties

6.1 *Compressive Resistance*—The required compressive resistance should be specified by the purchaser according to the application.

6.2 *Effective Thermal Resistance (effective R-value)*—Because the effective thermal resistance is affected by many variables, Table 1 defines standard conditions and information that must be reported with the effective thermal resistance. Manufacturers may also provide thermal resistance data at other conditions. In addition to temperature, temperature gradient, and thickness effects, size and shape may have a significant impact on the effective thermal resistance of superinsulation panels, depending on the thermal conductivity of the barrier relative to that of the core. Fig. 2 shows the influence of panel size and barrier thickness on the effective R-value. The effective thermal resistance can also be affected by temporary temperature excursions that could occur during panel installation, as discussed further in Appendix X3.

6.3 *Effective Thermal Resistance After Puncture*—This value represents the effective thermal resistance of the panel in the event of a barrier failure (that is, after the panel internal volume has reached ambient pressure) and should be reported by the supplier.

6.4 *Fire Characteristics*—Vacuum panel products may contain materials that are not flame-resistant. The fire performance of the material should be addressed through fire test requirements that are specific to the end use.

TABLE 1 Standard Effective Thermal Resistance Report Conditions and Related Information Requirements for New Vacuum Insulation Panels

Panel Dimensions
Maximum use temperature
Maximum use humidity at 24°C (75°F)
Projected standard-condition service life
Initial effective thermal resistance at 24°C (75°F) and 50 % relative humidity

6.5 *Creep Characteristics*—The creep properties of a VIP will determine its shape and thickness in an application where the VIP is subjected to an externally applied constant stress. This stress can be caused by the environmental temperature as well as by a mechanical load. The creep properties are important because the shape and thickness of the VIP directly affect its thermal performance. The required creep properties should be specified by the purchaser according to the application.

6.6 *Barrier Permeance*—The barrier permeance is required for the VIP Service Life calculations. Note that the barrier permeance must be measured and reported for individual gases of interest. Note that the barrier permeance may also be affected by the service environment.

6.7 *Dimensional Stability at Service Conditions*—The maximum allowable change in panel dimensions caused by the change from ambient to service environmental conditions should be specified by the purchaser.

7. Dimensions and Tolerances

7.1 *Dimensions*—The dimensions shall be as agreed upon by the purchaser and supplier.

7.2 *Tolerances*—Tolerances shall be as agreed upon by the purchaser and supplier.

8. Workmanship and Finish

8.1 The insulation shall have no defects that adversely affect its service qualities and ability to be installed.

9. Sampling

9.1 Quality control records, maintained by the manufacturer, will usually suffice in the relationship between the purchaser and the manufacturer. If they mutually agree to accept lots on the basis of quality control records, no further sampling is required.

9.2 If the above procedure is not acceptable, an alternate sampling procedure shall be agreed upon between the purchaser and the manufacturer.

10. Qualification Requirements

10.1 For the purpose of initial material or product qualification, insulation shall meet the physical and mechanical properties of Section 6.

10.2 Acceptance qualification for lots and shipments of qualified product should be agreed upon by purchaser and supplier.

11. Test Methods

11.1 Properties of the insulation shall be determined in accordance with the following methods.

11.2 *Compressive Resistance*—Test Method C 165 or another method acceptable to both the purchaser and supplier should be used.

11.3 *Barrier Permeance*—The barrier permeance should be measured using Test Method D 1434, the method described in Appendix X4, or another method acceptable to both the purchaser and supplier. Note that the barrier permeance must be measured for individual gases of interest. The effects of

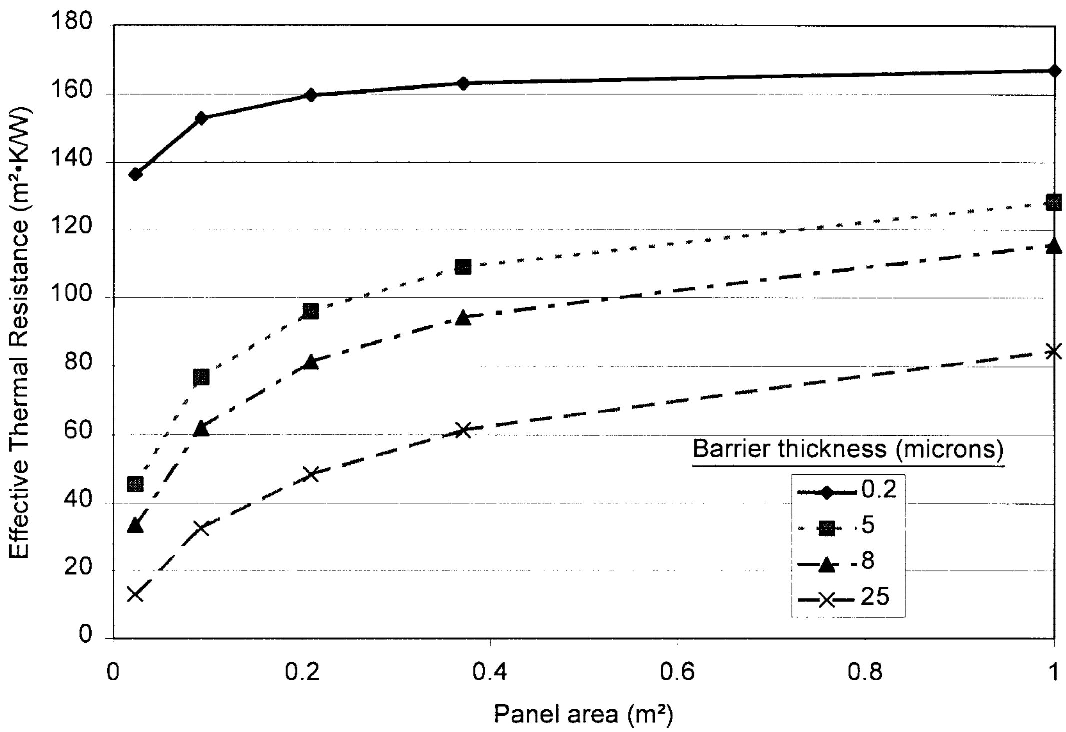


FIG. 2 Effective Thermal Resistance Changes with Panel Size and Barrier Thickness; All Other Panel Characteristics (Materials and Thickness) Held Constant

service temperature and humidity, any temperature excursion(s), and the chemical environment on the barrier permeance must be considered.

11.4 *Thermal Performance*:

11.4.1 *Center-of-Panel Thermal Resistivity*—The center-of-panel thermal resistivity is a measured value that is used to approximate the thermal resistivity of the evacuated core region. The center-of-panel thermal resistivity may be used, along with information about the barrier material and panel geometry, to calculate the effective panel thermal resistance. Use Test Methods C 177, C 518, or C 1114 in conjunction with Practice C 1045 to evaluate center-of-panel heat transfer properties. In the event of dispute, Test Method C 177 shall be the referee method. See Notes 1 and 2. Temperature differences shall be selected from Practice C 1058. The mean test temperature shall be selected according to the standard reporting temperatures shown in Table 1. It is often necessary to separate the panel barrier from the isothermal plates in a Test Method C 518 apparatus as shown in Fig. 3. When this configuration is used, thermocouples should be positioned to directly report the temperature on the center of the top and bottom faces of the

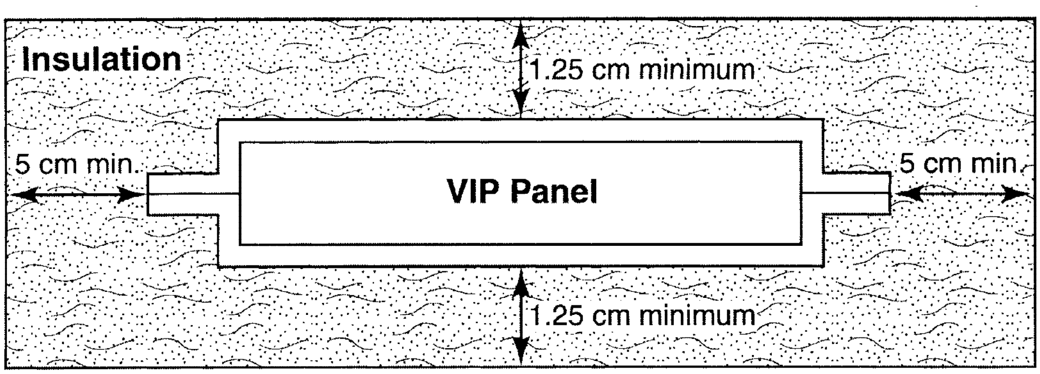


FIG. 3 Side View of the Standard Configuration Used to Measure the Effective Thermal Resistance of a Vacuum Insulation Panel

panel. The mean thermal resistivity of the center-of-panel tested shall not be less than the manufacturer's stated values.

11.4.1.1 The minimum panel size for this test is determined by the thermal conductivity of the barrier, the thickness of the barrier, the thermal conductivity of the core, and the size of the heat flux transducer or guarded hot plate surface used to make the measurement. Appendix X1 provides a fuller discussion of the relationship between these factors. See Note 3.

11.4.1.2 Another method to determine the core conductivity uses an array of heat flux transducers in the heat flow meter apparatus. These measurements can be analysed using a thermal modelling program to calculate the thermal resistivity of the filler or the magnitude of the thermal bridging through the barrier **(1)**.[11]

11.4.1.3 If Test Method C 1363 is used to measure the effective panel thermal resistance of the full size panel, the center-of-panel thermal resistivity measurement is not required. However, if numerical models are used to predict the effective thermal performance for panels of other sizes, the center-of-panel thermal resistivity must be measured.

11.4.1.4 The center-of-panel measurement can be used for quality control purposes. If panels are tested two weeks after manufacture as part of a quality-control program, this measurement will expose any panels with gross leaks.

NOTE 1—Due to the low thermal diffusivity of some superinsulators, it may be necessary to increase the time required to reach steady-state heat flow in the thermal resistance tests.

NOTE 2—Precision and bias are not yet available for these tests for these materials. Round-robin tests are planned to provide this information.

NOTE 3—For a sufficiently large panel, the flow through the panel's barrier will be a relatively small portion of the flow measured at the center of panel, so that thermal conductivity measurements made at the center of the panel will represent the conductivity of the panel's core region within an adequate margin of error.

11.4.2 *Effective Thermal Resistance*:

11.4.2.1 The effective thermal resistance differs significantly from the product of the center-of-panel resistivity and the thickness, and this system characteristic must take into account the details of the overall VIP design as well as its installation. The effective thermal resistance will vary over long periods of time. Therefore standard reporting conditions have been specified in Table 1. This issue is discussed further in 11.6.

11.4.2.2 The effective thermal resistance of a full-size panel can be measured using a calorimetric technique as described in Ref. **(2)**, or Test Method C 1363. In both cases the appropriate modeling corrections described in Ref. **(3)** must be applied. The test temperatures should shall be selected from Practice C 1058. The mean test temperature shall be selected according to the standard reporting temperatures shown in Table 1.

11.4.2.3 The effective thermal resistance of a full-size panel may be calculated by the use of finite element analysis, as described in Ref **(1)**. For this analysis, the center-of-panel (or core) thermal conductivity and that of the barrier material must be known.

11.4.2.4 A round-robin test is planned to examine the consistency of the various mathematical models used to calculate effective thermal resistance.

11.5 *Effective Thermal Performance after Puncture*—The panel barrier must be punctured with a hole at least 6 mm (0.25 in.) in diameter and the panel interior must be exposed to atmospheric pressure for at least seven days. Then the effective thermal resistance must be measured as described in 11.4.2. The mean thermal resistance of the material tested shall not be less than the manufacturer's stated values.

11.6 *Service Life*—The actual service life of a vacuum insulation panel is determined in large part by: the panel design and materials, the service environment, and the minimum acceptable thermal resistance. The standard-condition service life is defined as the period of time for which the panel will provide superinsulation performance in an environment of 24°C (75°F) and 50 % relative humidity. In making this determination, the manufacturer must consider, at the stated standard environmental conditions, the following: the outgassing of the filler material, the outgassing and permeability of the barrier material, the permeability of the seals, and the performance of any adsorbent materials contained within the panel. Then the expected decrease in thermal resistance that occurs as the vacuum insulation panel ages can be measured or computed from the relationship between thermal resistance and internal VIP pressure (for the appropriate mixture of gasses). The actual service life of a vacuum insulation panel can be shorter or longer than the standard-condition service life, depending on the service environment and the minimum required thermal resistance. Appendix X2 contains useful information about this complex issue.

11.7 *Creep Properties*—Test Methods C 480 or D 2221 or another method acceptable to both the purchaser and supplier should be used.

11.8 *Dimensional Stability at Service Conditions*—Test Method D 2126 should be used.

11.9 *Other Tests*—Depending upon the application, other tests may also be appropriate. This is discussed further in Appendix X4.

12. Inspection

12.1 Unless otherwise specified, Test Method C 390 shall govern the sampling and acceptance of material for conformance to inspection requirements. Exceptions to these requirements shall be stated in the purchase agreement.

13. Rejection and Resubmittal

13.1 Failure to conform to the requirements in this specification shall constitute cause for rejection. Rejection should be reported to the manufacturer or supplier promptly and in writing.

13.2 In case of shipment rejection, the manufacturer shall have the right to reinspect shipment and resubmit the lot after removal of that portion not conforming to requirements.

14. Packaging and Marking

14.1 *Packaging*—Unless otherwise specified, the insulation shall be supplied in the manufacturer's standard commercial packages to assure contents are undamaged at delivery.

[11] The boldface numbers given in parentheses refer to a list of references at the end of the text.

14.2 *Marking*—Unless otherwise specified, each package shall be marked with the:

14.2.1 Material name,

14.2.2 Manufacturer's name or trademark,

14.2.3 Handling instructions for the purchaser to follow to avoid panel damage once the product is removed from the manufacturer's package,

14.2.4 Storage Instructions for the purchaser to follow to avoid panel damage once the product is delivered,

NOTE 4—The storage time is a part of the panels' service life and the storage environmental conditions can affect panel performance as discussed in 3.2.10.

14.2.5 Panel dimensions, number of pieces,

14.2.6 Effective thermal resistance for the reporting conditions shown in Table 1, and

14.2.7 Date of manufacture.

15. Keywords

15.1 adsorbent; effective thermal resistance (effective R-value); superinsulation; thermal conductivity; thermal resistance; vacuum insulation

ANNEX

(Mandatory Information)

A1. ADDITIONAL SAFETY CONSIDERATIONS

A1.1 When applying these products, consider that temperatures of some cryogens, that is, liquid nitrogen, neon, helium, and hydrogen, are low enough to condense or solidify atmospheric gases. During such behavior oxygen enrichment of the condensed or solidified gases is likely to occur. Some insulation systems may have organic constituents, which in contact with oxygen enriched gases constitute a fire and explosion hazard. Caution should be taken to exclude atmospheric gases from these insulations where such oxygen enrichment could occur.

A1.2 When applying these products to a hot surface operating above 40°C (105°F), care should be taken to avoid burns. Consult the manufacturer or Guide C 1055 for hazard evaluation.

A1.3 The manufacturer shall provide the purchaser information regarding any hazards and recommended protective measures to be employed in the safe installation and use of the material.

APPENDIXES

(Nonmandatory Information)

X1. CALCULATIONS TO DETERMINE THE MINIMUM PANEL SIZE REQUIRED FOR A VALID CENTER-OF-PANEL THERMAL RESISTIVITY MEASUREMENT

X1.1 A simplified thermal model of a vacuum insulated panel can be constructed by considering two parallel and independent heat flow paths operating across the same temperature difference. The first is through the core of the panel and can be characterized by the panel's width, length, thickness, and the thermal conductivity of the core volume (λ_{core}). The second is through the panel's barrier and can be characterized by the barrier's thickness, thermal conductivity, and the panel's width, length, and thickness. The ratio of these two simplified heat flows, Z_{edge}, gives an indication of the relative importance of the heat flow through the panel's barrier. The calculation of Z_{edge} is shown in Eq X1.1-X1.5.

NOTE X1.1—This simplified model is a useful tool in characterizing the panel, but should not be used to calculate the heat transfer through the panel.

$$A_{core} = \text{width} \times \text{length} \quad \text{(X1.1)}$$

$$A_{barrier} = 2 \times (\text{width} + \text{length}) \times \text{thick}_{barrier} \quad \text{(X1.2)}$$

$$Q_{core} = \lambda_{core} \times A_{core} \times \Delta T \div \text{thick}_{panel} \quad \text{(X1.3)}$$

$$Q_{barrier} = \lambda_{barrier} \times A_{barrier} \times \Delta T \div \text{thick}_{panel} \quad \text{(X1.4)}$$

$$Z_{edge} = Q_{barrier}/Q_{core} \quad \text{(X1.5)}$$

X1.2 For a sufficiently large panel, the flow through the panels barrier will be relatively small and thermal conductivity measurements made at the center of the panel will represent the conductivity of the panel's core region within an adequate margin of error. To determine the size of a "sufficiently large" panel, a finite difference model of a vacuum insulation panel was run for a variety of panel parameters. The parameters that were varied are shown in Table X1.1 and the results are presented in Fig. X1.1. This figure was produced to show the relationship between measured center-of-panel heat flux and the heat flux that would be measured if the core of the panel were present without any edge effects, thus giving the relationship between the calculated center-of-panel conductivity and the conductivity of the panel's core. The panel was assumed to be square and the sensor was assumed to be located in the center of the panel. For a non-square panel, the smaller of the width or length should be used. This figure shows the ratio of the two theoretical heat flows (that is, Z_{edge}) from the simplified model on the x-axis. On the y-axis is the center-of-panel heat flux ratio, that is, the flux through the sensor area as calculated by the finite difference model ($q_{center\text{-}of\text{-}panel}$) divided by the ideal flux through the core region in the absence of any edge effects (q_{core}). The different symbols on this figure define the size of the panel relative to the size of the heat flux sensor. As can be seen in this figure, for a sufficiently large panel, the center-of-panel measurement should be within 5 % of the core value, that is, $q_{center\text{-}of\text{-}panel}/q_{core}$ is less than 1.05.

X1.3 For a panel with an unknown core conductivity, it may be necessary to determine the minimum panel size via an iterative procedure. That is, measure the center-of-panel conductivity with the smallest available sensor and the largest available panel. Use this measured value as an estimate of the core conductivity, λ_{core}, to calculate q_{core}. Then check Fig. X1.1 to determine if the panel was large enough. Repeat the test with a larger panel if the value of $q_{center\text{-}of\text{-}panel}/q_{core}$ is greater than 1.05.

X1.4 If it is not possible to test a panel large enough to satisfy the accuracy requirement, either because the panels are too small or because the barrier material is too conductive, then the finite difference model can be used with the output of a heat flux sensor array to determine q_{core}(and λ_{core}). **(1)**

TABLE X1.1 Parametric Evaluation of the Effect of Panel Size on Adequacy of Center-of-Panel Thermal Conductivity Measurements

Panel barrier thermal conductivity:	0.247 to 233 W/m-K (1.72 to 1,500 Btu-in./h-ft^2-°F)
Panel barrier thickness:	0.003 to 0.08 cm (0.001 to 0.03 in.)
Panel core region conductivity:	0.0035 to 0.0095 W/m-K (0.025 to 0.067 Btu-in./h-ft^2-°F)
Panel width:	15 to 100 cm (6 to 40 in.)
Sensor width:	7.6 to 20 cm (3 to 8 in.)

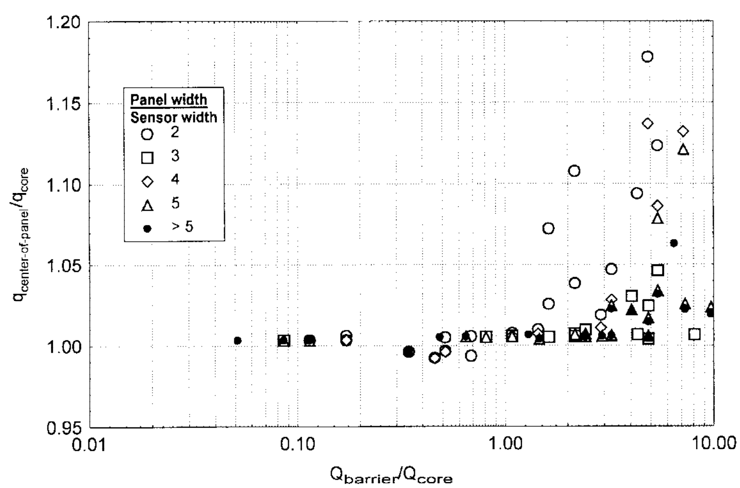
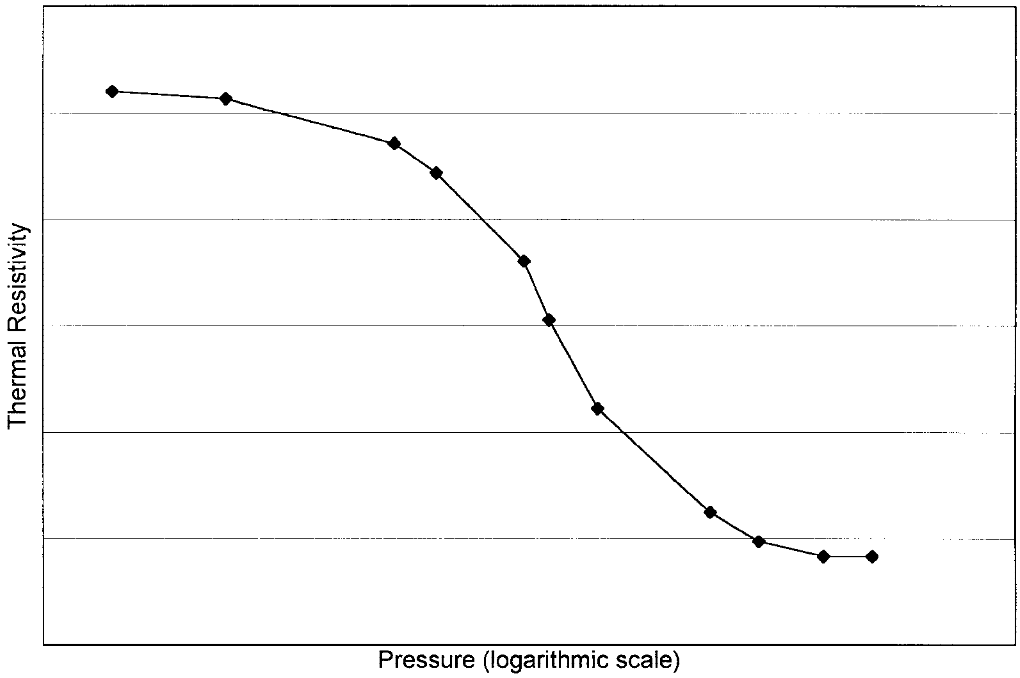


FIG. X1.1 Effect of Panel Construction on Measurement Requirements Based on the Parametric Analysis Summarized in Table X1.1

X2. PANEL AGING CALCULATIONS

X2.1 The high thermal resistances achieved by VIPs are primarily due to elimination of the gas-phase conduction coupled with some degree of opaqueness. The VIP, therefore, must be designed to resist the inward transport of air, water vapor, or any other gases. The useful life of a VIP is the time required for the interior pressure to increase to a point where gas-phase conduction becomes a factor. As the absolute pressure inside a VIP increases due, for example, to inward diffusion of air, the thermal resistivity decreases to that of an air-filled bed at atmospheric pressure. **(5)** Fig. X2.1 shows the typical shape of the thermal conductivity curve as a function of panel pressure. (Note that the pressure axis shown on this figure is logarithmic.) This data for apparent thermal conductivity as a function of pressure can be combined with data for pressure as a function of time to obtain thermal resistivity as a function of time. **(5)** This type of analysis is crucial for VIPs with permeable barriers or for VIPs with filler or barrier materials that will outgas into the interior volume.



NOTE 1—Results will vary for different core materials based on particle diameter or foam pore size. Results will also vary for different gases, such as might be introduced into the panel via outgassing phenomena.

FIG. X2.1 Typical Relationship Between Center-of-Panel Thermal Resistivity and Internal Panel Pressure

NOTE X2.1—If the dominant contributor toward the increased interior pressure is the outgassing of the barrier or VIP filler, then the pertinent gas is not air and the relationship between internal gas pressure and panel thermal resistance must be measured using the appropriate gas mixture.

X2.2 The internal VIP pressure will increase during the panel's lifetime due to permeation of air and water vapor through the barrier material and due to outgassing of both the filler and barrier materials. If any adsorbent effect is neglected,

$$V\frac{dP_i}{d\tau} = (k_{i,s} + k_{i,f})(P_{i,e} - P_i) + C_i\tau^{-\alpha} + B_i\tau^{-\beta} \qquad \text{(X2.1)}$$

X2.3 The left hand side of this equation represents the rate of change of the partial pressure of the ith gas. The first term on the right hand of Eq X2.1 describes the pressure increase in the panel due to gas permeation through the surface and the flanges of the barrier. The outgassing effects of the core and barrier materials are represented by the third and fourth terms in Eq X2.1. The coefficients C_i, B_i have units of pressure · volume/time (the time unit is raised to a power that depends upon the values of α and β, if α and β are equal to 1, then the time exponent is 0 and that portion of the units is eliminated) and are outgassing parameters for the specific filler and barrier materials. The exponent terms are also specific for each material, but are generally between 0.5 and 1. The values of C_i, B_i, α, and β must be empirically determined. One apparatus capable of making these measurements consists of bakeable stainless steel high vacuum benches equipped with a quadrupole mass spectrometer. The specimen is placed within a small glass container which is evacuated to a very low pressure and then sealed. The pressure within this volume is monitored over several days and small specimens of the gas within the volume are periodically withdrawn and admitted to the mass spectrometer for partial pressure measurement. (The gas background desorbed by the experimental bench should be taken into account by carrying out a blank run prior to each analysis.) The outgassing data are then interpolated according to the semi-empirical law quoted in the literature **(6)**:

$$g(\tau) = g_o(\tau)^{-\alpha}, \qquad \text{(X2.2)}$$

Where g (τ) is the outgassing rate at time, τ, g_o is the desorbed amount after 1 h, and α is a parameter related to the desorption mechanism, its value being usually comprised between 0.5 and 1, depending on the gas specie considered. Comparing Eq X2.1 and X2.2, it is apparent that the C_i and B_i terms are equal to the amount of gas desorbed in the first hour for each material.

X2.4 Eq X2.1 can be solved by numerical integration. However, assuming $P_{i,e} >> P_i$, as is the usual case in most panels, an accurate approximate analytical solution is given by:

$$P_i(\tau) = P_{init,i} + [(k_{i,s} + k_{i,f})P_{i,e}\tau + \int C_i\tau^{-\alpha i}\, d\tau + \int B_i\tau^{-\beta i}\, d\tau] \div V \qquad \text{(X2.3)}$$

The effect of any one gas diffusing through the barrier will cause the pressure within the panel to rise according to the following equation:

$$P_i(\tau) = P_{e,i} - (P_{e,i} - P_{init,i})e^{\left\{-p_i\frac{A}{V}\frac{RTdo,i}{M_i}\tau\right\}} \qquad \text{(X2.4)}$$

However, for the time period of interest, that is during the time when the internal pressure is much less than the external pressure, the pressure increase is linear and the diffusive effects of multiple gases are additive, as are the effect of diffusion through the surfaces and the flanges of the barrier. Therefore, the permeation rates used in Eq X2.1 and X2.3 can be defined:

$$k_i = p_i \frac{A}{V} \frac{RTd_{o,i}}{M_i} \quad \text{(X2.5)}$$

X2.5 The last two terms in Eq X2.3 can be solved easily so long as the integration is carried out starting at τ=1 (for both mathematical and physical reasons). For α and β less than 1, use Eq X2.6; for α and β equal to 1, use Eq X2.7. Since total pressure evolution in the panel is the sum of the various gas partial pressure contributions, the internal pressure of the VIP (again neglecting any adsorbent effect) varies with time according to the equation:

$$P(\tau) = \sum_{1}^{N} P_{init,i} + \left[\tau \sum_{1}^{N} P_{e,i}(k_{i,s} + k_{i,f}) + \sum_{1}^{N} \left(\frac{C_i}{1-\alpha_i} \right) \tau^{(1-\alpha_i)} + \sum_{1}^{N} \left(\frac{B_i}{1-\beta_i} \right) \tau^{(1-\beta_i)} \right] \div V \quad \text{(X2.6)}$$

$$P(\tau) = \sum_{1}^{N} P_{init,i} + [\tau \sum_{1}^{N} P_{e,i}(k_{i,s} + k_{i,f}) + \sum_{1}^{N} C_i \ln \tau + \sum_{1}^{N} B_i \ln \tau] \div V \quad \text{(X2.7)}$$

X2.6 To evaluate the pressure increase as a function of time and hence the service life in a VIP it is necessary to know, by literature or experiments, the value of the various parameters in Eq X2.6. In principle, these values can be different depending on the type of core and barrier materials used for VIP manufacturing. Some of these values are difficult to measure. For example, some experimental techniques (such as that described in Appendix X4) may measure the sum of the diffusion rates through the surface and the flanges rather than the individual diffusion coefficients.

X2.7 Special materials can be included inside the VIP to adsorb gas molecules and thus counteract their effect on the internal pressure. However, at some point, the adsorbent material will become saturated and the internal pressure will begin to rise. Also, the adsorbent material may be designed to collect only certain types of molecules. The effect of an adsorbent must therefore be carefully considered because of these two characteristics: an adsorbent has a finite capacity and it may adsorb some gases preferentially. An adsorbent of capacity G (stated in units of pressure · volume) can reduce the total pressure by an amount equal to that capacity divided by the VIP internal volume. However, the specific adsorption capacity for each gas must be considered separately. The calculation must be done in two steps to account for the fact that the adsorbent cannot adsorb more gas than is present. The intermediate calculations are shown in Eq X2.8-X2.12. Eq X2.8 is used if α and β are less than 1; use Eq X2.9 for α and β equal to 1. Eq X2.8 through Eq X2.14 should be used instead of Eq X2.6 and Eq X2.7 if an adsorbent is included in the VIP.

$$P_i^*(\tau) = P_{init,i} + \left[P_{e,i}\tau(k_{i,s} + k_{i,f}) + \left(\frac{C_i}{1-\alpha_i} \right) \tau^{(1-\alpha_i)} + \left(\frac{B_i}{1-\beta_i} \right) \tau^{(1-\beta_i)} \right] \div V - \frac{G_i}{V} \quad \text{(X2.8)}$$

$$P_i^*(\tau) = P_{init,i} + [P_{e,i}\tau(k_{i,s} + k_{i,f}) + C_i \ln \tau + B_i \ln \tau] \div V - \frac{G_i}{V} \quad \text{(X2.9)}$$

if:

$$(P_i^*(\tau) \geq 0) \quad \text{(X2.10)}$$

then:

$$Pi(\tau) = P_i^*(\tau) \quad \text{(X2.11)}$$

if:

$$(P_i^*(\tau) < 0) \quad \text{(X2.12)}$$

then:

$$Pi(\tau) = 0 \quad \text{(X2.13)}$$

$$P(\tau) = \sum_{1}^{N} P_i(\tau) \quad \text{(X2.14)}$$

X2.8 The service life is equal to the time that corresponds to the maximum pressure identified previously as corresponding to the minimum acceptable thermal resistance for the gas mixture composition that will be present within the panel.

X3. ADDITIONAL TESTING

X3.1 For some applications, additional performance tests may be appropriate. For example, if the vacuum insulation panels are to be incorporated into shipping containers or other mobile structures, it may be prudent to ask for vibration or drop tests, such as those described in Test Method D 999 or IEC68-2-6, Part 2, Test F. Other appropriate packaging tests may be found in Test Methods D 3103 and D 4169. The purchaser may also wish to specify the required puncture resistance which can be measured using test methods such as Technical Association of Pulp and Paper Industry (TAPPI) Standard T803, 10.7 of Specification C 1136, and Test Method D 3763. If the VIP is to be located in an environment where attack by chemical action is possible, appropriate durability tests should be specified. Other tests may be specified to verify the integrity of the evacuated assembly, such as Test Method E 493. If the panel will be subjected to transverse loads, the flexural properties may be specified using Test Method C 203. The required seal strength is related to the desired service life of the panel and can be measured using Test Method F 88.

X3.2 Additional testing should be performed by the user if the vacuum panels are exposed to excursions to high temperature either during installation or use. Examples of such temperature excursion sources are: devices which output high heat near a vacuum panel, use of hot melt adhesives, or use of polyurethane foam which undergoes an exothermic reaction during foam formation around a vacuum panel. Users should consider the potential impact of these short term effects on panel dimensions and insulation performance. Some of these impacts may be related to changes in the permeability of the panel barrier or the seals or in the core microstructure or to outgassing from either the panel core or barrier material.

X3.3 Similar to temperature excursions, panel exposure to certain chemical environments could affect barrier permeance and therefore panel performance and service life. The user may wish to perform additional tests if the panels will be exposed to such chemicals.

X4. MEASUREMENT TECHNIQUE FOR BARRIER PERMEABILITY

X4.1 This low-volume panel membrane permeability measurement procedure is described fully in **(7)**.

NOTE X4.1—This technique measures the combined permeability of the barrier material and the barrier seams.

X4.2 Construct an evacuated panel with a nearly solid filler so that the free volume is known and is only 1 to 5 % of panel volume. The filler material should be chosen to avoid or minimize outgassing as well. Place panel in controlled environment (controlled: surrounding gas, temperature, time). The panels should be supported by a grill-like structure to maximize the surface exposure to the gas environment. Measure the panels' internal pressure (the hand-held gage described in Ref. **(4)** works well on these panels) over multiple time increments. Plot $\ln((P-P_e)/(P_{init}-P_e))$ versus time; where P_e is the environmental pressure and P_{init} is the initial pressure inside the panel. The slope of the line, determined using a standard least squares regression technique, is relatable to the permeance of the gas through the barrier and flanges of the barrier material and the internal free volume, V, of the VIP as follows:

$$\text{SLOPE} = d(\ln((P-P_e)/(P_{init}-P_e)))\ /d\tau\ (-pATRd_o)/(VM) \quad \text{(X4.1)}$$

where: τ is time, p is the gas permeance, A is the permeating surface area of the VIP barrier material, T is the test temperature, R is the ideal gas constant, d_o is the density of the gas at standard temperature and pressure, V is the VIP internal free volume, and M is the molecular weight of the permeating gas. The steady state permeance can be calculated from the linear slope since all the other parameters are known.

X5. HISTORY OF THE SPECIFICATION

X5.1 Vacuum insulation systems have long been used for cryogenic applications. These systems have historically consisted of multi-layer evacuated jackets with active vacuum systems. In the early 1990s, sealed evacuated panels became commercially available. These panels were filled with either fiberglass or silica and had either metal or plastic barriers. The continuing design evolution includes open-celled foam and advanced powdered fillers, specialty multi-layer films, and the inclusion of new adsorbent systems. In order to help potential users understand the performance of these panels, a task group was formed in 1995 to create an ASTM material specification. This specification is the result of these on-going efforts. Due to the complexity of this non-homogenous insulation form, several appendices have been included to give testing advice. Efforts to systematically compare the results of these evaluation methods is underway. It is anticipated that the task group will address the need for standard test methods in the near future. Also, expansion of the specification to nonplanar evacuated shapes is likely, and insulation types and classes will be added as the market develops

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