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Standard Test Method for Using Heat Flow Meter Apparatus to Measure the Center-of-Panel Thermal ~~Resistivity~~ Transmission Properties of Vacuum Insulation Panels[1]

This standard is issued under the fixed designation C1667; 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 test method covers the measurement of steady-state thermal transmission through the center of a flat rectangular vacuum insulation panel using a heat flow meter apparatus.

1.2 Total heat transfer through the non-homogenous geometry of a vacuum insulation panel requires the determination of several factors, as discussed in Specification C1484. One of those factors is the center-of-panel thermal resistivity. The center-of-panel thermal resistivity is an approximation of the thermal resistivity of the core evacuated region.

1.3 This test method is based upon the technology of Test Method C518 but includes modifications for vacuum insulation panel applications as outlined in this test method.[2]

1.4 This test method shall be used in conjunction with Practice C1045 and Practice C1058.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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 practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C168 Terminology Relating to Thermal Insulation
C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
C740 Practice for Evacuated Reflective Insulation In Cryogenic Service
C1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions
C1058 Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation
C1484 Specification for Vacuum Insulation Panels
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

3. Terminology

3.1 *Definitions*—Terminology C168 applies to terms used in this specification.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *center-of-panel*—the location at the center of the largest planar surface of the panel, equidistant from each pair of opposite edges of that surface.

3.2.2 *center-of-panel apparent thermal resistivity*—the thermal performance of vacuum insulation panels includes an edge effect due to heat flow through the barrier material and this shunting of heat around the evacuated volume of the panel becomes more

[1] This test method is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

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[2] All references to particular sections of Test Method C518 within this document refer to the ~~2004~~2010 edition of Test Method C518.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

prevalent with greater barrier thermal conductivity, as shown in Fig. 1. For panels larger than a minimum size (as described in Annex A1), the center-of-panel apparent thermal resistivity is a close approximation of the intrinsic core thermal resistivity of the vacuum insulation panel. The effective thermal performance of a panel will vary with the size and shape of the panel.

3.2.2.1 *Discussion—*

Thermal resistivity, the reciprocal of apparent thermal conductivity, is used when discussing the center-of-panel thermal behavior.

3.2.3 *core*—the material placed within the evacuated volume of a vacuum insulation panel. This material may perform any or all of the following functions: prevent panel collapse due to atmospheric pressure, reduce radiation heat transfer, and reduce gas-phase conduction. The apparent thermal conductivity of the core, or λ_{core}, is defined as the apparent thermal conductivity of the core material under the same vacuum that would occur within a panel, but without the barrier material. This is the apparent thermal conductivity that would be measured in a vacuum chamber without the barrier material.

3.2.4 *effective panel thermal resistance (effective panel 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 vacuum insulation panel, that is, the entire panel. The effective thermal resistance will also vary with the panel mean temperature.

3.2.4.1 *Discussion—*

Thermal resistance, the reciprocal 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.

3.2.5 *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 panel thermal resistance.[4]

3.2.6 *panel barrier*—the material that envelops the evacuated volume and is used to separate the evacuated volume from the environment and to provide a long term barrier to gas and vapor diffusion.

[4] For further discussion on heat flow mechanisms in evacuated insulations, see Practice C740 on Evacuated Reflective Insulation in Cryogenic Service.

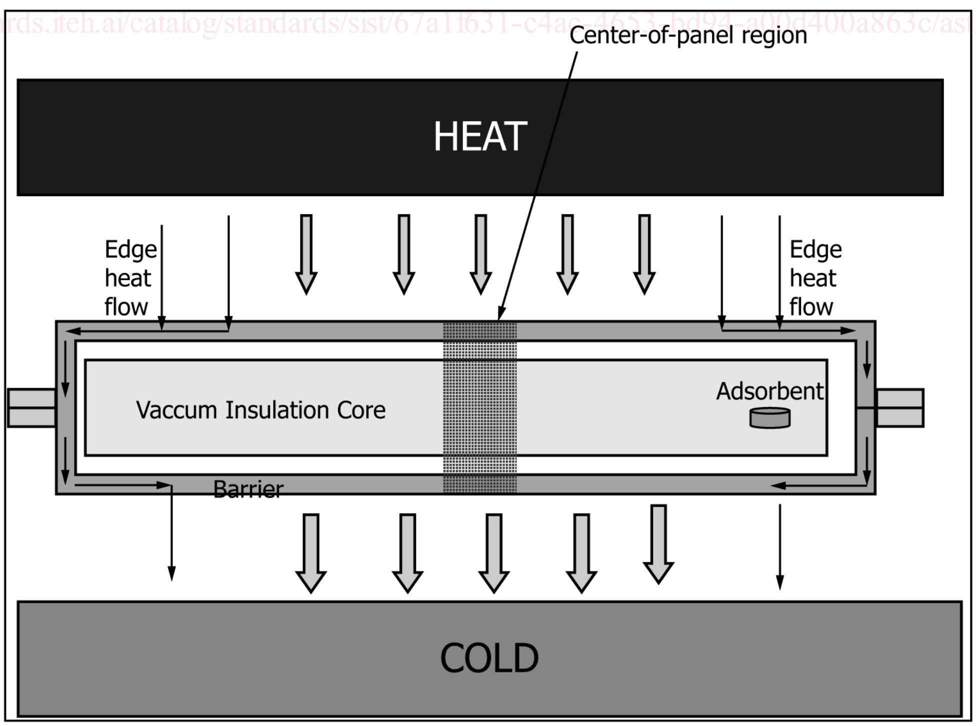

FIG. 1 Side View of a Vacuum Insulation Panel Showing Edge Heat Flow and the Center-of-Panel Region

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

3.3 *Symbols and Units:* $A_{barrier}$ = area of the barrier perpendicular to the largest panel faces, m^2
A_{core} = area of the largest panel face covering the core material, m^2
C = calibration standard conductance, W/m^2-K
E = heat flux transducer output, V
L_{panel} = panel thickness, m
$L_{calibration\ standard}$ = thickness of a single layer of the calibration standard material, m
$L_{calibration\ standard,\ target}$ = target total thickness of the calibration standard material, m
q = heat flux through the panel, W/m^2
$Q_{barrier}$ = heat flow through the barrier material, W
$Q_{center\text{-}of\text{-}panel}$ = estimated heat flow at the transducer (as calculated by the model), W
Q_{core} = heat flow through the core region, W
$R_{calibration\ standard}$ = thermal resistivity of the calibration standard, m-K/W
$R_{center\text{-}of\text{-}panel}$ = center of panel thermal resistivity, m-K/W
S = calibration factor, $(W/m^2)/V$
T_c = specimen cold surface temperature, K
T_h = specimen hot surface temperature, K
$t_{barrier}$ = thickness of the barrier material, m
W_1, W_2 = panel width, panel length, m
u_c = combined standard uncertainty
u_n = uncertainty component, for example, standard uncertainty for the measurement
Z_{edge} = an approximate estimate of the ratio of the heat flow through the barrier material to the heat flow through the core material, dimensionless
$\lambda_{barrier}$ = thermal conductivity of the barrier material, W/m-K
λ_{core} = apparent thermal conductivity of the core region, W/m-K

4. Summary of Test Method

4.1 This test method describes a modified application of Test Method C518 to evacuated panels. These panels fall outside the scope of Test Method C518, both in their non-homogeneity and in the current lack of specimens having an accepted reference value that are of similar size and have the necessary thermal characteristics. Therefore, modifications are necessary in the areas of apparatus calibration, plate separation, test procedures, precision and bias, and reporting.

NOTE 1—Primary calibration standards, using vacuum insulation panels, have not been prepared for this class of products due to uncertainties about their long-term stability characteristics.

5. Significance and Use

5.1 Heat flow meter apparatus are being used to measure the center-of-panel portion of a vacuum insulation panel, which typically has a very high value of thermal resistivity (that is, equal to or greater than 90 m-K/W). As described in Specification C1484, the center-of-panel thermal resistivity is used, along with the panel geometry and barrier material thermal conductivity, to determine the effective thermal resistance of the evacuated panel.

5.2 Using a heat flow meter apparatus to measure the thermal resistivity of non-homogenous and high thermal resistance specimens is a non-standard application of the equipment, and shall only be performed by qualified personnel with understanding of heat transfer and error propagation. Familiarity with the configuration of both the apparatus and the vacuum insulation panel is necessary.

5.3 The center-of-panel thermal transmission properties of evacuated panels vary due to the composition of the materials of construction, mean temperature and temperature difference, and the prior history. The selection of representative values for the thermal transmission properties of an evacuated panel for a particular application must be based on a consideration of these factors and will not apply necessarily without modification to all service conditions.

6. Apparatus

6.1 Follow Test Method C518, Section 5 except use Section ~~8~~8 of this test method for calibration.

7. Specimen Preparation

7.1 Vacuum insulation panels are typically rigid and the shape cannot be modified for testing purposes. However, to obtain representative thermal values for the panel, the two primary surfaces must be parallel and have limited surface irregularities.

7.2 If none of the standard product sizes are appropriate for the heat flow meter apparatus used in this test, then representative test specimens must be produced so that they accurately represent both the same average performance as the production product and the same typical product variability.

7.3 The specimens shall be of the same thickness as the average thickness to be applied in use.

7.4 The minimum panel size for this test is determined by the size of the heat flux transducer in the heat flow meter apparatus, the overall maximum specimen size limit for the apparatus, the thermal conductivity of the barrier, the thickness of the barrier, and the thermal conductivity of the core. Annex A1 contains a procedure to estimate the minimum acceptable panel size.

7.4.1 Preferably, specimens shall be of such size as to fully cover the plate assembly surfaces, with an allowance of up to 6 mm on each side to allow room for panel seals.

7.4.2 If the width or length, or both, of the specimen are smaller than the apparatus compartment, surround the specimen with high thermal resistance insulation. This surrounding material will reduce edge heat transfer and prevent air circulation around the specimen.

7.5 For panels with smooth parallel surfaces, the specimen thickness is represented by the plate separation.

7.6 For panels with irregular surfaces, to insure thermal contact with the apparatus surfaces, it is necessary to:

7.6.1 Measure the panel thickness with an accuracy of ±0.05 mm in at least five locations distributed over the surface of the panel and use the average of the local values. Care shall be taken so that the contact between the caliper jaws or the length meter's pressure foot does not damage the specimen surface.

7.6.2 Record the output of one thermocouple placed on the center of the top and one thermocouple placed on the center of the bottom of the panel. The temperatures recorded by the thermocouples, not the hot and cold plate temperatures, shall be used to calculate the center-of-panel apparent thermal resistivity.

7.6.3 Place one sheet (approximately 3 mm thick) of an elastomeric or soft foam rubber between each side of the panel and the corresponding apparatus plate. This sheet will improve contact between the controlled temperature plates and prevent air circulation between the panel and the plates.

8. Calibration

8.1 The apparatus shall be calibrated according to Test Method C518 sections 6.1 to 6.5.

8.2 Specimens having an accepted reference value with physical and thermal characteristics similar to vacuum insulation panels are not yet available. The linearity of the heat flux transducers at very low levels of heat flux must be verified using another method. The apparatus calibration must include the addition of at least one of the modified calibration procedures described in 8.5 and 8.6, that is Modified Calibration Procedure A or B. As described in 8.7, the two modified procedures can be combined if necessary to meet uncertainty goals. Although each method magnifies an element of experimental error (as discussed below), it is necessary to augment the standard Test Method C518 calibration for this particular application.

8.3 It is not intended that the heat flow meter apparatus calibration be altered based on the results of these supplementary procedures. Rather the results will be used by qualified personnel (as described in 5.2) to determine whether a particular heat flow meter apparatus will give meaningful results for a vacuum panel application, and if so, to provide guidance on interpreting and applying the Test Method C518 test results.

NOTE 2—Just as with the standard calibration technique, the supplementary calibration need not be repeated for every test if the equipment has been stable over a significant period of time. See Test Method C518 section 4.5.1.

NOTE 3—The heat flow meter apparatus may take a long time to reach a true steady-state condition for low conductance specimens, as described in Test Method C518 section 7.7.3.

8.4 In order to evaluate the linearity of the heat flux transducers at the reduced levels of heat flux that will occur with the vacuum insulation panels, a target heat flux is calculated from Eq 1, using the best information available about the center-of-panel thermal resistivity, the panel thickness, and the temperature difference of interest.

$$q_{target} = \frac{(T_h - T_c)}{R_{center\ of\ panel,\ estimated} \times L_{panel}} \tag{1}$$

8.5 *Modified Calibration Procedure A*—Make a series of test measurements using multiple thicknesses of the calibration standard, with a radiation-blocking septum between the layers. Calculate a target thickness for the heat flux level of interest using Eq 2, recognizing that the actual thickness will be an even multiple of the thickness of a single layer or the sum of the available calibration standard thicknesses.

$$L_{calibration\ standard,\ target} = \frac{(T_h - T_c)}{R_{calibration\ standard} \times q_{target}} \tag{2}$$

NOTE 4—The use of radiation-blocking septums in this procedure is not meant to imply that radiation is not a significant heat transfer mechanism within a vacuum insulation panel. Rather, the septums are used to allow the addition of previously measured conductances for each individual layer of the calibration standards. Brown Kraft paper has been used for this purpose.

8.5.1 As described in Test Method C518 section A1.8.2, for each stack, a first approximation is that the total thermal resistance is the sum of the individual thermal resistances.

8.5.2 All of these measurements shall be made at the same mean temperature and temperature difference that will be used for the vacuum insulation panel specimen measurement.

NOTE 5—Care must be observed in making the required measurements. Due to the low heat flux rate of the insulation stack and its thermal heat capacity, the test time parameters for determining the steady state will be significantly longer than normal testing. See 9.2.2.

8.5.3 For each heat flux transducer, calculate the calibration factor, S from Eq 3, at each heat flux level.

$$S = \frac{(T_h - T_c)}{E \times \sum_{Layers} \frac{1}{C}} \tag{3}$$

8.5.4 For each heat flux transducer, evaluate the variation in S as a function of heat flux. Determine whether the variation is acceptable and include this value as an element of the measurement uncertainty in the reported error analysis.

NOTE 6—Any change in the calibration factor for increased thickness reflects not only the effect of the reduced heat flux magnitude (which will be pertinent to the vacuum insulation panel measurement), but also the effect of increased lateral heat losses or gains caused by the increased edge area (which may not be pertinent for this application). The lateral heat losses can be minimized by keeping the mean test temperature equal to the temperature of the local environment.

8.6 *Modified Calibration Procedure B*—Make a series of test measurements with small temperature differences using a single calibration standard. Calculate the target temperature difference as shown in Eq 4.

$$(T_h - T_c)_{target} = R_{calibration\ standard} \times q_{target} \times L_{calibration\ standard} \tag{4}$$

8.6.1 Holding the mean temperature constant, adjust the plate temperatures as necessary to reduce the temperature difference across the calibration specimen.

8.6.2 For each heat flux transducer, calculate the calibration factor, S from Eq 3, at each heat flux level. For each heat flux transducer, evaluate the variation in S as a function of heat flux. Determine whether the variation is acceptable and include this value as an element of the measurement uncertainty in the reported error analysis.

8.6.3 For each heat flux transducer, the calibration factor S is a function of plate temperature. The user shall include the variation of S with temperature in the error analysis unless this variability has already been included in the calibration factor.

NOTE 7—At smaller temperature differences, the effect of the imprecision of the plate temperature measurements on the final result will be greater.

8.7 If neither Modified Calibration Procedure A or B are sufficient to reduce the experimental heat flux to the desired levels within an acceptable uncertainty, it will be necessary to combine them, that is, to use multiple calibration specimens with a reduced temperature difference.

8.7.1 Edge effect errors will be magnified with the stacked specimen method, compared to a single calibration thickness. Smaller temperature differences will magnify the impact of the imprecision of the temperature measurements on the final result. An error analysis of the specific apparatus shall be used as a guide to select the best combination of calibration standard thickness and temperature difference to reduce the calibration uncertainty.

9. Procedure

9.1 This test method shall only be performed by qualified personnel with experience in heat transfer analysis and experimental error propagation. To ensure accurate measurement, the operator shall be instructed fully in the operation of the equipment and must have detailed familiarity with the configuration of both the apparatus and the vacuum insulation panel.

9.2 Follow Test Method C518 section 7.6 with the following modifications.

9.2.1 Radiation will be an important heat transfer mechanism within a vacuum insulation panel, so select the plate temperatures to match the expected use temperatures. When possible, use the product standard rating conditions or follow Test Method C518 section 7.7.1 and Practice C1058.

9.2.2 These low thermal conductivity specimens usually require a longer settling time than more conductive materials. At least 10 successive observations must yield values of thermal conductivity that fall within 2 % of the mean value for these 10 readings. If the 10 readings show a monotonic variation then equilibrium has not been attained.

10. Calculations

10.1 Calculate the center-of-panel apparent thermal resistivity using the panel thickness, the temperature difference across the panel, and the heat flux through the panel as described in Practice C1045.

10.1.1 The heat flux, q, is the average of the heat fluxes from the hot and cold plates.

10.1.2 If the panel is in direct contact with the apparatus plates, as described in 7.5, then the temperature difference is the difference between the two plate temperatures and the panel thickness, L_{panel}, is the plate separation.

10.1.3 If the panel is not in direct contact with the apparatus plates, as described in 7.6, then the temperature difference is the difference between the temperatures reported by the two thermocouples attached to the panel, and the panel thickness, L_{panel}, is the average of the five measurements from 7.6.1.

11. Report

11.1 For each test, report the following information:

11.1.1 Identify the report with a unique numbering system to allow traceability back to the individual measurements taken during the test performed.

11.1.2 Identify the material and give a physical description.

11.1.3 Provide a brief conditioning history of the specimen, if known.

11.1.4 Thickness of the specimen as received and as tested, m.

11.1.5 Method and environment used for conditioning, if used.

11.1.6 Mean temperature of the test, K.

11.1.7 Heat flux through the specimen, W/m^2.

11.1.8 Thermal resistivity of the center-of-panel, m·K/W.

NOTE 8—The thermal resistance of the non-homogenous panel is not available from this procedure.

11.1.9 Duration of the measurement portion of the test, h.

11.1.10 Date of test.

11.1.11 Description of calibration test results from Section 8, including the date of the last heat flux transducer calibration, and the type or types of calibration materials used.

11.1.12 Estimated or calculated uncertainty in reported values.

11.1.13 List exceptions to the standard, if any.

11.1.14 The name of the operator performing the tests and the data analyst preparing the test report.

12. Precision and Bias

12.1 An interlaboratory comparison of the center-of-panel thermal conductivity of powder-filled evacuated insulation panels was conducted in the early 1990s. The heat flux meter apparatus used varied in maximum specimen size and transducer size. All of the apparatus used a single heat flux transducer. Also, three participants used equipment that, unlike today's apparatus, did not measure the temperatures of the bounding plates directly and the plates were not constructed of high-conductivity rigid metal. In this interlaboratory comparison, measurements on the larger-sized panels by six laboratories produced a two standard deviation (2σ) of 7.4 % about the mean. When the results for the smaller panels (down to 15×15 cm) are included the 2σ increases to 12.9 % about the mean.[5]

12.2 The precision of this test method is based on an interlaboratory study that was initiated in February of 2000 to compare different methods of determining the effective thermal resistance of vacuum insulation panels. This interlaboratory study contributed to the development of C1667, Standard Test Method for Using Heat Flow Meter Apparatus to Measure the Center-of-Panel Thermal Resistivity of Vacuum Insulation Panels. Nine laboratories participated in this study, eight of which used a total of nine apparatus meeting the requirements of C1667, and reporting from one to four replicate test results for six different vacuum insulation panels. Every "test result" reported represents an individual determination. Practice E691 was followed for the design and analysis of the data; the details are given in ASTM Research Report No. C16-1034.[6].

~~12.2.1 *Repeatability limit (r)*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the "*r*" value for that material; " *r*" is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day in the same laboratory.~~

~~12.2.1.1 Repeatability limits are listed in Table 1 below.~~

~~12.2.2 *Reproducibility limit (R)*—Two test results shall be judged not equivalent if they differ by more than the "*R*" value for that material; "*R*" is the interval representing the critical difference between two test results for the same material, obtained by different operators using different equipment in different laboratories.~~

~~12.2.2.1 Reproducibility limits are listed in Table 1 below.~~

~~12.2.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.~~

~~12.2.4 Any judgment in accordance with statements 12.2.1 and 12.2.2 would have an approximate 95% probability of being correct.~~

[5] Graves, R. S. and Kollie, T. G., "Interlaboratory Comparison Measurements of the Thermal Conductivity of Powder-Filled Evacuated Panel Superinsulation," *Thermal Conductivity* 22, Editor Timothy W. Tong, Technomic Publishing Co., Lancaster, PA 1994, pp. 435-446.

[6] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:C16-1034~~.~~

TABLE 1 Thermal Conductivity (~~W/ m-k~~*W/m-K*)

Panel	Average[A]	Sample Standard x Deviation	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
	$\bar{x}$	$S\bar{x}$	s_r	S_R	r	R
1A	0.005141	0.000348	0.000108	0.000360	0.000302	0.001009
1B	0.005172	0.000287	0.000078	0.000295	0.000219	0.000827
1C	0.004775	0.000233	0.000107	0.000250	0.000300	0.000701
2A	0.005237	0.000386	0.000144	0.000406	0.000403	0.001136
2B	0.005217	0.000372	0.000120	0.000386	0.000336	0.001080
2C	0.005144	0.000366	0.000108	0.000378	0.000301	0.001057

[A] The average of the laboratories' calculated averages.