R 82-2538

# Low-Density Thermal Insulation Calibrated Transfer Samples--A Description and A Discussion of the Material Variability

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National Bureau of Standards
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Washington, DC 20234

June 1982

Sponsored by
Department of Energy
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NBSIR 82-2538

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**NATIONAL BUREAU OF STANDARDS, Ernest Ambler,** ***Director***

# LOW-DENSITY THERMAL INSULATION CALIBRATED TRANSFER SAMPLES -- A DESCRIPTION AND A DISCUSSION OF THE MATERIAL VARIABILITY

by

Brian Rennex

## ABSTRACT

The National Bureau of Standards (NBS) has developed the capability to provide thick, low-density thermal insulation calibrated transfer samples to the thermal testing community. Previous research had indicated the need to measure thermal resistance of low-density insulation samples at thicknesses up to 150 mm (6 in). This is due to the "thickness effect," i.e., it is not possible to determine thermal resistance values at larger thicknesses based on tests at smaller thicknesses, such as at 25 mm (1 in). There was controversy as to the magnitude of the "thickness effect." This involved the manufacturers of insulation, the United States Federal Trade Commission, and thermal test laboratories. Another factor is that the systematic errors of apparatuses which measure thermal resistance increase significantly at greater test thicknesses. In order to ensure better consistency among the thermal resistance apparatuses, NBS agreed to develop and provide calibrated transfer samples at thicknesses up to 150 mm (6 in).

The calibrated transfer samples are described. The considerations that went into the selection and preparation of these low-density mineral-fiber samples are discussed. The contributions to the calibration uncertainty due to material variability are discussed and estimated to range between one percent and 2.5 percent.

Key Words: Building insulation; energy conservation; guarded hot plate; heat flow meter; heat transfer; low-density mineral fiber; thermal conductivity; thermal resistance; thickness effect.

## INTRODUCTION

The Thermal Insulation Performance Group at the National Bureau of Standards (NBS) has developed the capability to provide thick, low-density insulation calibrated transfer samples (CT samples) to the thermal testing community. The need for these samples resulted from a controversy involving insulation manufacturers, the United States Federal Trade Commission, and independent thermal test laboratories. This controversy involved the estimate of the measurement uncertainties of thermal resistance values at thicknesses of 50 mm to 300 mm (2 to 12 in).

Previous practice in the insulation industry and in independent test laboratories was to measure the thermal resistance at 25 or 38 mm (1 or 1.5 in). The value of the thermal resistivity (thermal resistance per unit thickness) was then multiplied times a greater thickness to determine the thermal resistance at this greater thickness. Clearly, the assumption used was that the thermal resistivity is a constant function of test thickness for the low-density insulation material. A number of papers in the last 30 years have indicated that the thermal resistivity decreases between test thicknesses of 25 to 300 mm (1 to 12 in) [Reference 1-12].* This phenomenon is referred to as the "thickness effect." If the change in thermal resistivity were significant, then it would be necessary to test at greater thicknesses than 25 mm (1 in). The economic ramification is that the test apparatus is more costly and the test times more lengthy at greater thicknesses.

Since the apparatus systematic errors can increase significantly at test thicknesses of 75 to 300 mm (3 to 12 in), it was decided that there was a need for thick, low-density calibration samples. These could be used by the thermal test laboratories to estimate apparatus systematic errors or to calibrate these apparatuses. In order to ensure greater consistency among the thermal apparatuses (both guarded hot plates and heat flow meters), NBS agreed to develop and provide the above mentioned CT samples.

This report discusses the sample description, the sample selection and preparation, and an estimate of the calibration uncertainty due to material variability. The thickness effect is discussed in detail in the aforementioned references, and the NBS guarded hot plate apparatus uncertainty will be discussed in a future report.**

## DESCRIPTION OF CALIBRATED TRANSFER SAMPLES

The CT samples consist of glass fiber insulation material in a density range of 8-11 $kg/m^3$ (0.5-0.7 $lb/ft^3$). They were selected from a lot which was produced by

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* In particular, the issue of the appropriate test thickness is discussed in the Federal Register, Vol. 45, No. 203, October 17, 1980; Staff Compliance Guidelines for the Federal Trade Commission Trade Regulation Rule; Labeling and Advertising of Home Insulation.

** This work was funded jointly by NBS and the Department of Energy.

the Johns-Manville Corporation*, with special measures to minimize the density variation over the lot area. The average fiber diameter was reported by Johns-Manville to be 3.8 μm. The samples were 305 mm (24 in) square. They were available in thicknesses of 25, 50, and 75 mm ( 1, 3, and 6 in). The 6 inch sample consisted of two stacked 3-inch specimens. Samples were provided for one-sided and two-sided apparatuses. Masks were provided for apparatuses with plate sizes larger than the 305-mm square sample size. The uncompressed thicknesses of the samples were about 1-1/8 in, 3-1/4 in, and 6-1/2 in. This was to allow some compression when testing at thicknesses of 1, 3, and 6 in -- to avoid voids between the sample surface and the plates. The above uncompressed specimen thicknesses were chosen to minimize the amount of compression necessary to not have those voids. Each CT sample was measured on the NBS 1-m guarded hot plate at a mean temperature of about 24°C (75°F) and at temperature difference of about 28°C (50°F). The value of the apparent thermal conductivity, or equivalently the thermal resistance was provided to the user. The user could then use this value to calibrate his apparatus.

## SAMPLE SELECTION

The average density of 9.6 kg/m$^3$ (0.6 lb/ft$^3$) was chosen because it is typical of the manufactured batt and blanket insulation material certified by the National Association of Home Builder's Research Foundation. This foundation certifies most of this type of low-density insulation material that is produced in the United States. Another reason for this choice was that the thickness effect was expected to be much smaller at higher densities [9]. It was considered desirable to learn more about the magnitude of the thickness effect at densities typical of use.

Specimens were selected from the lot based on the uniformity of the density over each specimen area. This was done for the following reasons. The thermal resistance value for the CT sample represents an average over the apparatus meter area. The meter area of the NBS and the user apparatus generally are different. For the CT samples, our measurements show that the thermal resistance values can be significantly different (by as much as five percent) for two different meter areas on the same CT samples. This is primarily due to the variability of the density over the sample area. This will be discussed in detail in the next section on uncertainty due to material variability. The important point here is that the density variability contributes to the uncertainty of the thermal resistance value provided to the user. To minimize this uncertainty the samples with the more uniform densities were selected.

The more uniform samples were selected visually. Insulation sheets of area 1.2 m x 2.4 m (4 ft x 8 ft) were photographed on a light table. The darker grey areas on the photograph corresponded to the more dense areas of the samples.

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* Since the results for the thickness effect might depend on the particular manufacturing process, the manufacturer is named to provide useful information. This identification does not imply recommendation by the National Bureau of Standards, nor does it imply that the material identified is necessarily the best for this purpose.

The best 10 percent of the lot was selected visually. The size of the samples (2 ft x 2 ft) was chosen to achieve a higher yield than what would have been possible with a larger area sample.

A mask of material from the same lot was used to surround the 2 ft x 2 ft sample for thermal resistance measurements on the NBS guarded hot plate. The NBS plate is a 1 m (40 in) diameter circle, and the meter area is a 406 mm (16 in) diameter circle. The edges of the 2 ft x 2 ft sample were outside of the meter area. Thus, they are not expected to affect the thermal resistance value, which is representative of the meter area only. (Another possible method of sample selection, that was not used, is discussed in Note 1.)

## APPARENT THERMAL CONDUCTIVITY UNCERTAINTY DUE TO MATERIAL VARIABILITY

Figure 1 shows the measured results and least-square fits of apparent thermal conductivity versus density data points. These represent the data obtained on the CT samples using the NBS 1 m guarded hot plate. Figure 1 shows that a three percent change in density corresponds to about a one percent change in thermal conductivity (or thermal resistance). Data on the measured values of the percentage difference between the average NBS and user meter area densities showed that most values were within four percent of each other. In two cases, this difference was about 15 percent. This means that there would have been about 1.3 percent (or in two cases a five percent) error, if the NBS meter area value of thermal resistance had been used to predict the user area value of thermal resistance.

The following method was used to reduce the above uncertainty due to material variability. The densities of NBS and user meter areas were measured. Then, the k versus density curve in Figure 1 was used to extrapolate from the apparent thermal conductivity value measured on the NBS meter area to that corresponding to the user meter area.

The following is a discussion of an estimate of the uncertainty in this thermal conductivity adjustment. It includes uncertainty estimates due to: 1) the density measurement, 2) the "k versus density" slope, and 3) the "k versus density" scatter.

The first source of uncertainty is due (see Note 2) to the meter area density determination. A stamp cutter was used to achieve good repeatability of the measured area. The meter area masses were measured with an upper-bound systematic (ubs) uncertainty of 0.03 percent, and the edges were defined within 1 mm. This resulted in a ubs uncertainty, due to differences in the two densities of 0.3 percent for a 10-in user meter area of 0.2 percent for an 18-in meter area. Using the slope in Figure 1, this corresponds to about 0.1 percent ubs uncertainty in the apparent thermal conductivity value (k-value). This uncertainty is referred to as $U_D$.

A second source of uncertainty is the uncertainty of the "k versus density" slope, used to adjust the k-value. In the density range of the CT samples the following empirical equation has traditionally been used to describe the k-value as a function of sample density, D.

$$k = a + b/D \tag{1}$$

The "a" term roughly corresponds to conduction heat transfer through the samples (which is mostly air by volume). The "b/D" term corresponds to the heat transfer through the sample via radiation [9]. The term $D_k$ is defined as the adjustment in k due to the difference in the two meter area densities.

$$D_k = k_{user} - k_{NBS} = b(1/D_{user} - 1/D_{NBS}) \;, \tag{2}$$

where b = 0.056 at a 1 in thickness, 0.063 at 3 in, and 0.064 at 6 in thicknesses -- with k in units of W/m•k and density in units of $kg/m^3$. The corresponding values with k in units of $Btu\text{-}in/hr\text{-}ft^2\text{-}°F$ and density in units of $lb/ft^3$ are b = 0.13 at 1 in, 0.146 at 3 in, and 0.149 at 6 in thicknesses. The value of the "a" term in SI units is 0.032 and in English units 0.222. The term "a" is constant as the density varies. This constrains the curves for different thicknesses to be roughly parallel, and this would be the expected result with a larger population of data points. These curves are plotted in Figure 1. The value of three times the standard deviation, of "b" using a least squares fit of the data to these curves, is three percent for the one and three inch curves and one percent for the six inch curve.

If one uses a very conservative value for an upper bound on the uncertainty in the term "b" of 20 percent (as compared to one or three percent), then one can estimate the uncertainty in k due to the uncertainty in "b" as follows: $U_b = 20\%(D_k/k)$, where $D_k$ is the quantity calculated in the last equation. For the CT samples, the value $U_b$ (the slope uncertainty) was typically less than 0.25 percent, although in two cases it was one percent.

The third contribution to the material variability uncertainty is due to the fact that there is scatter in the k versus D curve (see Figure 1). This means that distinct samples could have different k-values, even if the density values are the same. In the case of a single CT sample, the user and NBS meter areas are partly overlapping and partly distinct. If they were completely distinct, the uncertainty in k-value would be characterized by the scatter. If they were identical in area, there would not be an uncertainty due to material variability. The following equation was derived to estimate the uncertainty between these two extremes.

$$U_s = \left(1 - \frac{A'}{A}\right) \cdot S_d \tag{3}$$

The term "A′" is the smaller of the two areas, and "A" the larger. The term "$S_d$" is the standard deviation computed from the scatter of a k versus density curve based on data with 60 data points. These were measured by Johns-Manville on a heat flow meter apparatus with a repeatability of 0.2 percent. (The value for $S_d$ of 0.8 percent was received in a private communication from Johns-Manville. It represents the best information on the lot of material from which the CT samples were chosen.) The term "$U_s$" is being used as an upper bound on the possible uncertainty, since the standard deviation is multiplied by 3, and 99 percent of the data is expected to lie within this range. For a user meter area of 254 mm (10 in) square, $U_s$ has a value of roughly 1.2 percent. Note that in the case that the NBS and user meter areas are identical, $U_s$ is zero, and when $A'/A$ is very small, $U_s$ is approximately equal to 3 $S_d$.

To summarize the discussion on the uncertainty in the reported k-value -- due to the fact that the material is variable over the CT sample area and the NBS user meter areas are different -- there are three terms that contribute to the total material variability uncertainty, $U_{mv}$. The term "$U_D$" reflects the uncertainty in the meter area density determinations. The term "$U_b$" results from the uncertainty in curve slope parameter used to adjust the k-value. The term "$U_s$" results from the fact that there is scatter in a k versus density curve for distinct samples and the NBS and user meter areas are different. Each U term was treated as an upper bound on uncertainty. The estimate of total uncertainty is calculated simply by summing the terms.

$$U_{mv} = U_D + U_b + U_s \tag{4}$$

A typical value for $U_{mv}$ was about 1.6 percent. The range of $U_{mv}$ was about 1 to 2.5 percent for the CT samples. Note, that this is considerably smaller than the value of five percent that would have had to be used if no k-value adjustment were made.

## THICKNESS EFFECT RESULTS

Using the data shown in Figure 1, the mean k-value at 25 mm (1 in) is about 3.5 percent smaller than that at 152 mm (6 in). This is at a density of 9.6 $kg/m^3$ (0.6 $lb/ft^3$). This means the thickness effect is about 3.5 percent between these two thicknesses at this density. There is still a need to investigate the magnitude of the thickness effect for various lots of low-density material.

## RECOMMENDATIONS FOR FUTURE WORK

The uncertainty due to material variability was larger than that due to the apparatus error in the measurement of the k-value. The former varied from about 1 percent to 2.5 percent and the latter was about 1 percent. In the future the apparatus uncertainty is expected to be about 0.5 percent, after further apparatus studies are made. It is, thus, highly desirable to reduce the uncertainty due to material variability. NBS plans to explore the possibility that more uniform and durable material could be used.

## SUMMARY

The low-density glass-fiber insulation was found to be an adequate material for the Calibrated Transfer Specimens to achieve an uncertainty due to material variability of 1 to 2.5 percent. Problems and solutions associated with specimen selection and preparation were discussed. A method to estimate the uncertainty due to material variability was presented, and typical results were given.

Note 1:

An attempt was made to optically determine the difference beween the NBS meter-area average density and the density of a typical user meter-area, which was a 10 in square. This involved the digital scanning of the film negative of photos taken of the 4 ft x 8 ft samples on a light table, using an Optronix Scanner in the Metrology Building of the National Bureau of Standards. This device scanned unit sections of area, called piksels, corresponding to a square of side equal to 2/3 in. Thus, a 24 in x 24 in sample consisted of, roughly 36 x 36 = 1296 piksels. A grey-level number corresponding to the light transmission thru each piksel was obtained in the digital scan.

The intention was to determine a Grey Level <u>versus</u> Density curve with a small scatter. This was to have then been used to determine the average density based on the average grey-level values over the various meter areas within the sample. This would have then provided a method to adjust the k-value for the material variability due to density without disturbance of the sample. The density was measured directly by cutting and weighing sections of the specimen which had been optically scanned.

Unfortunately the scatter of the Grey Level <u>versus</u> Density curves was too large to give a sufficiently reliable adjustment. It was about 2 percent in density for 24-in square areas and about 14 percent for 8-in square areas. A large part of this error could have been in the area determination. Also, it is possible that the scatter might increase with smaller optical sampling areas.

Since the need was a knowledge of the respective meter-area average densities within a few tenths of a percent in density, this optical scan method was not used. Additional considerations were that the software development and operation were too intricate and time-consuming to justify the results. The recommendation for an optical scan method in the future is to use a collimated light beam with a scanning area corresponding to the meter area. This would be a quick and easy method once the initial calibration would be proven adequate.

Note 2:

A direct method of determining the meter-area densities was used. An anchor press and specially constructed stamp cutters were used to ensure a highly repeatable cut area. The main error (about a millimeter on a side) of the area determination was due to a bowing of the cut edge. The error in meter-area densities was about 0.3 percent for a 10-in square and about 0.2 percent for 16 and 18 in square meter areas. The samples were dried before cutting. A spray adhesive was used to spot glue the samples back together.

A quick check on the effect of the cutting on the measured thermal conductivity indicated a possible decrease of k-value of about 0.2 percent for a 10 in square cut. This might be a result of the compression during the cut causing a better laminar arrangement of the fibers and, hence, a higher thermal resistance. Also, if the cut is within the meter-area of the NBS apparatus there is another increase in R-value of the order of 0.2 percent due to gluing. A possible explanation of this phenomena is that the glue absorbs the thermal radiation and reduces thermal conductivity.

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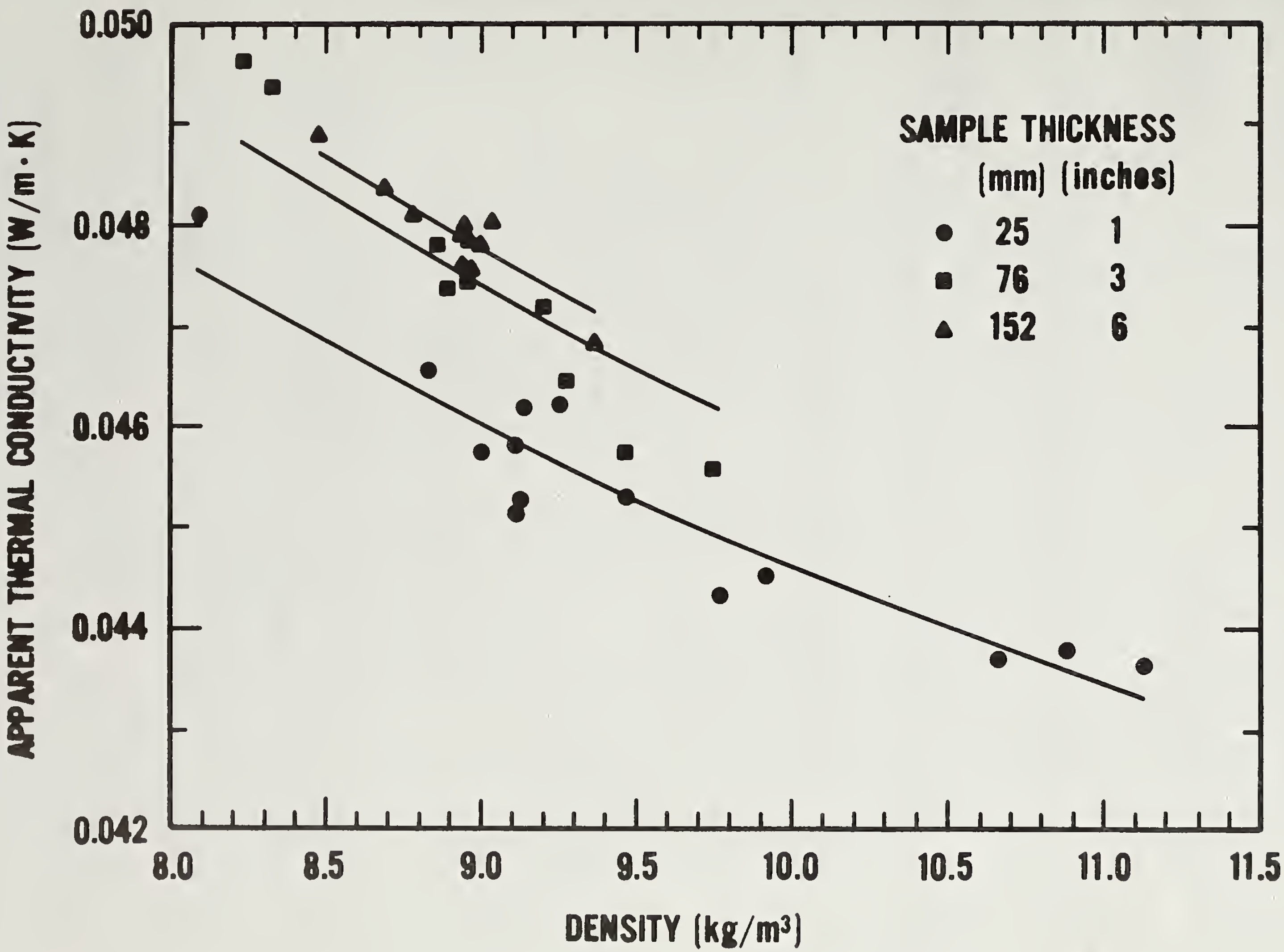
FIGURE 1. Apparent Thermal Conductivity vs Density*




*The densities correspond to the 16-in meter area of the NBS 1-m Guard Hot Plate. The data was taken at a mean temperature of 75 F and a temperature difference of 50 F. To convert from W/mK to Btu·in/ft$^2$·hr·F, multiply by 6.933. To convert from kg/m$^3$ to lb/ft$^3$, multiply by 6.2427 x 10$^{-2}$.

NBS-114A (REV. 9-78)

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|---|---|---|---|

| 4. TITLE AND SUBTITLE | 5. Publication Date |
|---|---|
| LOW-DENSITY THERMAL INSULATION CALIBRATED TRANSFER SAMPLES -- A DESCRIPTION AND A DISCUSSION OF THE MATERIAL VARIABILITY | June 1982 |
| | 6. Performing Organization Code |
| 7. AUTHOR(S) Brian G. Rennex | 8. Performing Organ. Report No. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>NATIONAL BUREAU OF STANDARDS<br>DEPARTMENT OF COMMERCE<br>WASHINGTON, DC 20234 | 10. Project/Task/Work Unit No.<br>11. Contract/Grant No. |
| 12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP) | 13. Type of Report & Period Covered<br>14. Sponsoring Agency Code |

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The National Bureau of Standards (NBS) has developed the capability to provide thick, low-density thermal insulation calibrated transfer samples to the thermal testing community. Previous research had indicated the need to measure thermal resistance of low-density insulation samples at thicknesses up to 150 mm (6 in.). This is due to the "thickness effect," i.e., it is not possible to determine thermal resistance values at larger thicknesses based on tests at smaller thicknesses, such as at 25 mm (1 in.). There was controversy as to the magnitude of the "thickness effect." This involved the manufacturers of insulation, the United States Federal Trade Commission, and thermal test laboratories. Another factor is that the systematic errors of apparatuses which measure thermal resistance increase significantly at greater test thicknesses. In order to ensure better consistency among the thermal resistance apparatuses, NBS agreed to develop and provide calibrated transfer samples at thicknesses up to 150 mm (6 in.).

The calibrated transfer samples are described. The considerations that went into the selection and preparation of these low-density mineral-fiber samples are discussed. The contributions to the calibration uncertainty due to material variability are discussed and estimated to range between 1 percent and 2.5 percent.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

building insulation; energy conservation; guarded hot plate; heat flow meter; heat transfer; low-density mineral fiber; thermal conductivity; thermal resistance; thickness effect

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