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ABSTRACT

Two national metrology institutes have conducted an international interlaboratory comparison on thermal conductivity for two thermal insulation reference materials. The Laboratoire national de métrologie et d'essais (LNE), France, and the National Institute of Standards and Technology (NIST), United States, present measurements obtained by the guarded-hot-plate method. The study involved two materials: expanded polystyrene board (EPS) and fibrous glass board (FGB). The EPS was provided by the LNE and is issued as a transfer specimen; the FGB provided by NIST was issued as Standard Reference Material (SRM) 1450c. For each reference material, the study was based on four independent measurements at a mean temperature of 24°C and two additional mean temperatures of 10°C and 35°C.

Keywords: thermal conductivity, insulation material, intercomparison

1. INTRODUCTION

The purpose of this international collaboration is to assess the agreement among test results from two guarded-hot-plate apparatus located in national standards laboratories in France and the United States. The laboratory participants were the Laboratoire national de métrologie et d'essais (LNE) and the National Institute of Standards and Technology (NIST). The tests were conducted in accordance with either test method, ISO 8302 or ASTM C 177, and the test data were reported to NIST for statistical analysis. The protocol follows the format of a round robin test program. The laboratory participants were requested to conduct four replicate measurements of each material at 23°C and two replicate measurements at 10°C and 35°C. This collaboration was organized and completed in 2013 by NIST and LNE.

A statistical analysis was carried out to quantify the agreement between the two laboratories and to identify potential sources of bias, if possible. The results are discussed in context with major findings from two other international guarded-hot-plate (GHP) comparisons. In addition, a statistical analysis was conducted to assess the agreement between the two laboratories and predicted values of a NIST thermal insulation Standard Reference Material (SRM). This article will present the GHP apparatus, test method, description of the protocol, data, statistical analysis, and the results of the comparison.

2. LABORATORY APPARATUS AND TEST METHOD

The GHP method, which has been standardized under the International Organization for Standardization (ISO 8302) and ASTM International (Test Method C 177), determines steady-state thermal transmission properties of flat slab specimens having a low thermal conductivity. The standard test methods for the GHP utilize the one-dimensional steady-state thermal conductivity equation for the determination of thermal conductivity (λ):

$$\lambda = \frac{QL}{2A\Delta T} \tag{1}$$

where Q is the time-rate of one-dimensional heat flow through the meter area of the GHP (W); A is

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the meter area of the apparatus normal to heat flow (m^2); ΔT (K) is the temperature difference across the specimen hot (T_h) and cold surfaces (T_c); and L(m) is the in-situ thickness of the pair of specimens. Values of λ are reported at the mean temperature, $T_m = (T_h - T_c) / 2$.

Table 1 summarizes the major parameters of the two apparatus used in this collaboration. The NIST GHP apparatus is cylindrical with a diameter (∅) of 500 mm and the design by LNE is 610 mm square. The apparatus were operated in a two-sided mode, i.e., heat flow through a pair of specimens. The expanded uncertainty (U) corresponds to a level of confidence of 95% with a coverage factor, $k = 2$ (JCGM 100:2008) and defines an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand (λ). The relative expanded uncertainty, U_r(%), in Table 1 is defined as $U/|\lambda|$ and was determined by each laboratory independently of this collaboration.

Table 1. Laboratory guarded-hot-plate apparatus.

Parameter	LNE	NIST
Plate (mm)	610 × 610	500 ∅
Meter plate (mm)	300 × 300	200 ∅
Plate emittance	0.86 ± 0.05	0.81†
Edge guarding	*	*
Temperature sensor	Type K thermocouple	Standard platinum resistance thermometer
Operation mode	Two-sided	Two-sided
U_r (%) ($k = 2$)	1.0%	1.0% (25 mm thickness) 1.5% (40 mm thickness)

Note: LNE, Laboratoire national de métrologie et d'essais; NST, National Institute of Standards and Technology.
†ASTM Test Method E 408-13.
*Edge insulation, temperature controlled peripheral guard, and additional outer edge insulation.

3. REFERENCE MATERIALS

Table 2 summarizes the reference materials by designation, material description, density, thickness, temperature range, and source.

The thermal conductivity (λ) of SRM 1450c is characterized statistically as a function of bulk density (ρ), in kg·m^{-3}, and mean temperature (T_m) in °C. The artifacts are batch certified and are accompanied by a global certificate, having one or more property values certified by a procedure that establishes traceability to an accurate realization of the unit in which the property values are expressed and for which each certified value is accompanied by an uncertainty at a stated level of confidence (ISO Guide 30/Amd. 1, 2008). Certified values of thermal conductivity for SRM 1450c (NIST, 2010) are given by Equation (2):

$$\lambda(T_m, \rho) = a_0 + a_1\rho + a_2(T_m + 273.15) \qquad (2)$$

In contrast, the thermal conductivity (λ) of each expanded polystyrene board (EPS) unit is individually measured for a customer. The thermal conductivity measurements are conducted at three different temperatures between 0°C and 60°C; generally at 10°C, 20°C, and 30°C. The certificate issued with the artifact includes a regression equation for thermal conductivity as a function of temperature determined by the least squares method and having expanded uncertainties (U) at a coverage of $k = 2$. Table 3 summarizes the regression coefficients (a_i), and relative expanded uncertainties (U_r) at a coverage factor of $k = 2$ for predicted values of SRM 1450c and the measured values for the EPS board.

3.1 Protocol

Table 4 summarizes the test sequence for the eight measurements for each material as well as the mean temperatures (T_m), temperature differences (ΔT), hot surface (T_h), and cold surface (T_c) temperatures. Each participant was requested to conduct two sets of measurements for each pair of specimens at mean temperatures of 10°C, 23°C, and 35°C with two additional replicate measurements at 23°C.

Table 2. Reference materials.

Designation	Description	Density (kg/m³)	Thickness (mm)	Temperature (°C)	Source
SRM† 1450c	Fibrous glass board (FGB)	150	25.4	7 to 67	NIST (NIST, 2010; Zarr, 1997)
EPS	Expanded polystyrene board	33	40	−10 to 60	LNE

Note: EPS, expanded polystyrene board; LNE, Laboratoire national de métrologie et d'essais; NST, National Institute of Standards and Technology, SRM, Standard Reference Material.
† SRM issued by NIST.

Table 3. Regression coefficients for reference materials.

Designation	a_0	a_1	a_2	U_r (k = 2)
SRM 1450c	-7.2661×10^{-3}	5.6252×10^{-5}	1.0741×10^{-4}	±1.6%
EPS†	–	–	–	±1.0%

Note: EPS, expanded polystyrene board;
SRM, Standard Reference Material,
†Individually certified.

Table 4. Proposed test temperatures.

#	T_m (°C)	ΔT (K)	T_h (°C)	T_c (°C)
1	10	20	20	0
2	23	20	33	13
3	35	20	45	25
4	23	20	33	13
5	23	20	33	13
6	10	20	20	0
7	23	20	33	13
8	35	20	45	25

All measurements were conducted with a ΔT of 20K. Replicate measurements were intended to be independent test results. Thus, the operator was requested to remove the specimen pair from the apparatus after measurements #3, #4, and #5 and reinstall the specimens after sufficient conditioning. The materials were tested at thicknesses determined by each laboratory with the only provision being that the clamping pressure exerted on the specimens by the measuring equipment should be limited to a range between 1,000 and 2,000 Pa.[1] The measurements were conducted starting at the facility having the larger apparatus (Table 1), i.e., at LNE and then at NIST.

4. ANALYSIS OF DATA AND RESULTS

4.1 Data

The measurement data from the participating laboratories for SRM 1450c and for EPS are presented in Tables 5 and 6, respectively. Each table is partitioned by laboratory (NIST and LNE) and their respective rows of data are arranged by measurement sequence (following the proposed protocol in Table 4). The quantity ρ was determined from the specimen mass divided by the corresponding total volume and represents the average for a specimen pair. The quantities T_m, ΔT, Q/A, and λ were determined during the GHP test. The quantity L was measured in-situ during the GHP test at NIST and was determined independently from the GHP apparatus at LNE.

Statistical analysis of the data was carried out by fitting linear regression models relating thermal conductivity to temperature to the data from each run in each laboratory. Mean predicted values from these models were then used to compare the results between laboratories. In addition to comparing the results between labs, each laboratory's results were also compared to the certified values for SRM 1450c, the fibrous glass board material.

4.2 Comparisons of thermal conductivities between laboratories

The statistical model assumed for the data on each material is:

$$\lambda_{ijkl} = (\gamma_{ij} + \beta_{ij} T_{m_k})\delta_{ij} + \varepsilon_{ijkl} \tag{3}$$

where λ_{ijkl} is the lth thermal conductivity ($l = 1,\ldots, n_k$) measured at the kth temperature (k = 10°C, 23°C, 35°C) in the jth laboratory j = NIST, LNE on the ith material i = FGB, EPS. The parameters γ_{ij} and β_{ij} are the intercept and slope for a straight-line model relating thermal conductivity to the mean temperature, T_{m_k}, of the GHP. In addition to the random measurement errors observable in the data, ε_{ijkl}, each lab assumes an additional source of uncertainty from a potential, unknown systematic error, δ_{ij}, that is specific to each laboratory and material (JCGM 100:2008). The potential systematic error, which cannot be seen in the laboratory data without reference to an outside standard, reflects small effects caused by specific equipment or procedures used in each lab.

In each case, the laboratory's knowledge of its potential systematic error is assumed to be normally distributed with a mean value of one and an associated relative standard uncertainty, τ_{ij}, estimated based on information from outside the current experiment

$$\delta_{ij} \sim N(1, \tau_{ij}). \tag{4}$$

The values of τ_{ij} used by NIST are $\tau_{\text{FGB, NIST}} = 0.50\%$ and $\tau_{\text{EPS, NIST}} = 0.75\%$, due to the difference in material thicknesses. The values of τ_{ij} used by LNE are $\tau_{\text{FGB, LNE}} = \tau_{\text{EPS,LNE}} = 0.50\%$. The degrees of freedom associated with each value of τ_{ij} are $v_{ij} = 60$, because the expanded uncertainties of these values are each obtained using a coverage factor of $k = 2$ from a Student's t distribution and the degrees of freedom are $v_{ij} = 60$ for a 95% two-sided uncertainty interval based on $k = 2$.

The random measurement errors are assumed to be mutually independent and normally distributed with a mean of zero and a standard deviation of σ_{ij}:

$$\varepsilon_{ijlk} \sim N(0, \sigma_{ij}) \tag{5}$$

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[1] The NIST 500 mm GHP apparatus was not able to establish this range of clamping pressures. For SRM 1450c and EPS the clamping pressures ranged from 190 to 410 Pa and from 300 to 610 Pa, respectively.

Table 5. Measured data for SRM 1450c, fibrous glass board.

NIST							LNE						
Rep.	ρ (kg/m^3)	L (mm)	T_m (°C)	ΔT (K)	Q/A (W/m^2)	λ (mW/mK)	**Rep.**	ρ (kg/m^3)	L (mm)	T_m (°C)	ΔT (K)	Q/A (W/m^2)	λ (mW/mK)
1	156.7	25.52	10.0	20.00	50.103	31.96	1	154.9	25.5	10	19.94	50.594	32.37
1	156.7	25.52	23.0	20.00	52.288	33.35	1	154.9	25.5	23	19.94	52.718	33.72
1	156.7	25.51	35.0	20.00	54.312	34.64	1	154.9	25.5	35	19.97	54.658	34.94
2	156.7	25.45	23.0	20.00	52.321	33.29	2	154.9	25.5	23	19.94	52.44	33.56
3	156.7	25.43	23.0	20.00	52.329	33.27	3	154.9	25.5	23	19.94	52.592	33.63
2	156.7	25.36	10.0	20.00	50.131	31.79	2	154.9	25.5	10	19.96	50.646	32.37
4	156.7	25.37	23.0	20.00	52.316	33.17	4	154.9	25.5	23	19.96	52.632	33.65
2	156.7	25.37	35.0	20.00	54.295	34.43	2	154.9	25.5	35	20.02	54.884	34.96

Note: SRM, Standard Reference Material; LNE, Laboratoire national de métrologie et d'essais; NIST, National Institute of Standards and Technology.

Table 6. Measured data for EPS.

NIST							LNE						
Rep.	ρ (kg/m^3)	L (mm)	T_m (°C)	ΔT (K)	Q/A (W/m^2)	λ (mW/mK)	**Rep.**	ρ (kg/m^3)	L (mm)	$T_m^{\dagger}$ (°C)	ΔT (K)	Q/A (W/m^2)	λ (mW/mK)
1	32.5	40.16	10.0	20.00	31.920	32.05	1	33.2	40.25	10	19.97	32.206	32.41
1	32.5	40.19	23.0	20.00	33.374	33.53	1	33.2	40.25	23	19.96	33.392	33.63
1	32.5	40.21	35.0	20.00	34.735	34.92	1	33.2	40.25	35	19.96	34.696	34.94
2	32.5	40.31	23.0	20.00	33.396	33.65	2	33.2	40.25	10	15*	24.226	32.42
3	32.5	40.18	23.0	20.00	33.359	33.51	2	33.2	40.25	23	19.97	33.5	33.71
2	32.5	40.16	10.0	20.00	31.939	32.07	2	33.2	40.25	35	19.99	34.778	34.98
4	32.5	40.20	23.0	20.00	33.414	33.58	3	33.2	40.25	23	19.92	33.324	33.64
2	32.5	40.22	35.0	20.00	34.813	35.00	4	33.2	40.25	23	19.97	33.416	33.64

Note: EPS, expanded polystyrene board; LNE, Laboratoire national de métrologie et d'essais; NIST, National Institute of Standards and Technology.
† For this material, the proposed run order (Table 4) was not followed.
* The actual ΔT was 15K instead of the proposed value of 20K (Table 4).

The number of measurements made at each temperature varied, with $n_{23} = 4$ and $n_{10} = n_{35} = 2$ for each material in each laboratory, as described earlier.

Except for the δ_{ij}, which were estimated using information external to this study, the unknown parameters in the aforementioned statistical model were estimated using linear regression analysis. The regression analysis was done separately for the data from each of the two runs within each lab for which measurements were made at multiple temperatures. Then, the two lines obtained for each laboratory were averaged to get the overall line for each lab. This run-by-run approach for fitting the model was done to avoid the presence of additional errors arising between runs which otherwise would affect the data points in an unbalanced fashion. The average lines for each laboratory and material are compared in Figure 1. The data collected at $T_m = 23$°C in the runs for which temperature was not varied are also shown for comparison, although they were not used in the fits of the regression models.

The basic measurands from each laboratory to be compared in this analysis are $\gamma_{ij} + \beta_{ij} T_m$, the mean predicted value of the true thermal conductivity of material i in laboratory j at temperature T_m. For this comparison, mean predicted values were computed for each material at each temperature for which data were collected, although different or additional temperatures could also be compared. At $T_m = 23$°C, there were four predicted values to be averaged for each lab, the results from the linear regression models for the runs in which temperature was varied and the two results from the runs in which temperature was not varied.[2] For $T_m = 10$°C and 35°C, there were two predicted values, from the fits of the two linear regression models, to be averaged for each laboratory.

To compare how the thermal conductivities relate between laboratories, expanded uncertainty intervals

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[2] For the averaging of individual measured values and predicted values from the regression to be completely correct, a weighted mean with weights inversely proportional to the variance of each result should be used. However, since the sample sizes differ by only a small amount ($n = 3$ for the regression for each run vs. $n = 1$ for each individual measurement) and variances of the predicted values do not benefit from the full effect of the averaging from the regression (because $T_m = 23\,°\mathrm{C} > \overline{T}_m = 22.6\overline{6}\,°\mathrm{C}$), an equally-weighted mean has been used.

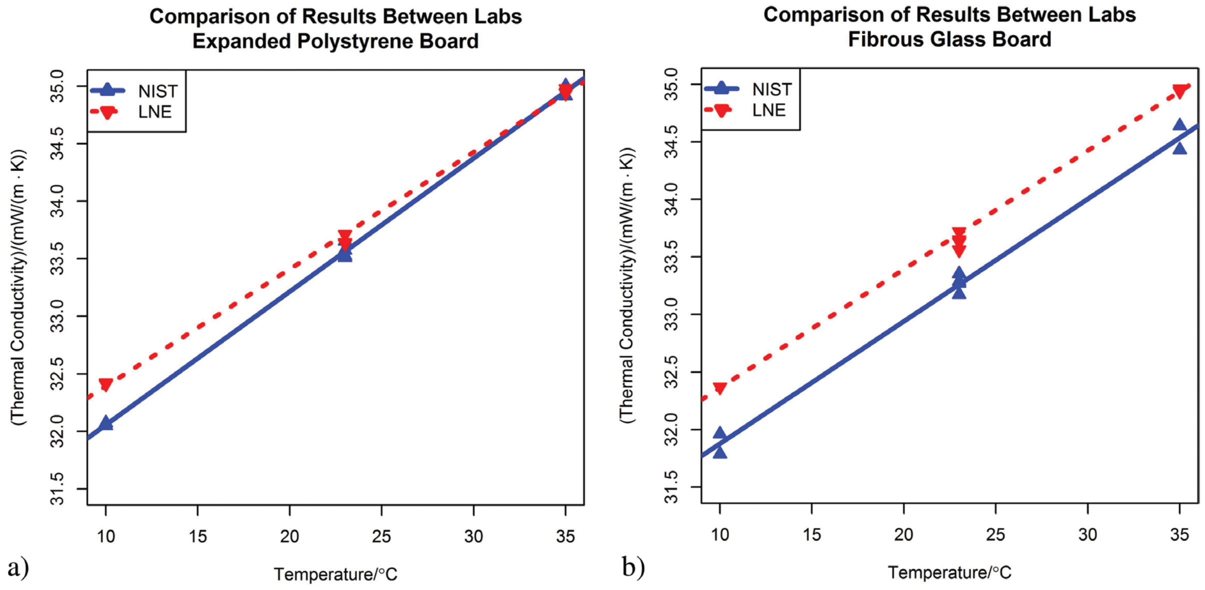

Figure 1. Comparison of laboratory results, from National Institute of Standards and Technology (NIST) (▲) and Laboratoire national de métrologie et d'essais (LNE) (▼). (a) Standard Reference Material (SRM 1450c), fibrous glass board; (b) expanded polystyrene board (EPS).

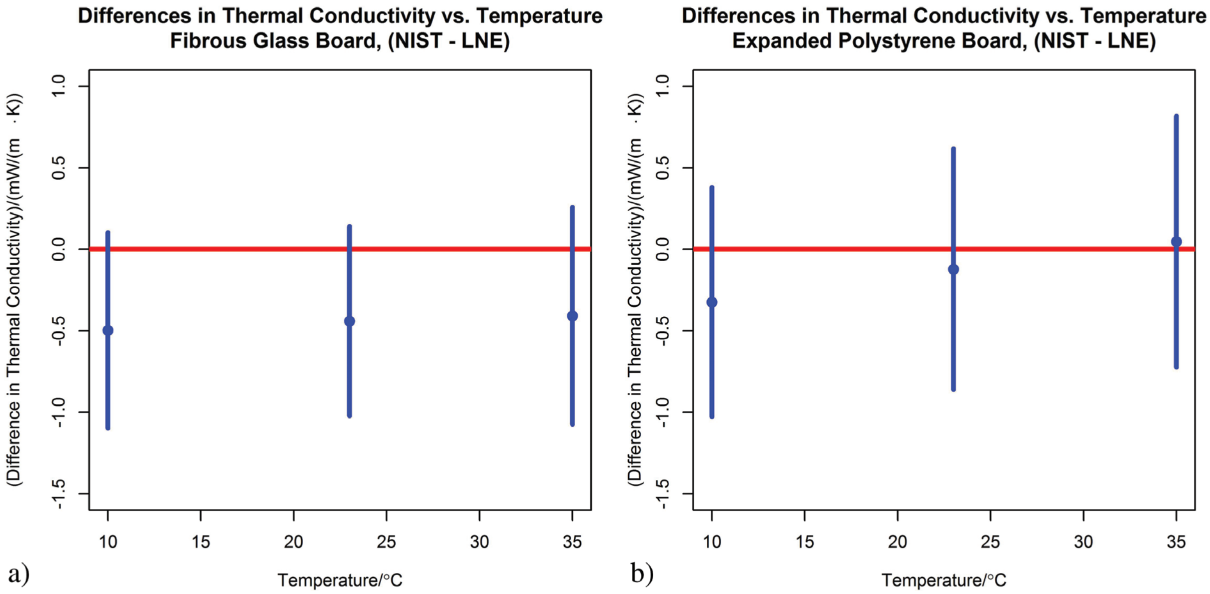

Figure 2. Differences in laboratory results for LNE and NIST. Error bars represent expanded uncertainties at the 95% level of confidence. (a) SRM 1450c, fibrous glass board; (b) expanded polystyrene board (EPS).

for the differences in the mean predicted values, $(\gamma_{i,\mathrm{NIST}} + \beta_{i,\mathrm{NIST}} T_\mathrm{m}) - (\gamma_{i,\mathrm{LNE}} + \beta_{i,\mathrm{LNE}} T_\mathrm{m})$, were used. The uncertainties arising from both random measurement error and the potential systematic error were propagated using the methods outlined in JCGM 100:2008 (2008) to assess the uncertainty of the results for the difference between labs. The measurement function used for the computation of the uncertainty intervals was:

$$y = (\hat{\gamma}_{i,\mathrm{NIST}} + \hat{\beta}_{i,\mathrm{NIST}} T_\mathrm{m})\,\delta_{i,\mathrm{NIST}} - (\hat{\gamma}_{i,\mathrm{LNE}} + \hat{\beta}_{i,\mathrm{LNE}} T_\mathrm{m})\,\delta_{i,\mathrm{LNE}} \qquad (6)$$

where y is the difference in thermal conductivity and the parameters with "hats" (^) over them represent the least-squares estimates of the true parameter values. The results of the uncertainty computations are shown in Figure 2.

The fact that all of the intervals for the differences in thermal conductivity shown in Figure 2 include the value

$$(\gamma_{i,\mathrm{NIST}} + \beta_{i,\mathrm{NIST}} T_\mathrm{m}) - (\gamma_{i,\mathrm{LNE}} + \beta_{i,\mathrm{LNE}} T_\mathrm{m}) = 0 \qquad (7)$$

indicates that there is no evidence of a statistically significant difference between the two laboratories.

Because there are comparisons at three temperatures for each material, the confidence level of each of the individual comparisons has been set at $100(1-\alpha 2)^{1/3}\% \approx 98.3\%$ (Abdi, 2007; Šidák, Zbyňek, 1967). This controls the probability that all three intervals for each material will be correct simultaneously so that the probability for each material will be approximately 95%. Thus, when the intervals are viewed as a set of results that answer the single question, “Do the results from the two labs agree for this material?” the probability of answering this question correctly will be approximately 95%.

4.3 Comparisons of thermal conductivities between laboratories and SRM 1450c

In addition to comparing how well the results from NIST and LNE agree with one another, the use of SRM 1450c as one of the materials in this study allows each lab’s results to be compared with the certified values for the SRM. This comparison will either provide additional assurance that the measurement processes at the two laboratories are working correctly or could point out a common source of deviation between the results from both labs and the true thermal conductivity of the material.

The statistical model for the data from each laboratory is the same as used in the linear regression analysis for the comparison of results between labs. The certified predicted values for the SRM are assumed to follow the regression relationship given in the certificate for this material, where λ_{SRM} is the certified thermal conductivity in mW/(m·K), ρ is the bulk density of the material measured by each laboratory, and T_{m} is the mean temperature of the GHP in degree Celsius.

$$\lambda_{\mathrm{SRM}} = -7.2661 + 0.056252\rho + 0.010741(T_{\mathrm{m}} + 273.15) \quad (8)$$

A standard uncertainty of 0.25 mW/(m·K) is given in the certificate for each predicted value as well. Because the expanded uncertainty for this material is based on a coverage factor of $k = 2$, the degrees of freedom to be used with standard uncertainty in all uncertainty computations are $v_{\mathrm{SRM}} = 60$.

To compare how the thermal conductivities relate between each laboratory and the certified values of the SRM, expanded uncertainty intervals for the differences in the mean predicted values, $(\gamma_{ij} + \beta_{ij}T_{\mathrm{m}}) - \lambda_{\mathrm{SRM}}$, were used. The measurement function used for the computation of each lab’s results vs. the certified values for SRM 1450c was

$$y = (\hat{\gamma}_{ij} + \hat{\beta}_{ij}T_m)\delta_{ij} - \lambda_{\mathrm{SRM}} \quad (9)$$

where the notation is the same as described for Equation (6).

The results from the comparison of the each laboratory’s result compared to the certified value of the SRM are shown in Figure 3. As for the comparisons between the laboratories, the fact that each uncertainty interval contains the value $(\gamma_{ij} + \beta_{ij}T_{\mathrm{m}}) - \lambda_{\mathrm{SRM}} = 0$ indicates that there are no significant differences between values obtained at either of the laboratories and the certified value of SRM 1450c.

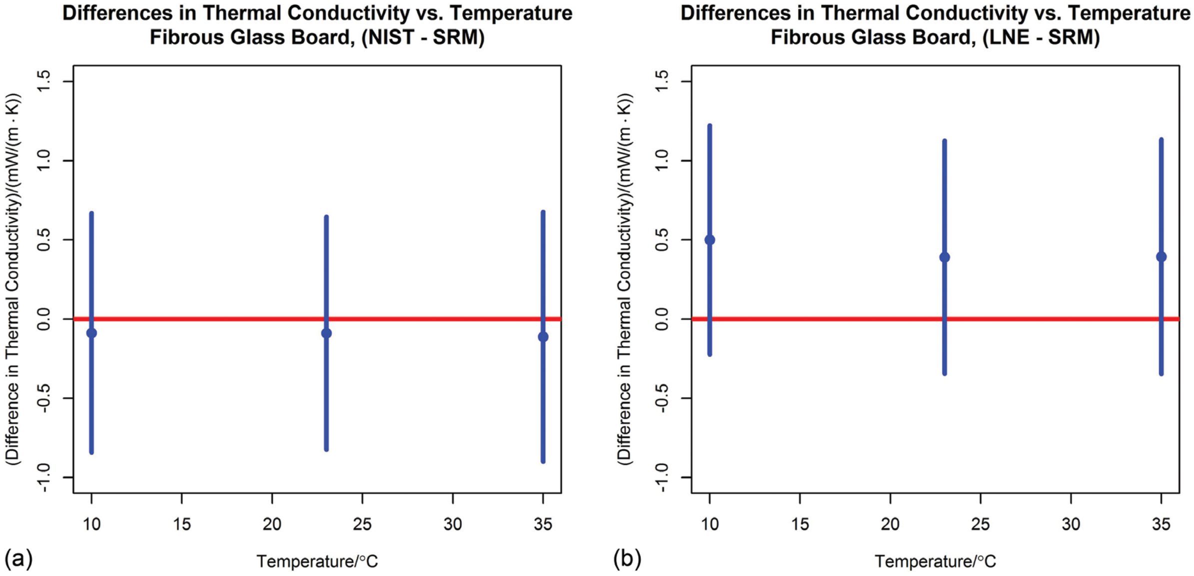

Figure 3. Differences in laboratory data from certified values of SRM 1450c, fibrous glass board. (a) NIST 500 mm diameter GHP; (b) LNE 610 mm by 610 mm GHP. Error bars represent expanded uncertainties at the 95% level of confidence.

A per-interval confidence level of ~98.3% (Abdi, 2007; Šidák, 1967) was again used to control the confidence levels so that the probability will be ~95% that all three intervals across the temperature range capture the true thermal conductivity simultaneously.

5. DISCUSSION

Identifying the possible causes of interlaboratory variation is difficult, particularly when the differences are on the order of ≤1%. Because LNE and NIST have participated in several recent GHP comparisons (with their data openly documented), it is useful to review the earlier comparisons with the current results. An extensive reassessment of these comparisons is beyond the scope of this article; however, a simple evaluation of the results provides useful insights. Table 7 summarizes the recent GHP comparisons in which LNE and NIST have participated from 1997 to the present, and Table 8 summarizes the equipment used and technical contacts. In Table 7, the original temperature units from the earlier comparisons are retained.

A review of the replicate and temperature data from the aforementioned comparisons (Hay et al., 2010, 2013; Zarr & Filliben, 2002, 2005) reveals the following observations.

- *Comparison 1 (1997–2000)*: For the first comparison (Table 7), multiple specimens having similar bulk densities were obtained for four regional reference materials that were selected by consensus of the participants. In the test protocol, the laboratories were requested to use spacer stops only for SRM 1451 and limit the clamping pressures for the other materials between 1,000 and 2,000 Pa. Results of the comparison revealed that, for the three fibrous materials (compressible, semi-rigid, and rigid), the NIST thermal conductivity data were lower than the LNE data over the temperature range of 7°C–47°C by ≤1%. The offset was relatively

Table 7. Recent international guarded-hot-plate comparisons among national metrology institutes.

Years, Temperature range (Ref.)	Labs	Pilot	Materials			
			Designation	Description	kg/m³	Mm
1997–2000, Multiple specimens, 7°C–50°C (Zarr and Filliben, 2002, 2005)	5	NIST	SRM 1451 IRMM-440 JTCCM candidate SRM 1453	Fibrous-glass blanket Glass-fiber board Mineral-oxide fiber board Exp. polystyrene board	13 70 200 38	25 35 25 13
2007–2011, Round robin, 10°C–40°C (Hay et al., 2010; Hay et al., 2013)	7	LNE	IRMM-440 EPS35 EPS70	Glass-fiber board Exp. polystyrene board Exp. polystyrene board	72 22 22	35 35 70
2013–2014, Round robin, 10°C–35°C	2	Bi-lateral	SRM 1450c EPS	Fibrous-glass board Exp. polystyrene board	150 33	25.4 40

Note: EPS, expanded polystyrene board; LNE, Laboratoire national de métrologie et d'essais; NIST, National Institute of Standards and Technology; SRM, Standard Reference Material; IRMM, European Reference Material; JTCCM, Japan Testing Center for Construction Materials.

Table 8. Summary of equipment used and laboratory contacts for LNE and NIST.

Parameter	1997–2000		2007–2011		2013–2014	
	LNE	NIST	LNE	NIST	LNE	NIST
Plate (mm)	610 × 610	1016 ∅	610 × 610	1016 ∅	610 × 610	500 ∅
Meter plate (mm)	300 × 300	406.4 ∅	300 × 300	406.4 ∅	300 × 300	200 ∅
Plate geometry	Square	Round	Square	Round	Square	Round
Plate emittance	0.86 ± 0.05	0.89	0.86 ± 0.05	0.89	0.86 ± 0.05	0.81
Temperature sensor	Type K	PRT	Type K	PRT	Type K	SPRT
Edge guarding	*	air	*	air	*	*
Operation mode	Two-sided	Two-sided	Two-sided	Two-sided	Two-sided	Two-sided
Technical contact	G. Venuti, S. Quin	R. Zarr	B. Hay	R. Zarr	A. Koenen	R. Zarr

Note: LNE, Laboratoire national de métrologie et d'essais; NIST, National Institute of Standards and Technology; PRT, platinum resistance thermometer; SPRT, standard platinum resistance thermometer.

*Edge insulation, temperature controlled peripheral guard, and additional outer edge insulation.

consistent, similar to the behavior shown in Figure 1a. For the thin (13-mm thick) “white beads” expanded polystyrene board; however, the offset in the thermal conductivity data was more distinct at lower temperatures (approaching 7°C). As the temperature increased, the differences decreased and the LNE thermal conductivity data crossed above the NIST data near 25°C, also similar in behavior to Figure 1b.

- *Comparison 2 (2007–2011)*: In contrast to Comparison 1, the second comparison followed a round-robin format to minimize issues of material variability by circulating the same pairs of specimens among the laboratory participants. The materials were selected by LNE and were, in general, thicker than the earlier study and consisted of two different types of materials: resin-bonded glass fiber board and gray EPS containing graphite “to avoid the ‘thickness effect’ that is observed usually for normal white EPS” (Zarr & Filliben, 2002). A set of four spacers of polyoxymethylene, also known as acetal, were provided by LNE for testing the pair of the resin-bonded glass fiber specimens. Replicate thermal conductivity data at 23°C revealed that the mean thermal conductivity values for NIST were lower than the LNE data by 0.06%, 0.03%, and 0.4% for IRMM-440, EPS35, and EPS70, respectively. Similar results were documented for each material over the temperature range of 10°C–40°C.
- *Current Comparison (2013–2014)*: Like Comparison 2, this study followed a round-robin format and used the two different types of materials: fibrous glass board and “white” expanded polystyrene board. For the test protocol, it was presumed that the relatively high value of bulk density for SRM 1450c would preclude the need for spacer stops to control changes in specimen thickness during testing. In hindsight, this omission is a probable reason for the small thickness compression noted by NIST for their in-situ thickness data. With regards to equipment, as noted in Table 8, NIST used a 500-mm GHP apparatus as an alternative for their 1016-mm GHP apparatus.

From the aforementioned observations, the following possible explanations for the small systematic differences in thermal conductivity data noted between LNE and NIST can be inferred.

- *Materials*: With regards to materials, it would appear that gray EPS containing graphite (used to reduce the effect of radiative heat transfer) provides more consistent results than white EPS. Additional testing with side-by-side white and gray EPS materials would be required to confirm this hypothesis. For fibrous materials, which can range from compressible to rigid depending on bulk density, the usage of spacer stops appears to provide more consistent results than not using spacer stops. Again, additional testing, side-by-side with and without spacers, would be required to confirm this hypothesis. In Comparison 2, the measurements for the 70-mm thick EPS specimen would suggest that there is a very small potential difference because of increased thickness.
- *Equipment*: With regards to equipment, when assessing Comparisons 1 and 3, the introduction of a new smaller 500-mm diameter apparatus by NIST would suggest that plate size does not appear to be a factor – both sets of comparison data reveal that the NIST data are slightly lower. Alternatively, the differences could be associated with plate geometry, i.e., square plates vs. round plates. The plate-geometry effect, however, was not evident in Comparison 2. Another possibility is that the respective laboratory apparatus used in this comparison share within-lab design philosophies (i.e., similar type sensors, calibrations, guard designs, etc.) that are subsequently passed on to the next generation of GHP apparatus resulting in the small differences.
- *Procedural*: Finally, it is possible that there are (entrenched) procedural differences at each laboratory that could override apparatus designs and, thus, cause the small differences noted in both comparisons.

6. CONCLUSION

This bilateral comparison of GHP laboratories at LNE and NIST revealed that, with their current standard uncertainties of 0.5%–0.75% used to account for potential lab-to-lab differences in equipment and procedures combined with the standard uncertainty associated with the random measurement variation observed, there is no difference in their respective measurements for specimens of fibrous-glass board and expanded polystyrene board. In general, from 1997 to the present (17 years), comparisons of the thermal conductivity data obtained from the GHP apparatus at LNE and NIST are in good agreement, on the order of ≤1%, over the temperature range of 7°C–47°C. Potential explanations for the small systematic differences that are indicated by the data are suggested and include material, equipment, and possible procedural effects. At present, additional research to confirm these hypotheses is considered optional, not urgent. In either case, it would be useful for both laboratories to describe their complete uncertainty budgets to develop standard guidelines for future interlaboratory comparisons.

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