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Publisher's version / Version de l'éditeur:

Proceedings, Conference on Thermal Insulation, Materials, and Systems for Energy Conservation in the 80's, 08 December 1981, Clearwater, FL, USA, pp. 277-292, 1983

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COMMENTS ON CALIBRATION AND DESIGN OF A HEAT FLOW METER

by M. Bomberg and K.R. Solvason

Reprinted from
Thermal Insulation, Materials, and Systems
for Energy Conservation in the '80s
ASTM, STP 789, 1983
p. 277 - 292

DBR Paper No. 1106
Division of Building Research

Price $1.25 OTTAWA NRCC 22416

Canada

RÉSUMÉ

À la suite de re-étalonnage de deux instruments de laboratoire, l'appareil de mesure de l'écoulement de la chaleur (HFM) a été entièrement repensé. La nouvelle conception permet un étalonnage indépendant des caractéristiques du matériau mis à l'épreuve, c'est-à-dire qu'il donne la même courbe d'étalonnement pour des échantillons épais et peu denses ou minces et très denses. L'étalonnage dans les limites de précision de ±1% pour l'écoulement normalisé est étudié en détail; la précision du HFM pour les échantillons épais et peu denses en fibre de verre semble être meilleure que celle mesurée avec un GHP (plaque chaude gardée) dans les mêmes conditions d'essai.

Authorized Reprint from
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American Society for Testing and Materials
1916 Race Street, Philadelphia, Pa. 19103
1983

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Comments on Calibration and Design of a Heat Flow Meter

REFERENCE: Bomberg, M. and Solvason, K. R., **"Comments on Calibration and Design of a Heat Flow Meter,"** *Thermal Insulation, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789,* F. A. Govan, D. M. Greason, and J. D. McAllister, Eds., American Society for Testing and Materials, 1983, pp. 277-292.

ABSTRACT: After a review of the calibration of two heat flow meter (HFM) transducers, the HFM has been redesigned. The new design produces a calibration independent of the characteristics of the material being tested; that is, it produces the same calibration curve for thick, low-density specimens as for thin, high-density ones. Calibration within ±1 percent of transfer standard accuracy is discussed; the HFM precision for thick specimens of low-density glass fiber appears to be higher than that of a guarded hot plate under the same testing conditions.

KEY WORDS: heat flow meter, guarded hot plate, thermal conductivity, thermal resistance, HFM calibration, HFM design, precision and accuracy

The need for thermal resistance measurements of thick specimens (100 to 180 mm) of low-density thermal insulation and subsequent changes in ASTM test standards [*1*] has increased interest in the use of the heat flow meter (HFM), described in ASTM Test for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter (C 518).[2] Papers presented at 1977 and 1978 ASTM symposia [*2-4*] discussed calibration procedures and, in particular, the difficulty of defining the range for which the calibration coefficient is valid. Some laboratories use different calibration coefficients for the same HFM, depending on the thickness and characteristics of the test specimen.

This paper reviews the calibration of two HFM transducers for which differences in calibration coefficient had been observed, depending on the thermal properties of the material adjacent to the HFM surface. This rather unsatisfactory performance of the heat flow meters warranted rebuilding one, a

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[2]The italic numbers in brackets refer to the list of references appended to this paper.

cork-faced HFM, and designing and constructing a new, metal-faced instrument. The new HFM was provided with a more precise method of maintaining unidirectional heat flow in the transducer and of reducing edge loss error. Although more difficult to operate than the rebuilt HFM, the new design should provide a reference level for error analysis.

Calibration of both the rebuilt and new instruments was carried out on a 50-mm-thick high-density glass fiber transfer standard, and was followed by a comparative test series for the guarded hot plate (GHP), the new design, and the rebuilt HFM. The results obtained on the cork-faced HFM agree well with the reference data from the GHP and the new HFM, showing maximum differences of less than 1.5 percent. This indicates that good precision and accuracy can be obtained with the rebuilt HFM apparatus and that the same calibration coefficient is adequate for testing 25 to 200 mm thick specimens.

Calibration of HFM Transducers Before Rebuilding

Description of Transducers

Two types of HFM transducer were examined in this study. Type ARM (Fig. 1*a*) represents a meter with a fairly homogeneous meter core, a low sensitivity, and minimal thermal bridging effect. Type SG (Fig. 1*b*) represents a less homogeneous meter core with a higher sensitivity and a larger thermal bridging effect. The performance of the two HFM transducers may be assumed to be representative of similar meters in current use.

Two 600-mm HFM plates, SG1 and SG2, were built using commercially available heat flow meters [*2*] rebuilt at the Division of Building Research, National Research Council of Canada, to provide additional measurements of the temperature on both main surfaces. A 1.5-mm-thick cork sheet was glued to each side of the HFM plate to provide a thermal damper.

In the metering area (250 by 250 mm) a 0.1-mm-thick sheet of copper was divided into four squares (0.6-mm gap) and a thermocouple soldered in the center of each was glued to the cork. The remaining part of the cork surface was covered with a Mylar film of similar thickness. The surfaces were painted with (black) Nextel brand velvet coating, Series 101, providing an infrared emittance of the surfaces, $\epsilon = 0.89$. Thermocouples were added to each face of the HFM to monitor mean temperature and thermal resistance of the HFM during calibration.

The 300-mm-square HFM plates (ARM 1 and ARM 2) were built [*5*] on a 6.3-mm core of Armstrong cork (No. 975), average density 496 kg/m^3, following the construction method described by Zabawsky [*6*]. Nine pairs of chromel-constantan thermocouple junctions were installed to provide a central 150 by 150 mm metering area. The total thickness of the HFM, including

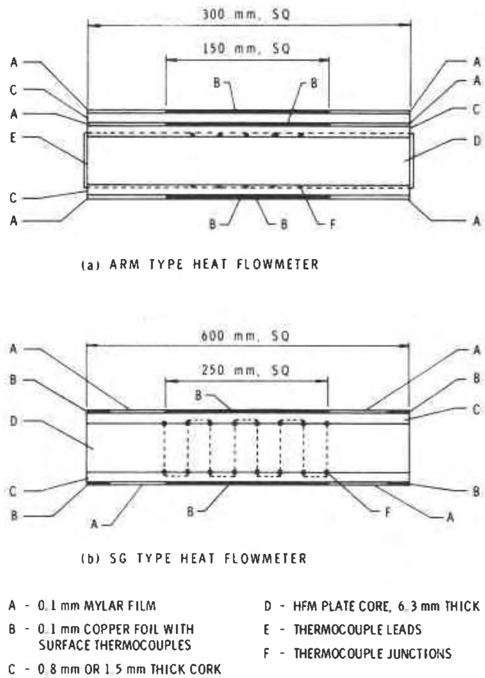


FIG. 1—*ARM and SG type HFM transducers after rebuilding.*

cork cover sheets, copper, and Mylar films, is about 8.4 mm. The surfaces were covered with the same black Nextel paint as the SG heat flow meters, yielding the same emittance.

Reference Level for Calibration

The HFM apparatus was calibrated in relation to a 300-mm-square GHP apparatus with a 150-mm-square metering area and to a 600-mm-square GHP with a 300-mm-square metering area. The latter apparatus was originally designed as a symmetrical guarded hot plate in which identical specimens could be placed on each side of the hot plate. For this series of tests it was desirable, however, to have each specimen measured separately. In order to obtain a one-sided GHP, a dummy sample and an HFM were inserted between one side of the hot plate and the cold plate, which was connected to a separate bath maintaining a temperature almost the same as that of the hot plate, thereby reducing the heat flow through the high-resistance dummy specimen to a very small amount. Figure 2 is a schematic of this one-sided GHP.

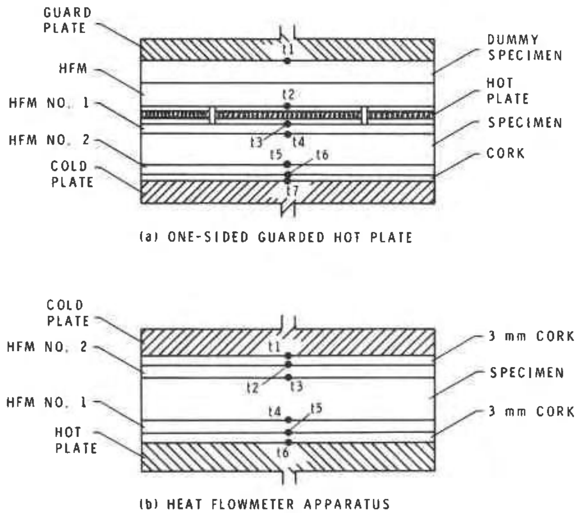


FIG. 2—*Schematic of calibration series analyzed in Table 1.*

Calibration Technique

The calibration of HFMs is basically the determination of the relation between thermopile output and heat flux. The calibration can take the form of an inverse sensitivity coefficient, $C = q/v$, where q is the heat flux through the calibrated specimen and v is the electromagnetic force of the HFM.

The DBR/NRCC HFMs are used over a range of temperature, so that their output must be calibrated versus the mean temperature of the transducer. Change in the calibration coefficient C with mean temperature is due to change in the resistance of the core material as well as to nonlinear temperature dependence of the thermopile output voltage [*7,8*].

The performance of an HFM is characterized by its sensitivity and precision. Precision of a calibration depends upon both the design and operation of the apparatus and upon the accuracy of the determination of the heat flux through the HFM. Two methods were used to determine the heat flux. The first involved the use of calibrated specimens whose thermal resistance had previously been determined in the GHP. The heat flux in the HFM was then inferred from the temperature difference across the specimen. This method is referred to as the calibration of the HFM.

In the second method, referred to as calibration of the HFM transducer plates, the HFM plates and a dummy sample were placed between the plates of the one-sided GHP. The heat flux through the metering area of the HFM was assumed to be the same as that of the GHP main heater.

Both methods have advantages and disadvantages. In the calibration of the HFM transducer plates, q is measured directly and does not depend on a calibrated specimen whose properties may change after calibration. The accuracy of this method depends, however, on the assumption that the heat flux through the dummy specimen and the HFM is strictly one-dimensional. As will be shown later, this may not be a valid assumption.

Calibration of the HFM overcomes the aforementioned difficulty by calibrating the entire apparatus, but any change in apparent thermal conductivity of the calibrated specimen between the initial test in the GHP and the HFM test causes an error in the calibration of the HFM. Possible causes of such a change can be associated with test conditions or specimen preparation and handling.

As there is available extensive literature on calibration of HFM apparatus [*9–13*] and on HFM plate construction [*14–16*], this discussion will be limited to the results of a calibration series.

Results of SG Transducers Calibration

The calibration coefficient of the SG1 transducer in the HFM was determined in a test series using three different calibrated specimens:

1. 26-mm low-density glass fiber (LDGF) from Lot 1, tested with spacers.
2. 26-mm LDGF specimens from Lot 2, tested with wooden frames.
3. 26-mm high-density glass fiber (HDGF) specimens.

The results are shown in Fig. 3. The calibration coefficient obtained for each of the calibrated specimens appears to be different to an extent exceeding the 99 percent probability level. There is also a difference in the slope of the $C = C(T)$ function for low-density and high-density glass fiber specimens. Similar results were obtained on the SG2 transducer.

In a second test series the following calibration procedures were examined, using 26 mm thick high-density and low-density glass fiber specimens and 39, 78, and 156 mm thick extruded polystyrene:

1. The two HFM plates are placed in series with two transfer standards, one on either side of the hot plate and the heat flux measured on the GHP.
2. As above, but the heat flux was calculated from the temperature difference across the transfer standards.
3. The two HFM plates were placed in the one-sided GHP and the heat flux was measured on the GHP.
4. The double HFM was calibrated from the transfer standards.

In procedures 1 and 2 the GHP was used in the same way as for standard testing, with two specimens adjacent to the heater plate of the GHP and the two HFM plates between the specimens and the cold plates. The test was repeated, maintaining the same conditions, with the HFMs in the same positions and the specimens interchanged; the calibration factor for each HFM

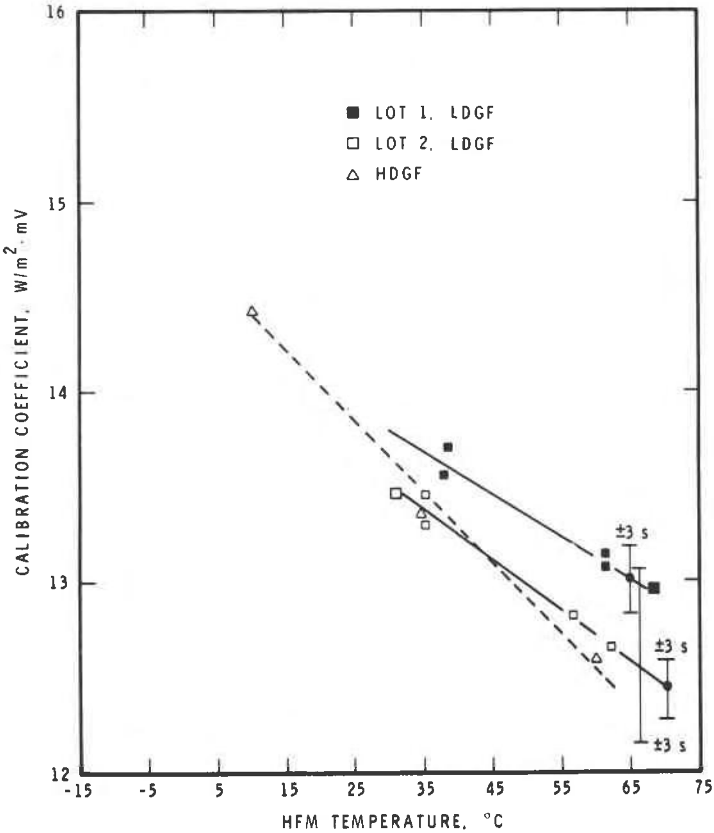


FIG. 3—*Calibration of HFM on 26-mm-thick low-density glass fiber (LDGF) and high-density glass fiber (HDGF) specimens. SG1 transducer.*

plate was obtained by averaging the results of the two tests to correct for any mismatch of calibrated specimens.

In Procedures 3 and 4 the same HFM plate, SG2, was always placed on the cold side; the other plate was placed either between two specimens or on the hot side (Procedure 3), or on the hot side only (Procedure 4). Figure 2*b* shows a double HFM.

Table 1 gives the results of the SG type heat flow meter calibration with four different calibrating procedures on four different materials, leading to the following conclusions:

1. The precision of all calibrating series, with the exception of Procedure 3, was very good. It used the one-sided GHP, which introduced a larger scatter into the calibration results.
2. Precision of the calibration function was influenced neither by material

TABLE 1—*Calibration coefficients and their confidence intervals as described by three standard deviations (SD) for SG-type heat flow meters (each series contains four or five measurements).*

Test Series	Calibration Procedure and Specimens Used	SG1 on Hot Side[a]		SG2 on Cold Side	
		C_1 at 35°C	3 SD of C_1	C_2 at 13°C	3 SD of C_2
1	#1, two HFM plates on cold sides in GHP, HDGF transfer standard, heat flux from the GHP	13.65[a]	0.23	14.66	0.25
2	#2, as above, but heat flux from HDGF transfer standard	13.55[a]	0.18	14.51	0.21
3	#3, two HFM plates in one-sided GHP, HDGF between the plates, heat flux from the GHP	13.72	0.62	14.81	0.63
4	#4, double HFM apparatus, HDGF between the plates, heat flux from the transfer standard	13.51	0.23	14.51	0.24
5	#4, as above, 39, 78, and 156 mm thick extruded polystyrene transfer standards	13.48	0.09	14.50	0.21
6	#4, as above, Lot 1, LDGF transfer standards	13.72	0.19	14.80	0.29
7	#4, as above, Lot 2, LDGF transfer standards	13.40	0.16	14.38	0.15

[a]In calibration series 1 and 2, SG1 plates were not positioned on the hot side.

selection nor by the varying thickness of transfer standards, for example from 39 to 156 mm for extruded polystyrenes.

3. Tests done on low-density glass fiber specimens from Lot 2 appear to have a slightly higher precision than those from Lot 1, probably because of larger errors in thickness measurements introduced by the spacers. The difference between hard GHP surfaces and elastic HFM surfaces caused about 1 mm difference in the measured thickness of the specimen in tests performed on the same specimen with the same spacers.

4. There is good agreement between Test series 4 and 5, that is, when using high-density glass fiber or polystyrene transfer standards. The agreement between a double HFM calibration and calibration of the HFM plates in the GHP, if the heat flux is calculated from the transfer standards (Procedure 2), is also good.

5. There is a difference in procedures based on heat flux determination from the GHP and those from the transfer standard. This is illustrated by the results of Procedures 1 and 2. A systematic shift may be observed with methods of calibration. The heat flux determined from the transfer standards was from 0.7 to 1.0 percent less than the heat flux indicated by the GHP.

6. Agreement of calibrating procedures based on polystyrene and high-density glass fiber transfer standards on the one hand and low-density glass fiber specimens on the other is poor. Although most of the results fall within the confidence limits, there is a significant difference in the slope of the calibration curves, as shown in Fig. 3.

Results of ARM Transducer Calibration

Table 2 gives results of calibration of ARM-type transducers with high-density glass fiber and polystyrene transfer standards. Table 3 shows the calibration coefficient for the same transducers inserted in the 300 mm^2 GHP in the following manner:

1. ARM transducer alone—Test 1.
2. ARM transducer in series with 12-mm RTV rubber—Test 2.
3. ARM transducer between 3-mm cork and 12-mm RTV rubber—Test 3.

The thermal properties of the layer adjacent to the transducer surface, as shown in Table 3, have a large effect on the apparent calibration coefficient. A review of calibrating techniques on the older HFM transducers, SG and ARM types, disclosed two problems:

1. There is a difference in the slope of the calibration coefficient as a function of temperature, depending on the material used for transfer standards.
2. The calibration coefficient is influenced by the thermal properties of the material adjacent to the HFM surface.

The reason for the discrepancies may be associated with either the lateral component of heat flow in the system or a slight difference in apparent resistance of low-density materials with horizontal heat flow in the GHP as compared with vertical heat flow in the HFM apparatus. These and other effects are discussed further in the following section on design considerations for modifying the apparatus.

TABLE 2—*Calibration coefficients and their confidence intervals as described by three standard deviations (SD) for ARM-type HFM plates (the series contained 10 measurements).*

Calibration Procedure and Specimens Used	ARM 1, Hot Side		ARM 2, Cold Side	
	C_1 at 35°C	3 SD of C_1	C_2 at 13°C	3 SD of C_2
#4, double HFM heat flux from HDGF and polystyrene transfer standards	25.03	0.30	24.69	0.48

TABLE 3—*Calibration coefficients of ARM 1 and ARM 2 heat flow meters as affected by change of the layer adjacent to surfaces (heat flux determined from GHP.*

Test Number	Test Code	Materials in Contact with HFM	Heat Flux, W/m²	ARM 1		ARM 2	
				T_m,°C	C_1, W/m²mV	T_m,°C	C_2, W/m²mV
1	345-81	hot and cold plate of GHP	219.9	24.1	27.76	24.3	27.07
2	345-85	hot plate, 12-mm RTV rubber	77.4	26.6	27.70	26.6	27.11
3	345-87	3-mm cork, 12-mm RTV rubber	56.6	24.6	26.20	24.7	25.72

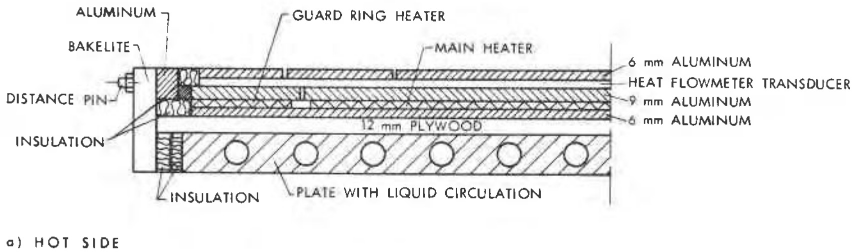
Changes in Design of Heat Flow Meter

Most errors in the calibration coefficient determination are inversely proportional to the heat flux. The HFM should therefore be calibrated using thin transfer standards or calibrated specimens and thus relatively high heat fluxes. This calibration will, however, only be valid for the low heat flux associated with thick specimens if the output of the thermopile is proportional to the heat flux through the specimen under all test conditions. The design must ensure a uniform temperature at the HFM surface adjacent to the specimen so that the higher edge heat loss associated with thick specimens will not produce lower edge surface temperatures on the HFM and thus avoid any additional distortion of the heat flow lines. It is at least equally important that it should not produce a lateral heat flow in the core of the HFM. If lateral heat flow does occur in the core, the thermopile output will probably not be proportional to the heat flux into the specimen.

The sensitivity of the HFM calibration to the properties of the specimen probably arises from the fact that the resistance of the HFM core is not uniform, but has low resistance paths through the thermopile junctions. The output will thus be slightly higher when high conductivity material contacts the surface in the location of the thermopile junctions. This effect can be eliminated by facing the HFM case with a high conductivity layer, such as a metal plate, that will provide an isothermal surface adjacent to the specimen. Alternatively, the HFM plate can be faced with a layer of low conductivity material such as 1.5 to 2 mm cork. This will allow the temperature of the surface adjacent to the specimen to vary, depending on the nature of the contact resistances with the specimen. In both cases the thermal regime at the HFM surface will always be the same, regardless of the properties of the specimen.

Figures 4 and 5 are schematics of two new designs:

1. Design 1, based on electric heating with the HFM transducer placed between aluminum plates.



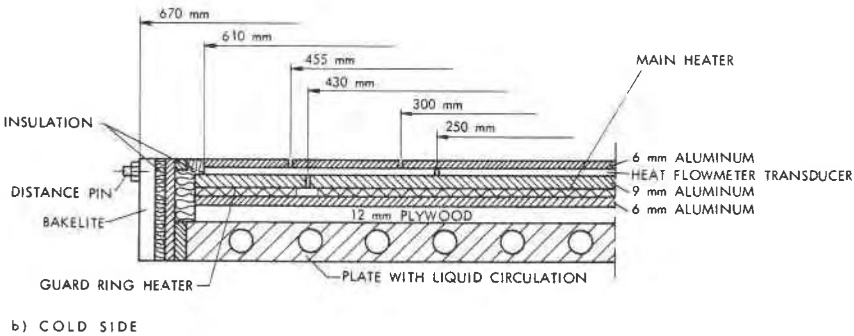


FIG. 4—*Schematic of Heat Flow Meter #1.*

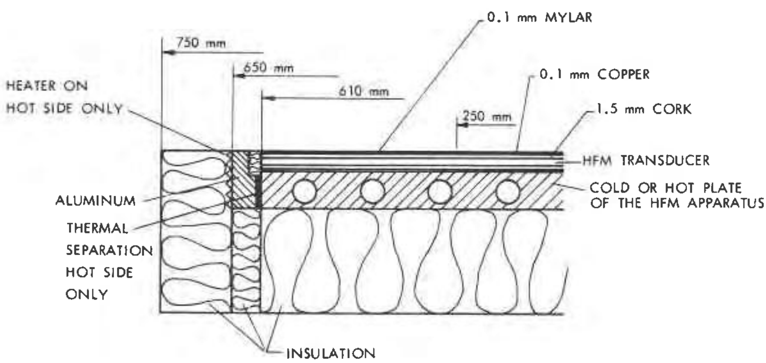


FIG. 5—*Schematic of rebuilt Heat Flow Meter #2.*

2. Design 2, based on liquid-circulated cooling and heating plates, cork and copper facing of the transducer, and perimeter heating/cooling bars.

Figure 4 shows details (Design 1) of the hot and cold plates of the HFM. One liquid bath functions as the heat sink for both plates, while the temperature of the HFM transducer is controlled by means of electric heaters. The main heater, 430 mm square, maintains the required temperature. The guard ring heater, extending to 620 mm square, is controlled as for a GHP system. With this arrangement an increase in edge losses when testing thick specimens will not create a significant lateral heat flow in the HFM transducer.

Both main and guard ring heaters are sandwiched between 6 and 9 mm aluminum plates and attached to the heat sinks (liquid plates) with a thermal separator of 12-mm plywood. The top 9-mm aluminum plate of the heater sandwich is also a part of the HFM transducer assembly. The transducer metering area is 250 by 250 mm and the compensating area is 610 by 610 mm. They are separated by a small air gap. The transducer is sandwiched between the 9-mm-thick heater plate and a 6-mm-thick aluminum face plate. The metal face plate is divided into a main area 300 by 300 mm and two rings each 152 mm wide. The metal faces and the guard rings are designed to equalize temperature differences caused by nonhomogeneity of the transducer or test specimen. The HFM transducer sandwich is attached to the heater assembly with nylon screws.

An additional temperature guard is provided by a metal profile placed in contact with the heater sandwich on the hot side and with the heat sink on the cold side (Figs. 4*a* and *b*). The metal profile is covered with insulation and with bakelite covers used for positioning the plates.

The expected advantages are as follows:

1. Very stable and precise control of the plate temperatures will be possible with the electric heaters.
2. Guard ring heater will compensate for edge loss effects, reducing the need for edge insulation as well as the lateral heat flow component in the HFM transducer.
3. Additional edge cooling or heating will be provided by the metal profile surrounding the HFM transducer.

Design 2, shown in Fig. 5, for faster testing employs the following elements to ensure an isothermal surround for the HFM transducer at all levels of edge heat loss:

1. A metal profile surrounding the HFM transducer for additional cooling on the cold side and additional heating on the hot side.
2. A guard ring heater in the form of a perimeter heater.
3. Standard edge insulation ($R = 3$ m^{2}K/W) added to the HFM.

The design requires a very stable temperature on the HFM liquid plates to prevent large fluctuations in thermopile output. Modifications were therefore made to the liquid baths and pumps that circulate the brine through the cold and hot plates.

The SG1 and SG2 HFM transducers described previously were used in Design 2 with small modifications. The Mylar film at the perimeter of the transducer was replaced by four strips of copper 20 mm wide, allowing measurement of the transducer surface temperature next to its edge. This indicates whether the temperature difference in the direction perpendicular to the measured heat flow lines is negligible, and that one-directional heat flow through the metering area of the HFM transducer can be assumed.

Calibration and Performance of Rebuilt Apparatus

Medium-density glass fiberboard transfer standards were used for the calibration of both heat flow meters. Two specimens were placed together, with paper septum in between, creating an approximately 50-mm-thick specimen. An example of calibration is shown in Table 4, which presents the results of a calibration of SG1 and SG2 transducers in Heat Flow Meter #2 (cork-faced).

Edge insulation and ambient temperature control were carefully applied during calibration, for which manual readings were taken. About 7 temperature and 20 HFM output readings were averaged for each of the calibration points.

The calibration coefficients obtained for SG1 ($C_{21} = 14.85 - 0.033T$) and for SG2 ($C_{22} = 15.15 - 0.037T$), with standard deviations of 0.1 and 0.2 percent respectively, may be compared with calibration coefficients from the old series (using 25-mm-thick transfer standards), $C_{21\text{hot}} = 14.80 - 0.038T$ and $C_{22\text{cold}} = 15.07 - 0.044T$, with a standard deviation of 0.5 percent for both transducers. For 35°C on the hot side the calibration coefficient for SG1 changed from 13.5 to 13.7, that is, about 1.5 percent; similarly, the SG2 calibration coefficient calculated at 13°C changed from 14.5 to 14.7.

Although the change in calibration coefficients for SG1 and SG2 heat flow meters does not exceed three standard deviations, it appears that some systematic shifts took place, either owing to the aging of the HFM core or to a decrease in lateral heat loss.

Design 2 can be compared with Design 1 with regard to instrument errors

TABLE 4—*Calibration of Heat Flow Meter #2.*

R-Value of Transfer Standard, m^2K/W	Bottom Plate		Top Plate	
	C, W/m^2mV	*T*, °C	*C*, W/m^2mV	*T*, °C
1.727	14.18	21.0	15.20	−0.9
1.693	14.00	25.5	14.97	4.7
1.639	13.74	33.5	14.70	12.5
1.626	13.67	35.2	14.57	14.5
1.555	13.34	45.6	14.19	24.8
1.520	13.19	51.1	14.09	29.7

and operation. It has a small time lag, and the 2-h stabilization period has been sufficient for most test specimens.

Table 5 and Fig. 6 compare a few results from the 600-mm vertical, double-sided guarded hot plate with HFM #1 and #2. The agreement among the three instruments is good. Both heat flow meters appear to yield slightly higher thermal resistance for a polystyrene/paper stack than do the data from the GHP, and slightly lower than the GHP estimate corrected for errors. Good agreement was also obtained for GHP and HFM on a low-density glass fiber/paper stack of six 25-mm specimens. The new HFM instruments appear to be reliable on 150 to 200 mm thick low-density thermal insulations.

Conclusions

The agreement between the GHP and HFM for both polystyrene and low-density layered specimens 150 to 200 mm thick (maximum probable errors) is good (Table 5 and Fig. 6). The differences do not exceed 1.5 percent. This indicates good precision for the rebuilt HFM. As a difference in the slope of the calibration coefficient shown in Fig. 3 relates to the same transducers, it appears that rebuilding improved HFM performance and reduced the effect of lateral heat flow on transducer calibration.

The test results for thick, layered specimens (separated by paper septa) are satisfactory, but those for thick, low-density specimens are unsatisfactory. They produced a wider error band in both GHP [*17*] and HFM measurements. Two tests performed on 89-mm-thick low-density glass fiber specimens divided with paper septa gave the results (HFM #1):

$$T_m = 25.9°C \qquad R = 3.90\ m^2K/W$$
$$T_m = 24.6°C \qquad R = 4.03\ m^2K/W$$

The averages for the GHP test series for the same mean temperatures were 3.86 and 3.88 m^2K/W, that is, about 1 and 4 percent lower.

This example once more focuses attention on the importance of the selection of the materials for use as transfer standards or calibrated specimens in the process of HFM calibration or verification.

Acknowledgments

The authors wish to thank their colleagues in Thermal Properties Section DBR/NRCC: J. Theriault and R. Marchand for their contribution to the development of the testing methods, and N. Normandin for making the measurements.

Thanks are also extended to D. Stephenson, Energy Coordinator, DBR/NRCC, S. Klarsfeld, Isover-St. Gobain, Rantigny, France, and C. Pelanne, Johns-Manville R/D, Denver, Colorado, for detailed discussion of the problems of testing thermal insulating materials.

TABLE 5—*Comparison of GHP and HFM test results.*

Specimen Description	Instrument No.	HFM				GHP				Recalculated GHP R_0	$\frac{R_0 - R_H}{R_0}$, %
		L, mm	T, °C	R_H, m^2K/W	No. of Tests	L, mm	T, °C	R, m^2K/W	No. of Tests		
Polystyrene/ paper stack							24.0	3.75[a]	8		
	1	149.4	17.8	3.88	2	149.4	17.8			3.84	−1.0
	2	149.0	24.3	3.76	2	149.0	24.3			3.74	−0.5
						100.3	24.3	2.52	2		
	1	200.6	24.6	5.11	2	200.6	24.6			5.04	−1.4
	2	200.6	23.9	5.01	1	200.6	23.9			5.05	0.7
Low-density glass fiber/ paper stack						76.5	23.8	1.56	2		
	2	153.0	26.1	3.10	2	153.0	26.1			3.08	−0.7
						76.5	39.1	1.41	1		
	2	153.0	40.7	2.81	1	153.0	40.7			2.78	−1.0

[a]Correction for GHP errors as discussed by Bomberg and Solvason [*17*] would bring R_G from 3.75 to 3.80 m^2K/W.

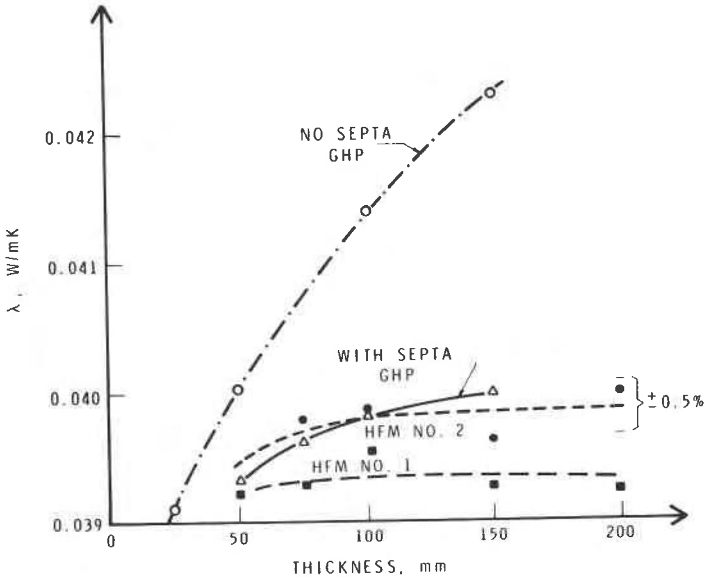


FIG. 6—*Apparent thermal conductivity of polystyrene stack with and without paper septa.*

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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