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An intercomparison of heat flow meter apparatus within the United Kingdom and Eire

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Abstract. The heat flow meter (HFM) technique is widely used for rapid and reliable measurement of apparent thermal conductivity of thermal insulation materials. In the British Isles there is a large number of HFM apparatus of different sizes and forms, mainly in the quality assurance and research laboratories of thermal insulation manufacturers. With the advent of European legislation requiring manufacturers to declare thermal performance values of their products, the National Physical Laboratory organised an intercomparison to assess the comparability and accuracy of industrial HFM measurements in the UK and Eire with the aim of helping to establish consistent measurements.

Seventeen HFM apparatus featured in the intercomparison, with NPL using a guarded hot-plate apparatus to provide baseline thermal conductivity values. Measurements were made at 10 °C and 23 °C, on two thicknesses of samples of expanded polystyrene, extruded polystyrene, and high density rock fibre. With few exceptions, the measurements agreed to within ±5%. In a total of 154 data points 69% were within ±3%, and 50% were within ±2%. Measurement differences due to calibration issues and equilibrium time variations are discussed, together with proposals for further reduction of measurement uncertainties.

1 Introduction

Following its initial development in the 1920s and standardisation by ASTM (1963), the heat flow meter (HFM) method was introduced by Pelanne and Bradley (1963) as a potential commercial tool for rapid and reliable measurements of the apparent thermal conductivity, λ_a, of thermal insulation materials and products. Work has continued on developing the method especially following the two energy crises which increased the use of thermal insulation. It has now become the most widely used tool for providing thermal performance data, particularly for quality control and quality assurance. Various national standards and also the international standard ISO 8301 (1991) cover the technique.

Its major advantages over the absolute standard guarded hot-plate method are its simpler design and speed of operation. More recently there have been major advances in, and availability of, very stable, very thin large integrated area heat flux transducers and the development of improved computer-aided operation and temperature control. These factors have been the spur to the use of the method to provide the increasing number of measurements for internal manufacturing quality issues and the various national and other regulatory requirements which now or will apply to published thermal performance values for thermal insulation products.

Among the most essential requirements are the availability of reference material or transfer standards to calibrate the whole system for any particular set of conditions. It is important to stress that this calibration is an apparatus constant with the major advantage that the test specimen can be considered as being self-guarding. Provided calibration specimens of similar thicknesses, and preferably of similar thermal resistances as the test specimens, are available then heat losses can be considered to be minimised, if not eliminated, for each selected condition. Under such conditions accuracy to better than ±5% can be obtained with a reproducibility of 1% or better (ISO 8301 : 1991).

At present there are few internationally accepted reference materials available, mainly because of the cost of development and/or measurement. The current reference materials are, mainly, medium to high density fibrous glass boards or blankets of limited thicknesses. Most commercial apparatus are reliant on the use of any one of this type of standard, certified, or similar traceable reference material at one thickness, or one particular transfer standard. Without extensive performance checks of the apparatus and/or detailed calculations, there will be uncertainty in the assumption that the accuracy of any one measurement system is the same for a wide range of materials having different values of λ_a and/or specimen thicknesses.

There have been examples of interlaboratory comparisons of HFM apparatus carried out in North America (Hust and Pelanne 1985), Scandinavia (Uvslokk 1995), and most recently, France (Quin and Hameury 1997). Overall, it appears that while the general accuracy level is within $\pm 5\%$ it is possible to attain $\pm 3\%$ or better, especially when using large apparatus and individually measured thick transfer standards.

Currently in the British Isles there are many HFM apparatus of different sizes and forms operating particularly in the quality assurance and research laboratories of thermal insulation manufacturers. The majority are commercial instruments that operate in 'semi-automatic' mode with direct read-out of thermal property. They are produced by several manufacturers, mostly American, each claiming similar ranges of accuracy and reproducibility for measurements on different products.

Because of the above potential differences, there is a need to investigate and assess the issues of comparability and accuracy. Furthermore, there is forthcoming European legislation requiring manufacturers to provide declared thermal performance for their products. Thus, there is the added need to establish consistent thermal performance measurements within the UK as a prelude to satisfying this legislation.

As a result, the National Physical Laboratory (NPL) initiated an intercomparison between organisations in the UK and Eire that use HFM apparatus. The aim was not only to establish a consistent level of current measurement methodology but also to show that the results could be of great value to all organisations that intended to improve their measurements capability. To this end NPL carried out guarded hot-plate measurements in accordance with ISO 8302 to provide baseline values for the exercise.

2 Materials

A number of materials and measurement factors were considered prior to the final choice. It was decided that the materials should:

(i) be different types, readily available, homogeneous, stable and reproducible in thickness and mass, and hence density, to acceptably small tolerances;

(ii) be representative of those currently used, especially in building construction;

(iii) have ranges of apparent thermal conductivity and thickness to cover a range of thermal resistance;

(iv) illustrate the existence of the 'thickness effect' (or boundary effect) but only to a small extent (Jones 1972). The density should be low enough in at least one case to ensure that small differences in thermal conductivity with increase in thickness can be measured and separated from those which are due to apparatus parameters. In addition at least one material should have a high enough density not to exhibit the effect.

As a result three candidate materials were considered as having the required attributes for the study. These were expanded polystyrene (EPS), having a relatively high density, extruded polystyrene (XPS), and a high density mineral fibre.

Discussions were held with established contacts at different manufacturers of the above product types and three standard commercial products having a good batch reproducibility were chosen. These were expanded polystyrene from Vencel Resil (density $\rho = 20$ kg m^{-3}), extruded polystyrene from Dow ($\rho = 32$ kg m^{-3}), and a high density rockwool ($\rho = 200$ kg m^{-3}) from Rockwool UK. The manufacturers indicated that they would select a limited number of boards from one batch having the required higher tolerance in thickness and density.

Based upon the expected number of participants and the sizes of the various apparatus the final requirements were a supply of 10 standard 2.4 m × 1.2 m boards (or equivalent) of each material in two thicknesses. Details of the materials, suppliers and technical contacts are provided in table 1.

Table 1. Materials supplied for measurement comparison.

Material	Manufacturer/contact	Nominal size/mm^3	Nominal density/kg m^{-3}
Extruded polystyrene	Dow Chemical UK Ltd, Kings Lynn, Norfolk	2400 × 1200 × 50 2400 × 1200 × 33	32
Expanded polystyrene	Vencel Resil Ltd, Grays, Essex	2400 × 1200 × 50 2400 × 1200 × 25	20
Rockwool	Rockwool Ltd, Bridgend, Mid Glamorgan	900 × 600 × 50 900 × 600 × 30	200

On receipt at NPL the boards were cut into the required number of specimens or specimen pairs of appropriate sizes for the individual apparatus and given identification numbers. The lateral dimensions and masses of each specimen were measured and specimen densities calculated by the use of nominal board thicknesses. The density results indicated that the two cellular plastic materials had a very uniform density such that the apparent thermal conductivity would not be affected significantly by any small difference that might occur as a result of the actual test thickness differing from the nominal. However, despite careful selection the density of the mineral fibre material did show a variation of some ±10% around the nominal value of 200 kg m^{-3}. It was therefore decided that a density correction would be required when the results were analysed.

3 Scope and participants

The scope covered two separate series of measurements on three materials, each at two thicknesses at one or two temperatures in the approximate range 10 – 25 °C. This was necessary to allow for operational differences in the various apparatus. Some operated at a fixed mean temperature of either 10 °C or 23 °C (both ±1 °C) while others operated at any desired temperature and temperature difference.

3.1 *First series*

The first series of measurements was undertaken by NPL using a 305 mm square guarded hot-plate apparatus in accordance with ISO 8302 in order to provide baseline data. These values were used solely for comparison and it is not implied that the NPL guarded hot-plate values are exact. However, as reported recently (Salmon and Tye 1999), the results of a similar interlaboratory comparison of UK guarded hot plates indicated that the attainable accuracy was of the order of ±1% to ±2%.

A comprehensive series of measurements was made at three mean temperatures in the range 10 °C and 24 °C with a repeat measurement at one of the temperatures. Because of density variations in the mineral fibre material, NPL also measured two additional specimens of this material to determine the variation of λ_a with density.

3.2 *Second series*

The second series of measurements was carried out by all organisations having HFM apparatus. For those able to measure only at a fixed temperature, two separate measurements were requested at that temperature. Those able to measure at any temperature were requested to undertake two measurements at a mean temperature of either 10 °C or 23 °C, with an approximate temperature difference of 20 °C, and also given the option of including a measurement at the second mean temperature.

3.3 *Organisations*

Table 2 lists the 17 participating organisations. To ensure anonymity each organisation has been identified with a single code number. Two organisations each requested that two different apparatus be included because they were used for different purposes within their organisation and comparison would be of significant assistance to their internal measurements programmes. It should also be noted that two apparatus included in this study did not conform in design to the relevant national and international standards. However, these were included in the study for completeness to ensure that all known apparatus could be evaluated.

Table 2. Organisations participating in the HFM intercomparison.

Organisation	Location
Blagden Chemicals Ltd	Sully, South Glamorgan
British Gypsum-Isover	Runcorn, Cheshire
Callenders Ltd	Basildon, Essex
Cape Insulations Products Ltd	Washington, Tyne & Wear
Celotex Ltd	Hadleigh, Essex
Dow Chemicals UK Ltd	Kings Lynn, Norfolk
Gearing Scientific	Ashwell, Hertfordshire
ICI Polyurethanes	Shepton Mallet, Somerset
Montell Carrington Ltd	Carrington, Lancashire
Moy-Isover Ltd	Clonmel, Co. Tipperary
National Physical Laboratory	Teddington, Middlesex
Nortest	Castle Ashby, Northants
Owens Corning Building Products UK Ltd	St Helens, Lancashire
Owens Corning Polyfoam UK Ltd	Hartlepool, Teeside
Rockwool Ltd	Bridgend, Mid-Glamorgan
Superglass Insulation Ltd	Stirling, Central Region, Scotland
Vencel Resil Ltd	Belvedere, Kent

4 Measurement protocol

Each participant was provided with a specimen or specimen pair of the required size for their particular apparatus, together with a detailed standard test and reporting protocol to be followed in order to minimise effects of differing operational procedures. Each participant was requested to adhere, as far as possible, both to this protocol and to the basic requirements of ISO 8301, while following the recommended operational procedure of the apparatus.

5 Results

5.1 *Guarded hot plate*

The results of the measurements covering the temperature range for each material and the density range of the mineral fibre material have been reported elsewhere (Salmon and Tye 1999). For the limited temperature range covered, the thermal conductivity of the polystyrenes as a function of temperature can be represented by the following linear equations, where θ is the temperature in degrees Celsius, which are least squares fits to the guarded hot-plate measured values.

For EPS, 25 mm: $\lambda_a/\text{mW m}^{-1}\text{ K}^{-1} = 0.1377(\theta/°\text{C}) + 32.631\,.$ (1)

For EPS, 50 mm: $\lambda_a/\text{mW m}^{-1}\text{ K}^{-1} = 0.1496(\theta/°\text{C}) + 32.878\,.$ (2)

For XPS, 33 mm: $\lambda_a/\text{mW m}^{-1}\text{ K}^{-1} = 0.109(\theta/°\text{C}) + 26.079\,.$ (3)

For XPS, 50 mm: $\lambda_a/\text{mW m}^{-1}\text{ K}^{-1} = 0.1206(\theta/°\text{C}) + 26.262\,.$ (4)

The results for the various rockwool specimens illustrating the dependence on density are shown in figure 1, together with the following equation derived for a density of 200 kg m^{-3}:

$$\lambda_a/\text{mW m}^{-1}\text{ K}^{-1} = 0.1234\ (\theta/°\text{C}) + 34.537. \quad (5)$$

The above data were used as the basis for making the necessary temperature and/or density corrections to the results from the participants.

For the rockwool data, thermal conductivity values were calculated at temperatures of 10 °C, 15 °C, 19 °C, and 24 °C from the least squares fit equations for each density specimen shown in figure 1. These values were normalised by dividing by the results at a density of 193.5 kg m^{-3}. The normalised values were plotted against density and the mean percentage variation of the material with density was determined. With this density correction, all the raw NPL guarded hot-plate results were then corrected to a density of 200 kg m^{-3}, as shown in figure 1, to form a baseline for comparison of all other results. The density correction for this batch of rockwool is 0.12% per kg m^{-3}; see equation (5).

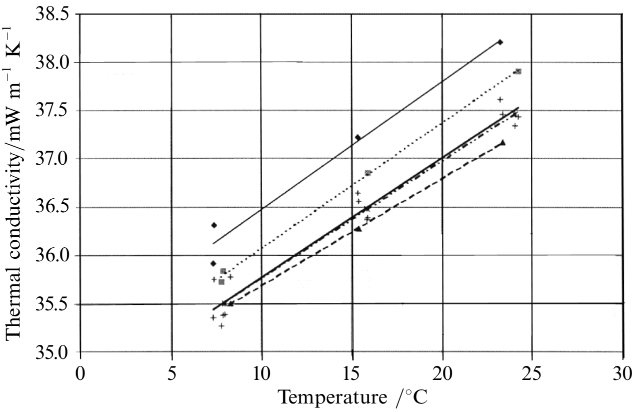

Figure 1. NPL guarded hot-plate results for rockwool 30 mm and 50 mm thick at four different densities: 194, 203, 210, and 213 kg m^{-3}.

5.2 *Heat flow meter*

Figures 2, 3, and 4 contain the respective results for the thin and thick EPS, XPS, and rockwool specimens. Each figure contains for comparison the linear curve fitted to the

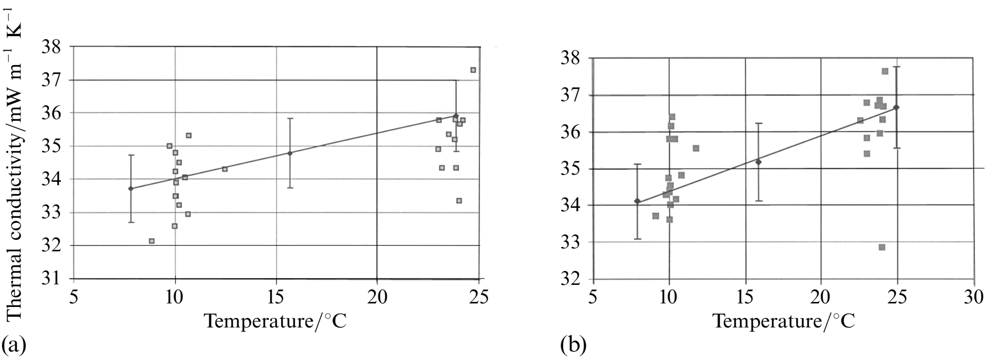

Figure 2. Heat flow meter results for (a) 25 mm thick and (b) 50 mm thick expanded polystyrene (EPS).

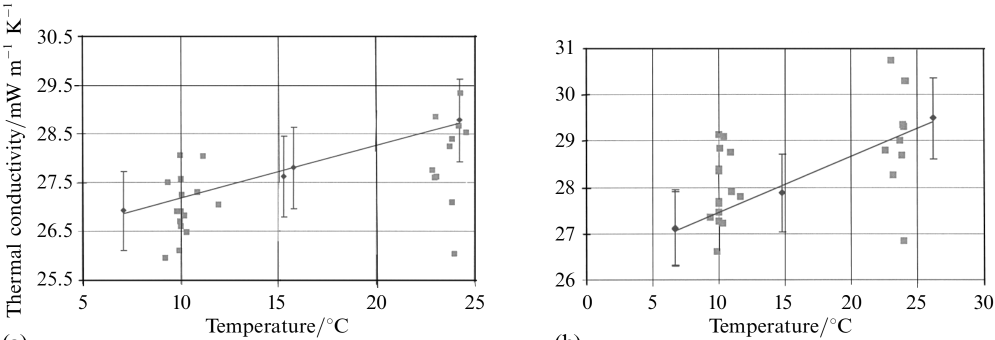

Figure 3. Heat flow meter results for (a) 33 mm thick and (b) 50 mm thick extruded polystyrene (XPS).

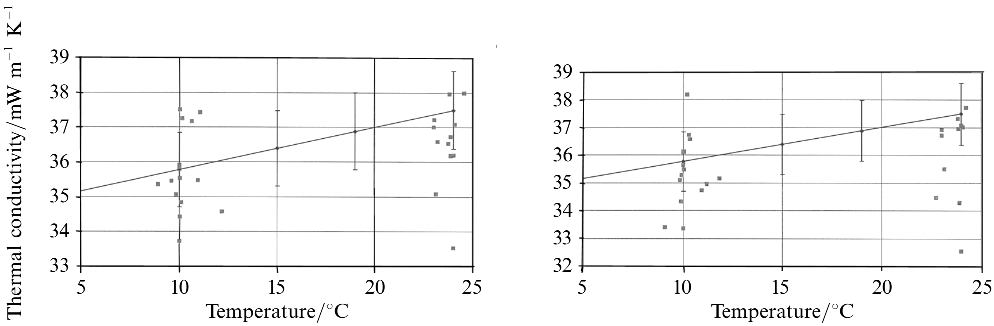

Figure 4. Heat flow meter results for (a) 30 mm thick and (b) 50 mm thick rockwool normalised to a density of 200 kg m^{-3}. 3% errors bars shown.

NPL guarded hot-plate measured thermal conductivity values. The averaged thermal conductivity values are based on duplicate measurements which indicate that the reproducibility of the overwhelming majority of the participating apparatus is 1% or better. For each measured thermal conductivity value a corresponding value has been calculated at the same temperature from the NPL data as described in section 5.1. In the case of the rockwool, a density correction to 200 kg m^{-3} has also been included.

6 Discussion

6.1 *Guarded hot-plate baseline data*

During analysis of the results it appeared that the values for the thick XPS provided by two late participants were much higher than expected, especially when compared with those obtained for the thin specimens. Because of their late involvement these organisations undertook measurements in June and August respectively, much later than the February/March period for the other participants. Thus, the possibility existed that the batch of material was changing with time and therefore the specimens measured by the later participants had different characteristics.

In September NPL carried out guarded hot-plate measurements of a further pair of thick specimens cut from the batch. The resultant mean values obtained were 29.2 mW m^{-1} K^{-1} and 30.6 mW m^{-1} K^{-1} at 10 °C and 23 °C, respectively. These indicated clearly that the material did have a different and higher λ_a value and that it might be changing with time.

The existence of a 'thickness effect' for the cases of the EPS and XPS materials is shown clearly in figures 2 and 3. For the EPS material the effect was shown by a difference in the thermal conductivity results of about 1.4% between the 25 mm and 50 mm thick specimens. Similarly, for the XPS material the effect was shown by a difference of the order of 0.8% between the results for the 33 mm and 50 mm thick specimens. However, as expected there was no evidence of any thickness effect for the high density rockwool material.

6.2 *Heat flow meter*

Figures 5–7 show the magnitude of the differences from the guarded hot-plate baseline values for one thickness and both temperatures of the EPS, XPS, and rockwool, respectively. The behaviour of the thinner specimens is very similar. An examination of all values for each material indicates that the overwhelming majority is well within ±5% for each. Table 3 summarises this range of agreement. From a total of 155 data points only 20 are outside ±5% while 102 are within ±3%, and of the latter 83 are within ±2%. If the results from the two nonconforming apparatus are deleted only 10 are outside ±5% while 79 are within ±2%. Furthermore, the earlier discussion concerning the uncertainty in the values for specimens from board 8 reduces the number in excess of ±5% to 8.

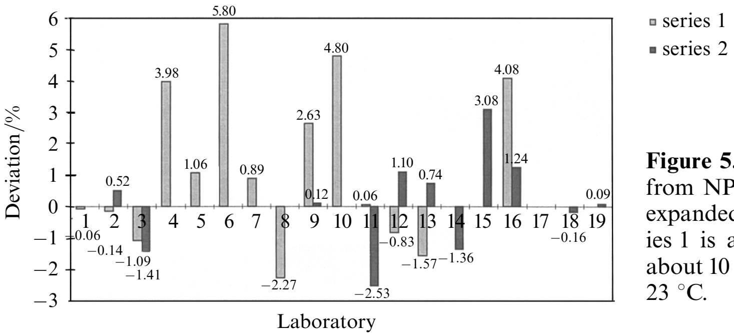

Figure 5. Percentage differences from NPL values for 50 mm thick expanded polystyrene results. Series 1 is at a mean temperature of about 10 °C and series 2 is at about 23 °C.

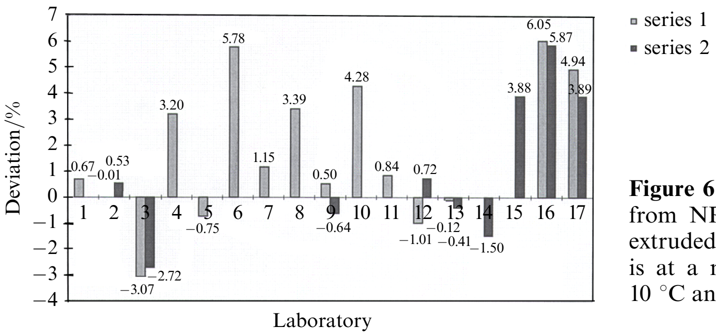

Figure 6. Percentage differences from NPL values for 50 mm thick extruded polystyrene results. Series 1 is at a mean temperature of about 10 °C and series 2 is at about 23 °C.

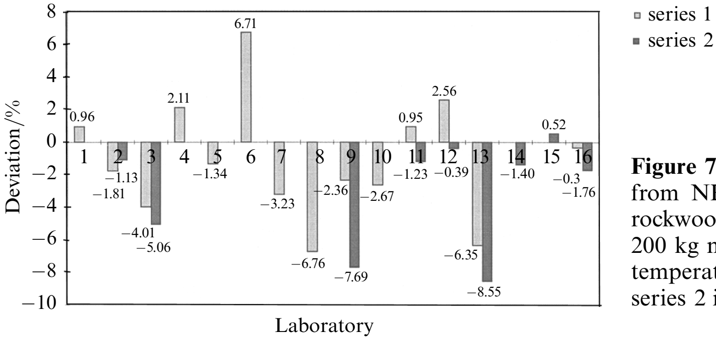

Figure 7. Percentage differences from NPL values for 50 mm thick rockwool results at a mean density of 200 kg m^{-3}. Series 1 is at a mean temperature of about 10 °C and series 2 is at about 23 °C.

Table 3. Deviation of the HFM data points for 18 organisations from the NPL baseline.

Difference from baseline	Expanded polystyrene		Extruded polystyrene		Rockwool	
	25 mm	50 mm	32 mm	50 mm	32 mm	50 mm
All results						
$> \pm 5\%$	2	2	2	4	3	7
$\pm 3\%$ to $\pm 5\%$	7	4	5	7	8	2
Within $\pm 3\%$	16	20	19	14	16	17
Within $\pm 2\%$	13	17	14	13	13	13
Excluding nonconforming apparatus						
$> \pm 5\%$	0	2	1	3	1	6
$\pm 3\%$ to $\pm 5\%$	6	3	5	6	4	2
Within $\pm 3\%$	15	17	17	14	16	16
Within $\pm 2\%$	13	17	13	12	12	12

This general degree of agreement and consistency between different apparatus is encouraging. To a great extent the results mirror closely those obtained in the other, similar intercomparisons mentioned earlier. In these latter cases the agreement was found to be mainly within $\pm 3\%$.

However, while the general level of agreement is good there are two cases where apparatus performance is not as expected and where additional comment is required and possible solutions recommended.

(i) Whereas the existence of a small thickness effect is shown clearly by the guarded hot-plate measurements on the two cellular plastics it is not exhibited to the same degree by the various HFM apparatus. In a number of cases an effect is shown but of much greater magnitude than expected or observed in the GHPs. Conversely, some results indicated an effect in the opposite direction, ie a lower thermal conductivity value for the thicker specimen. Furthermore, for the rockwool where no effect is expected or observed, many of the results were significantly different for the two thicknesses. The levels of agreement are within the generally accepted $\pm 2\%$ to $\pm 3\%$ but significantly different from each other for the two thicknesses.

(ii) In general the overall level of agreement and consistency for both measurement conditions, especially for the rockwool, is less for the thicker than for the thin specimens, even when the results for the two small nonconforming apparatus are removed.

There are two possible individual causes for this apparently inconsistent behaviour. However, dependent on the particular apparatus, they may also be interrelated.

(i) The first may be due to insufficient time being allowed for the apparatus to attain equilibrium, especially for the thicker denser specimens. This factor may not have been appreciated fully, especially by those operators having major experience in measuring only low density materials and/or thin test specimens.

However, the relevant national and international standards do provide adequate guidelines relating to the establishment of equilibrium conditions. These should be followed rigorously, especially when undertaking tests on specimens that may differ from those normally measured.

(ii) The second may be due to effects of apparatus calibration. In this intercomparison all apparatus were calibrated with one type of reference material or transfer standard but from different sources. This was either a moderate ($\sim$80 kg m^{-3}) or high ($\sim$150 kg m^{-3}) density glass fibre board having a thermal conductivity in the range 32 mW m^{-1} K^{-1} to 34 mW m^{-1} K^{-1} over the present temperature range.

It follows that the thermal resistance of the transfer standard is comparable to that of the thin test specimens and any net edge heat exchanges may be minimal. However, for thicker test specimens the thermal resistance is significantly lower (by a factor of at least two) and in this case the design of a particular apparatus, especially with respect to guarding and surround insulation, may be such that net edge heat exchange cannot be neglected for calibration and test conditions.

This problem can only be overcome or minimised by the use of other reference materials having higher thermal resistance values matching more closely that of a test specimen. This problem highlights the existing lack of reference materials in terms of the range of thermal conductance values available.

Until additional reference materials in different thicknesses become available, this situation can be resolved only by the use of a certified transfer standard(s), ie an individually measured specimen of a specific thickness having a certified thermal resistance value obtained by measurement in a guarded hot plate. Use of such transfer standards will ensure that any HFM apparatus designed and operated in accordance with the requirements of appropriate international and national standards will attain a precision within the present accepted limits of $\pm 3\%$ on thermal insulation specimens at thicknesses up to the maximum for the size of the individual apparatus.

In conclusion there is one general issue concerning calibration that needs to be addressed. This relates to the degree of equivalency of calibration of different apparatus based upon the use of reference materials or transfer standards from more than one source. This is especially relevant now that comparisons between countries and/or geographical areas are becoming important in requiring declared performance values for thermal insulation products.

In the present investigation the majority of the apparatus involved used similar reference specimens but from different calibration sources, either the National Institute of Standards (NIST) in the USA or the NPL in the UK. Separately, three apparatus involved the use of a calibration curve supplied by the manufacturers which related to values obtained from NIST source material. It is possible that differences exist between the calibrations and these could affect the values obtained such that the overall differences are smaller or larger than those indicated in the present investigation.

To investigate possible differences in results due to the use of different calibration sources measurements were made in the NPL HFM with the calibration supplied by the manufacturer. The measurements were then repeated with a calibration based on the newly developed and potential certified European IRMM reference material (Lamberty 1999). In developing data for this material, guarded hot-plate measurements had been made, over the temperature range 0–40 °C, by six European laboratories, including NPL. The results were most encouraging and provided confidence in their use because all values agreed to better than $\pm 1.0\%$ over the whole temperature range.

Table 4 summarises the results obtained with the two calibrations. They indicate that there is a constant difference of the order of approximately 2%–3% between the two calibrations for each of the test specimens, irrespective of their thickness.

It is seen that this is one area where more work is necessary, especially prior to any international comparison of HFM apparatus. To this end NPL had proposed to other national standards organisations in the USA, Canada, France, and Japan that each laboratory undertake guarded hot-plate measurements on specimens of reference materials obtained from and used within their respective countries. This proposal was made initially to ensure that such reference materials could be accepted internationally rather than nationally. However, it was also envisaged that the availability of such accepted materials having values substantiated by five national organisations would be a valuable contribution to ensuring worldwide equivalency of calibration of HFM apparatus. The proposal has been accepted and a comparison organised by Bob Zarr at NIST is now in progress.

Table 4. HFM values based on two different calibration specimens.

Material identification	Thickness/mm	Thermal conductivity/mW m^{-1} K^{-1}				Difference/%	
		Manufacturer's calibration (NIST)		NPL calibration (IRMM)			
		10 °C	24 °C	10 °C	24 °C	10°C	24 °C
EPS 24.1	48.88	35.8	37.4	34.5	36.3	2.9	3.0
EPS 16.1	24.56	35.0	36.5	33.9	35.7	3.2	2.2
XPS 8.1	50.38	29.7	31.2	28.8	30.3	3.1	3.0
XPS 3.2	32.54	28.0	29.2	27.2	28.5	2.9	2.5
Rockwool 35.1	51.02	36.6	38.1	35.6	37.1	2.8	2.7
Rockwool 31.1	32.10	36.4	37.9	35.3	36.8	3.1	3.0

7 Conclusions

An intercomparison of 17 HFM apparatus currently operating in the United Kingdom and Eire has been carried out. The investigation included measurements made with the NPL guarded hot-plate apparatus to substantiate material homogeneity and provide baseline data for comparison. Measurements were made at approximately 10 °C and 23 °C on two thicknesses of samples of expanded polystyrene, extruded polystyrene, and high density rock fibre.

The results indicated that, with few exceptions, the overall agreement was within ±5% and that for the majority of HFM apparatus it was ±2% to ±3%. Reasons for differences due to calibration issues and equilibrium time variations have been discussed, together with proposed solutions to reduce uncertainties in future test and quality control measurements.

Acknowledgements. In all cases the manufacturers donated the materials for the study and undertook the preliminary selection of the boards from which the various test specimens were prepared. This contribution by the manufacturers and the cooperation of their technical representatives, Mr J Bowdidge of Rockwool, Mr S Davis of Dow Chemical, and Mr D Thomsett of Vencel Resil, respectively, is recognised and greatly appreciated by all involved in the study. The authors would also like to express their appreciation to all the participants for their ready cooperation.

References

ASTM C518-63, 1963, ASTM, 1916 Race Street, Philadelphia, PA 19103-1187, USA (and subsequent revisions)

Hust J G, Pelanne C M, 1985, "Round robin on the apparent thermal conductivity of low density glass fibre insulation using guarded hot plate and heat flow meter apparatus", NBSIR 85-3026, NIST, Boulder, CO, USA

ISO 8301, 1991, "ISO 8301 : 1991(E): Thermal insulation—determination of steady state thermal resistance and related properties—heat flow meter apparatus" (Geneva: International Standards Organisation)

Jones T T, 1972 *Plast. Polym.* **40** 33 – 39

Lamberty A, 1999, "Re-certification of BCR CRM 064", IRMM Geel, Belgium

Pelanne C M, Bradley C B, 1963 *Mater. Res. Stand.* **1 – 2** 549 – 560

Quin S, Hameury J, 1997 *High Temp. – High Press.* **29** 649 – 652

Salmon D R, Tye R P, 1999, paper presented at the International Thermal Conductivity Conference, Ann Arbor, MI, USA, June 1999

Uvslokk S, 1995, "Equipment for measuring thermal transmissivity and thermal resistance—Intercalibration", Nordtest Technical Report 249, NBRI, Forskningsveien 3B, PO Box 123 Blindern, N-0314 Oslo, Norway