

An inter-comparison of guarded hot plate and heat flow meter apparatus within the United Kingdom and Ireland

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ABSTRACT

Two inter-comparisons have been carried out between organisations in the British Isles that undertake measurements of the thermal properties of insulations and other low thermal conductivity materials by appropriate standard methods. The overall aims were to establish that consistent levels of measurement practice were being maintained to declared or acceptable precision limits and to provide information that could be used to assist all organisations to improve their measurement capabilities.

The first inter-comparison involved the seven organisations that are accredited by the United Kingdom Accreditation Service for measurements using the guarded hot plate method in accordance with the ISO8302. The second included the seventeen organisations that use the heat flow meter apparatus according to ISO8301 in research and quality control laboratories particularly those associated with manufacturers of different thermal insulation products.

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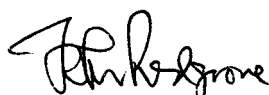
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Approved on behalf of the Managing Director, NPL
By John Redgrove, Head of Thermophysics, Centre for Basic, Thermal and Length Metrology

A handwritten signature in black ink, appearing to read 'John Redgrove', is positioned below the text of the approval statement.

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1 EXECUTIVE SUMMARY

Two inter-comparisons have been carried out between organisations in the British Isles that undertake measurements of the thermal properties of insulations and other low thermal conductivity materials by appropriate standard methods. The overall aims were to establish that consistent levels of measurement practice were being maintained to declared or acceptable precision limits and to provide information that could be used to assist all organisations to improve their measurement capabilities.

The first inter-comparison involved the seven organisations that are accredited by the United Kingdom Accreditation Service for measurements using the guarded hot plate method in accordance with ISO8302. The second included the seventeen organisations that use the heat flow meter apparatus according to ISO8301 in research and quality control laboratories particularly those associated with manufacturers of different thermal insulation products.

As a result of discussions with manufacturers three different materials (standard products) having good batch reproducibility and stability were chosen in two thicknesses to provide a range of thermal resistances and to illustrate the existence of a measurement effect due to radiative heat transmission. The materials were an expanded polystyrene (density, $\rho = 20 \text{ kg/m}^3$), an extruded polystyrene ($\rho = 32 \text{ kg/m}^3$) and a high-density mineral fibre board ($\rho = 200 \text{ kg/m}^3$). The manufacturers selected the boards from batches having the higher tolerance on thickness and density required for this study and submitted them to NPL for initial characterisation and preparation of the appropriate measurement specimens. Initial characterisation indicated that a density correction would be required for the mineral fibre but not the two polystyrenes.

Measurements by the participants were undertaken at 10°C and/or 23°C mean temperature in accordance with the appropriate international standards and using a strict protocol involving pre- and post-measurement procedure and reporting of results for subsequent analysis by NPL. All results were corrected for temperature and, for the mineral fibre board only, density using the results of a more comprehensive series of measurements carried out by NPL at three or more temperatures and for a range of densities of the mineral fibre board. The NPL “baseline data” were then used for the assessment of the results.

Overall the results of the inter-comparisons proved to be very satisfactory for the guarded hot plates and highly encouraging for the heat flow meter apparatus. They not only indicated that the stated levels of measurement precision were generally within the respective accepted limits but also provided information which could be used to assist in improving measurement procedures and precision in the participating laboratories.

For the guarded hot plates the overall precision with the exception of two anomalous data points, was within the accepted level of $\pm 2\%$ for the temperature range of this study. The measurements clearly indicated the existence of the expected “thickness effect”, of the order of 0.8 to 1.5%, for the two polystyrene products and also the consistency of values for the two thicknesses of high density mineral fibre board.

In the heat flow meter comparison for a total of 154 data points, 106 were within $\pm 3\%$, of which 77 were within $\pm 2\%$, and only 20 were outside $\pm 5\%$. However the existence of the thickness effect was not exhibited consistently. In a number of cases an effect is either illustrated but much greater or in the opposite direction to that expected. Some results, while still within the acceptable precision levels, predicted a thickness effect for the mineral fibre board where no effect exists. It was also apparent that more consistency of measurement was obtained both for the two cellular products than for the mineral fibre board and for the thinner of the two specimens of each material. Individual and often interrelated causes, due to apparatus calibration and short equilibrium times, for this inconsistent behaviour are suggested and discussed together with means to address the problem and improve measurement procedure. Finally one batch of material was discovered, most unexpectedly to have a thermal conductivity that increased with time. However overall consistency of measurement was still achieved by comparing the participant's results with separate measurements carried out by NPL at various times during the total time span of all measurements.

Section 10 of this document contains a summary of the discussions and conclusions of a one day debriefing meeting attended by many of the participants and the written comments of other participants after the receipt of the respective draft reports.

2 INTRODUCTION

Recently, due particularly to the impact of various energy crises, much attention has been paid to the development and use of insulations with improved thermal performance for the building envelope. In particular, there has been a considerable increase in the use of the more rapid and simple secondary heat flow meter method of measurement, ISO 8301¹, for measuring the thermal performance of such insulation materials and products. However, the guarded hot plate method, ISO8302², is still the primary method needed to measure the properties of the reference materials and transfer standards required for this alternative method of test. In addition it is required as the "referee" method to resolve differences that may occur. It also remains the most precise method available for low thermal conductance specimens where such precision is needed.

Within the European Union legislation is being drafted for manufacturers to provide declared thermal performance values for their products. In addition the various national standards for thermal conductivity measurement are being harmonised into a set of standards based on ISO 8302. As a result there is an established need for the various EU member states to ensure that their measurement capabilities are at or above the levels mandated for these requirements.

The guarded hot plate method is recognised worldwide as the primary or standard means of measuring the thermal conduction properties of materials of low thermal conductance. It is used especially for evaluation of the apparent thermal conductivity, λ , of thermal insulations, including those used for the building envelope. The method has been standardised by many national standards organisations. More recently, activities within the ISO TC161 Thermal Insulation Committee have resulted in the promulgation of the International Standard ISO 8302.

Over its many years of use, a number of national and international intercomparisons have been carried out over the temperature range 0 °C to 40 °C, for example the Institut International du Froid study in the late 1960s³, the ASTM C16 Thermal Insulation Committee round robin in the 1970s⁴ and the ISO TC161 Thermal Insulation Committee series of measurements in the mid 1980s⁵. In general the results of these intercomparisons have indicated, with few exceptions, that an overall level of precision of $\pm 2\%$ to $\pm 3\%$ with a reproducibility of $\pm 1\%$ to $\pm 1.5\%$ can be attained over this limited temperature range.

Whilst the guarded hot plate method was developed very early in the 20th century the heat flow meter method was introduced only some 35 years ago⁶ as a viable potential commercial tool for undertaking rapid and reliable measurements of apparent thermal conductivity of thermal insulation materials and products. Since then, due especially to the impact of the two energy crises on the increased use of thermal insulation, much work has continued on developments of the method. It has now become the most widely used tool for providing thermal performance data, especially for quality control and quality assurance purposes, within the thermal insulation producer and user communities. The technique is the subject of various national standards, e.g. ASTM C518, established in 1968, and most recently the international standard ISO 8301, in 1992.

Its major advantages over the recognised absolute standard guarded hot-plate method are relative simplicity of 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 using the method to provide the increasing number of measurements required to address internal manufacturing quality issues and the various national and other regulatory requirements which now or soon will apply to published thermal performance values for thermal insulation products. These apply especially to those used within the building envelope.

The most important item required for the method is the availability of a reference material(s) or transfer standard(s) to calibrate the whole system for any particular set of conditions. It is important to stress that such calibration is an apparatus constant and the major advantage of the in-situ calibration is that the test specimen can be considered somewhat self-guarding. Providing 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 eliminated (or at least minimised) for each particular condition at which a calibration is undertaken. Under such conditions good accuracy to $\pm 5\%$ or better can be obtained⁷ and the method is capable of very high reproducibility of 1% or better.

However at present, despite the obvious need for a range of reference materials and transfer standards, there are few available. This is due mainly to cost considerations in their development and/or individual measurement. The current reference materials are, in general, medium to high density fibrous glass boards or blankets. Most commercial apparatus are especially 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. Thus, there can be some uncertainty in assuming that the accuracy of any one measurement system is the same for the whole range of materials having different thermal conductivity values and/or specimen thicknesses, i.e. range of thermal resistances.

There have been examples of inter-laboratory comparisons of heat flow meter apparatus carried out in North America⁽⁸⁻¹⁰⁾, Scandinavia⁽¹¹⁾ and most recently, France⁽¹²⁾. Overall, it appears that the general accuracy level is indeed within $\pm 5\%$ and it is possible to attain $\pm 3\%$ especially when using large size apparatus and individually measured thick transfer standards.

Currently in the British Isles there are seven organisations that are accredited by the United Kingdom Accreditation Service (UKAS) for measurement of thermal conductivity by means of the guarded hot plate method. With two exceptions these hot plates have a 305 mm square heater plate configuration and are used primarily for research, testing for external clients and for internal quality assurance of several different thermal insulation building products. The majority of these measurement systems were designed and constructed by the individual laboratories but two or three were built commercially. All claim to have the same or similar ranges of measurement uncertainty and reproducibility.

Supplementing these capabilities there are at least seventeen organisations having heat flow meter apparatus of different sizes and forms operating particularly in the quality assurance

and research laboratories of manufacturers of different thermal insulation products. The majority of these systems are commercial instruments produced by several different manufacturers, mostly from the USA, each claiming the same or similar ranges of accuracy and reproducibility for measurements on different products and product types. In most cases they are operated in a “semi-automated” mode with direct read-out of thermal conductivity or thermal conductance, C . Because of the possible differences due to the above factors, there is a need to investigate and assess the issues of comparability and accuracy and to establish consistent thermal performance measurements within the UK as a prelude to satisfying European legislation related to manufacturers providing declared thermal performance of their products.

Thus, for the United Kingdom, within the Thermal Metrology Standards Programme of the Department of Trade and Industry, the National Physical Laboratory initiated intercomparisons of guarded hot plate and heat flow meter apparatus in current use. The objectives of these intercomparisons were to investigate and assess the issues of comparability and accuracy within organisations using heat flow meter apparatus to measure the thermal performance of insulation products and between accredited UKAS laboratories. The aim was not only to establish a consistent national level of measurement capability comparable to that of other member countries but also to show that the results could be of great value and assistance to those organisations that intended to improve their capability.

This report describes these two interlinked guarded hot plate and heat flow meter intercomparisons.

3 MATERIALS FOR THE STUDY

For the purposes of the inter-comparisons it was necessary to consider a number of materials and measurement factors prior to the final choice. These were that the materials:

1. should be of different types, readily available (not specially fabricated), homogeneous, stable and reproducible in thickness and mass, hence density, to acceptably small tolerances.
2. should be representative of those currently being used, especially for use in building envelope construction.
3. have ranges of apparent thermal conductivity and thickness in order to cover a range of thermal resistance.
4. illustrate the existence of the “thickness effect”⁽¹³⁾ (sometimes called boundary effect) but only to a small extent. Thus 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 especially in calibration errors. In addition at least one material should have a high enough density to ensure that the “thickness effect” is eliminated.

From consideration of these factors three candidate materials were considered as having the required attributes for the study. These were expanded polystyrene having a relatively high density, extruded polystyrene and a high-density mineral fibre.

Discussions were held with established contacts at different manufacturers of the above product types. As a result three materials (products) were chosen. These were an expanded polystyrene (density, $\rho = 20 \text{ kg/m}^3$) an extruded polystyrene ($\rho = 32 \text{ kg/m}^3$) and a high-density rockwool ($\rho = 200 \text{ kg/m}^3$). In each case these were manufactured as standard products in standard thicknesses and had good batch reproducibility. The manufacturers indicated that they would subsequently select a limited number of boards from a batch having the required higher tolerance in thickness and density needed for this study.

Based upon the expected number of participants and the sizes of the various apparatus that might be used the final requirements were a supply of 10 standard 2.4 m x 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	Size (Nominal) / mm	Density /(kg/m³)
Extruded Polystyrene	Dow Chemical UK Ltd. Kings Lynn, Norfolk Mr. S. Davis	2400 x 1200 x 50 2400 x 1200 x 33	32
Expanded Polystyrene	Vencel Resil Ltd. Grays, Essex Mr. D. Thomsett	2400 x 1200 x 50 2400 x 1200 x 25	20
Rockwool	Rockwool Ltd. Bridgend, Mid Glamorgan Mr. J. Bowdidge	900 x 600 x 50 900 x 600 x 30	200

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 co-operation 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.

On receipt of the boards at NPL they were cut into the required number of individual specimens or pairs of specimens of appropriate sizes for the individual apparatus and given identification numbers. Table 2, Table 3 and Table 4 contain dimensional and mass details of each material series and also include calculated density values based on the measured masses and lateral dimensions and the nominal board thicknesses.

The density results indicated that the two polystyrenes were very reproducible but despite the careful selection the mineral fibre did exhibit a variation of some $\pm 10\%$ about the nominal value. As a consequence, it was decided that a density correction would be necessary for the mineral fibre board but not for the two foamed polystyrenes or cellular plastics.

Table 2. Dimensional details for Rockwool specimens

Rockwool data					
Specimen details as measured at NPL on 20 Jan 1998.					
Spec.	Mass	Thickness	Width	Breadth	Density
	g	mm	mm	mm	kg/m ³
35.1	3698.0	50	600.5	595.7	206.8
35.2	3745.8	50	600.5	600.0	207.9
36.1	3682.4	50	601.2	600.0	204.2
36.2	3590.8	50	601.0	597.5	200.0
30.1	2207.3	30	599.0	601.0	204.4
30.2	2143.2	30	599.2	601.0	198.4
31.1	2237.8	30	598.5	601.0	207.4
31.2	2249.8	30	599.5	601.0	208.1
	1291.3	30	450.0	450.5	212.3
	1266.7	30	450.0	450.2	208.4
37.1	2039.7	50	449.0	450.0	201.9
37.2	2118.0	50	449.5	450.0	209.4
	257.7	30	199.5	199.7	215.6
	262.5	30	199.5	199.8	219.5
	416.6	50	199.5	199.5	209.3
	428.7	50	199.0	199.5	216.0
	528.7	30	298.0	298.2	198.3
	628.7	30	298.0	298.2	235.8
	532.7	30	298.0	298.4	199.7
	536.6	30	298.5	299.0	200.4
	511.1	30	299.0	298.2	191.1
		30	299.0	299.0	220.0
	557.1	30	298.2	299.3	208.1
	517.5	30	299.5	298.2	193.1
	521.5	30	298.2	298.2	195.5
	509.7	30	299.5	297.1	190.9
	578.5	30	298.0	298.0	217.1
	523.2	30	298.3	297.5	196.5
	554.3	30	299.0	297.0	208.1
	606.7	30	300.0	298.3	226.0
	499.2	30	298.5	298.5	186.8
	534.5	30	297.5	299.7	199.8
	900.0	50	296.5	298.0	203.7
	876.6	50	296.5	298.0	198.4
	886.6	50	296.5	299.5	199.7
	856.0	50	297.0	299.5	192.5
	904.1	50	297.5	297.5	204.3
	880.1	50	297.0	297.8	199.0
	885.6	50	297.0	299.5	199.1
	951.1	50	296.5	299.0	214.6
	918.4	50	297.8	297.3	207.5
	876.5	50	297.5	297.5	198.1
	952.7	50	297.5	298.0	214.9
	995.7	50	296.7	298.0	225.2
	947.6	50	297.2	299.5	212.9
		50	297.5	300.0	198.1
	876.2	50	297.5	299.5	196.7
	892.4	50	298.0	299.5	200.0

Table 3. Dimensional details for Dow specimens

Specimen details as measured at NPL on 21 Jan 1998.					
Spec.	Mass	Thickness	Width	Breadth	Density
	g	mm	mm	mm	kg/m ³
1.1	379.4	33	598.2	598.6	32.1
1.2	378.9	33	597.2	598.4	32.1
2.1	379.1	33	597.5	598.6	32.1
2.2	379.2	33	597.0	598.8	32.1
3.1	378.8	33	597.9	598.0	32.1
3.2	378.6	33	597.0	598.2	32.1
7.1	595.5	50	598.2	602.3	33.1
7.2	594.8	50	597.3	602.0	33.1
8.1	596.8	50	597.8	602.3	33.2
8.2	596.7	50	598.8	602.0	33.1
9.1	594.4	50	596.8	602.0	33.1
9.2	596.2	50	599.5	602.5	33.0
4.1	214.3	33	449.5	449.5	32.1
4.2	214.3	33	450.0	450.0	32.1
10.1	334.4	50	449.2	449.5	33.1
10.2	334.7	50	450.0	450.0	33.1
4.3	41.7	33	199.2	199.5	31.8
4.4	41.9	33	199.2	199.6	31.9
10.3	65.5	50	199.0	199.0	33.1
10.4	66.3	50	199.2	199.2	33.4
5.1	93.6	33	297.0	297.8	32.1
5.2	93.7	33	297.0	297.5	32.1
5.3	93.7	33	296.8	297.7	32.1
5.4	93.8	33	297.3	297.3	32.2
5.5	93.2	33	297.0	297.0	32.0
5.6	93.3	33	297.0	297.0	32.1
5.7	93.3	33	297.0	297.2	32.0
5.8	93.2	33	296.9	297.0	32.0
6.1	93.1	33	297.0	297.0	32.0
6.2	93.1	33	297.0	297.1	32.0
6.3	93.2	33	297.0	297.0	32.0
6.4	93.2	33	297.0	297.2	32.0
6.5	93.7	33	297.0	297.2	32.2
6.6	93.8	33	297.0	297.5	32.2
6.7	93.7	33	296.5	297.5	32.2
6.8	93.4	33	296.0	297.4	32.2
11.1	147.2	50	298.2	298.7	33.1
11.2	146.6	50	296.8	298.5	33.1
11.3	146.6	50	297.0	298.5	33.1
11.4	146.9	50	296.9	299.2	33.1
11.5	146.6	50	297.0	299.0	33.0
11.6	146.8	50	296.5	300.0	33.0
11.7	146.9	50	297.0	300.0	33.0
11.8	147.1	50	297.5	300.0	33.0
12.1	148.2	50	299.7	299.9	33.0
12.2	146.8	50	297.0	300.0	33.0
12.3	146.8	50	297.0	299.8	33.0
12.4	146.7	50	296.8	299.3	33.0
12.5	146.6	50	296.3	298.7	33.1
12.6	146.6	50	296.9	298.8	33.1
12.7	146.5	50	296.6	298.8	33.1
12.8	147.6	50	298.5	299.1	33.1

Table 4. Dimensional data for Vencel Resil specimens

Vencel Resil data									
Specimen details as measured at NPL on 21 Jan 1998									
25 mm thick specimens					50 mm thick specimens				
Spec.	Mass g	Width mm	Breadth mm	Density kg/m ³	Spec.	Mass g	Width mm	Breadth mm	Density kg/m ³
13.1	184.8	612.0	612.0	19.7	21.1	372.2	612.0	612.0	19.9
14.1	188.7	612.0	612.0	20.2	22.1	376.5	611.0	612.0	20.1
15.1	186.5	612.0	612.0	19.9	23.1	376	612.0	612.0	20.1
16.1	183.5	612.0	612.0	19.6	24.1	376.9	612.0	612.0	20.1
17.1	101.5	450.0	450.4	20.0	21.2	89.7	304.8	304.8	19.3
17.2	100.6	450.0	450.2	19.9	21.3	94.2	304.0	304.7	20.3
17.6	20	199.0	199.5	20.2	21.4	96.3	304.7	305.0	20.7
17.7	19.7	199.1	199.5	19.8	21.5	89.4	304.0	305.0	19.3
17.8	19.7	199.5	199.7	19.8	21.6	91.4	304.3	305.0	19.7
17.9	19.8	199.0	199.3	20.0	22.2	91.2	304.6	304.6	19.7
17.1	19.8	199.5	199.5	19.9	22.3	94	305.0	305.0	20.2
13.2	46.4	304.8	305.0	20.0	22.4	95.1	304.8	305.2	20.4
13.3	47.1	304.9	305.0	20.3	22.5	90.9	303.8	305.0	19.6
13.4	46.6	304.8	305.0	20.1	22.6	92.2	304.4	304.9	19.9
13.5	45.9	304.5	305.0	19.8	23.2	92	304.5	304.5	19.8
13.6	46	304.0	305.0	19.8	23.3	95.3	304.2	305.0	20.5
14.2	47.3	304.5	304.6	20.4	23.4	96.2	305.0	305.0	20.7
14.3	46.8	305.0	305.0	20.1	23.5	93.5	303.8	304.8	20.2
14.4	47.3	304.5	305.0	20.4	23.6	95.9	304.1	304.9	20.7
14.5	45.7	303.8	305.0	19.7	24.2	90.2	304.5	305.0	19.4
14.6	45.6	304.0	304.5	19.7	24.3	97.6	304.5	305.0	21.0
15.2	47.9	304.8	304.9	20.6	24.4	100.1	304.7	304.7	21.6
15.3	46.8	304.7	305.0	20.1	24.5	91.3	303.7	304.7	19.7
15.4	46.9	305.0	305.0	20.2	24.6	94.7	304.2	304.5	20.4
15.5	46	304.2	305.0	19.8	25.1	198.2	450.0	450.0	19.6
15.6	45.6	304.0	304.7	19.7	25.2	197.1	450.0	450.4	19.4
16.2	45.8	305.0	305.0	19.7	25.3	90.1	304.5	305.0	19.4
16.3	45.4	305.0	305.1	19.5	25.4	91.5	304.8	305.0	19.7
16.4	45.7	304.8	305.0	19.7	25.5	92.3	304.5	305.1	19.9
16.5	45	304.3	304.8	19.4	25.6	38.2	199.0	199.2	19.3
16.6	44.4	304.0	304.9	19.2	25.7	39.2	199.2	199.2	19.8
17.3	45.7	305.0	305.0	19.7	25.8	39.3	199.0	199.0	19.8
17.4	45.5	305.0	305.0	19.6	25.9	39.9	199.0	199.2	20.1
17.5	45.9	305.0	305.0	19.7	25.10	40	199.2	199.5	20.1

4 SCOPE AND PARTICIPANTS

As a result of prior knowledge of those having apparatus, plus a response to a press release outlining the exercise, a total of 17 organisations were invited and subsequently agreed to participate in the heat flow meter inter-comparison. Similarly all UKAS accredited laboratories were invited and all agreed to participate in the guarded hot plate inter-comparison. Table 5 lists all the participating organisations including the principal investigator involved in the measurements.

The plan was to carry out two separate series of measurements on each of the 3 materials at two thicknesses at one or more temperatures in the approximate range 10°C to 25°C.

- a) In the first series of measurements NPL carried out a comprehensive series of measurements at three mean temperatures in the above range with a repeat measurement at one of the temperatures. In addition, due to the density variations in the mineral fibre material, measurements were made on two additional specimens of this material to determine the variation of thermal conductivity with density over a limited density range. The results of the series of measurements provided baseline data for a comparison with all of the other guarded hot plate data and the heat flow meter data obtained in the two inter-comparisons. It is not intended to infer that the NPL guarded hot plate values are exact or the most accurate. They are used only to provide information on which a valid comparison of other apparatus can be undertaken.
- b) The second series of measurements would be carried out by all the other participants using their respective methods. One measurement plus a repeat was requested at a mean temperature of either 10°C or 23°C with an approximate temperature difference of 20°C to 25°C across the specimen. For those organisations having heat flow meter apparatus with fixed temperature conditions, two separate measurements were requested at the particular condition. Those having apparatus with variable conditions were requested to undertake two measurements at a mean temperature of either 10°C or 23°C and given the option of also carrying out an additional set of measurements at the alternative mean temperature.

Two organisations each requested that two different apparatus be included since 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 and to ensure that all known apparatus could be evaluated.

To ensure anonymity each participating organisation was identified with a single code number. Table 6 lists the participants in the heat flow meter intercomparison by code and contains relevant details concerning the heat flow meter apparatus type, size and manufacturer where appropriate.

Table 5. List of Organisations Participating in the Inter-Comparisons

Organisation	Location	Principal Investigator
Heat flow meters		
Blagden Chemicals Ltd.	Sully, South Glamorgan	D. Johnstone
British Gypsum-Isover	Runcorn, Cheshire	J. Christopher
Callenders Ltd.	Basildon, Essex	N. Heath
Cape Insulations Products Ltd	Washington Tyne & Wear	A. Charlton
Celotex Ltd.	Hadleigh, Essex	R. Dakin
Dow Chemicals UK Ltd.	Kings Lynn, Norfolk	R. Foster
Gearing Scientific	Ashwell, Herts	J. Gearing
ICI Polyurethanes	Shepton Mallet, Somerset	D. Entwistle
Montell Carrington Ltd.	Carrington, Lancs.	R. Harcourt
Moy-Isover Ltd.	Clonmel, Co. Tipperary	M. O'Reilly
National Physical Laboratory	Teddington, Middx.	D. Salmon
Nortest	Castle Ashby, Northants.	B. Robson
Owens Corning Building Products UK Ltd.	St. Helens, Lancs	A. Aindow
Owens Corning Polyfoam UK Ltd.	Hartlepool	D. Baggett
Rockwool Ltd.	Bridgend, Mid. Glam.	A. Birtchnell
Superglass Insulation Ltd.	Stirling, Scotland	N. Adam
Vencel Resil Ltd.	Belvedere, Kent	M.E. Tanner
Guarded hot plate		
British Board of Agrment	Watford, Hertfordshire	J. Denyer
Marley Building Materials	Coleshill, Birmingham	P. Primmer
Stanger Testing Services Ltd.	Whiteinch, Glasgow	S. Burn
Building Investigation and Tesing Services Ltd.	Redhill, Surrey	R. Collins
H + H Celcon	Ryarsh, Kent	G. Pye / Doug Harris
National Physical Laboratory	Teddington, Middx.	D. Salmon
University of Salford	Salford, Lancs.	A. Simpson

Table 6. Details of Participants' Heat Flow Meter Apparatus

<u>Participant No.</u>	<u>Apparatus Size, mm</u>	<u>Fixed (F) or Variable (V)</u> <u>Mean Temperature</u>	<u>Manufacturer & Type*</u>
1.	305x305	V	A, Lambda 2300F
2.	305x305	V	A, Lambda 2300F
3.	305x305	V	A, Lambda 2300F
4.	305x305	F(10)	D
5.	610x610	F(10)	In house method
6.	305x305	F(10)	A, K-Matic
7.	305x305	F(10)	A, K-Matic
8.	305x305	F(10)	A, K-Matic
9.	305x305	V	A, Rapid-K
10.	305x305	F(10)	A, K-Matic
11.	305x305	V	B, Fox 304
12a	305x305	F(10)	D
12b	450x450	F 24	In-house
13a	305x305	V	A, Rapid-K
13b	200x200	F(24)	C, Model 888
14.	200x200	F(24)	C, TCA-8
15.	450x450	F(24)	D
16.	200x200	V	B, Fox 200
17.	610x610	V	B, Fox 600 (special features)

*A Dynatech Corp - now Holometrix Inc.

B Lasercomp Inc.

C Anacon Inc.

D Yarsley Test Laboratories

5 MEASUREMENT PROTOCOL

Each participant was provided with a specimen or specimen pair of the required size(s) for their particular apparatus. Table 7 contains identification and specimen details of each participant.

Table 7. Identification of specimens supplied to partners

305 mm samples						
Lab	Dow, 33	Dow, 50	VR, 25	VR, 50	R'wool, 30	R'wool, 50
1	6.5	12.2	14.6	23.4	34.5	38.4
2	5.1	12.3	15.2	23.5	34.6	38.3
3	6.3	11.8	14.4	23.2	34.3	38.6
4	6.2	11.7	14.3	22.6	34.2	38.7
6	5.8	11.1	13.6	22.4	33.8	39.1
7	5.2	12.4	15.3	23.6	34.7	38.2
8	5.7	11.2	13.5	22.3	33.7	39.2
9	5.5	11.4	13.3	21.6	33.5	39.4
10	5.3	12.5	15.4	21.5	34.8	38.1
11	6.4	12.1	14.5	23.3	34.4	38.5
12	6.1	11.6	14.2	22.5	34.1	38.8
13	5.6	11.3	13.4	22.2	33.6	39.3
16	1.2.1	8.2.1	17.8	25.6	30.2.4	35.2.2
17	6.7/6.8	12.7/12.8	16.2/16.3	21.3/21.4	33.1/33.2	39.7/39.8
18	5.4/6.6	11.5/12.6	15.5/15.6	24.2/24.3	33.3/33.4	39.5/39.6
19	1.2.4/1.2.3	8.5.2/8.2.3	16.4/16.6	24.4/24.5	30.2.2/30.2.3	35.2.3/35.2.4
21	6.7/6.8	12.7/12.8	17.4/17.5	21.3/21.4	33.6/33.8	39.5/39.6
22	2.2.1/2.2.2	8.1.1/8.1.2	16.6/17.3	21.5/24.6	33.3/33.4	39.1/39.3
23	2.2.3/2.2.4	8.1.3/8.1.4	16.2/16.3		33.1/33.2	39.7/39.8
200 mm samples						
13	4.3	10.3	17.7	25.9	32.4	37.4
14	4.4	10.4	17.6	25.10	32.3	37.3
450 mm and 500 mm samples						
15	4.1	10.1	17.1	25.1	32.1	37.1
20	3.1/3.2	9.1/9.2	18.1/18.2	26.1/26.2	31.1/31.2	35.1/36.1
610 mm samples						
5	2.1	7.2	14.1	22.1	31.2	36.1
12	1.1	7.1	13.1	21.1	30.1	36.2
17	3.2	8.1	16.1	24.1	31.1	35.1

In order to minimise possible effects of different operational procedures, the following standard

test protocol was provided for each participant to follow.

TEST PROTOCOL FOR INTERCOMPARISONS

General Requirements

Separate specimens or specimen pairs will be supplied from the material listed in Table 1. Keep all the specimens in a temperature and humidity controlled environment to minimise moisture pick up until they are tested. If possible measure each specimen at 10 °C and 23 °C. It is realised that this means 12 measurements, if this is not possible then the order for reducing the number of tests is as follows:-

1. measure at one temperature only. NPL will characterise all the materials to allow normalisation of all results to a single temperature (6 tests).
2. measure MFB specimens plus either the EXPS or EPS specimens at one temperature (4 tests).
3. measure specimens from each product type at one temperature and one thickness only (3 tests). This is the minimum number of tests to participate in the exercise.

Return measurement results to D. R. Salmon at NPL.

Retain specimens until the analysis of the results has been completed in case repeat measurements are required.

Measurement Procedure

1. Measure and record density in accordance with current standards (BS EN 1602:1996)
2. Where relevant to the heat flow meter apparatus calibrate with the usual reference material(s) to determine the calibration constants at the respective mean temperatures and specimen thicknesses.
3. Insert the specimen or specimen pair into the apparatus, aligning reference mark with the direction of heat flow.
4. Set apparatus to desired thickness or measure the thickness at which the plates are in good contact with the specimen surfaces.
5. Take measurements of thermal conductivity allowing specimen to attain equilibrium in accordance with ISO 8302 or ISO 8301 as appropriate.
6. Calculate the apparent thermal conductivity (and/or thermal resistance) for the specimen pair.
7. Remove the specimen from the apparatus.
8. After at least a 2 hour interval, replace the specimen in the apparatus in the same orientation.
9. Repeat steps 3 to 7.
10. Re-weigh specimens and check dimensions.
11. Dry MFB specimens and determine oven dry density.

Reporting of Results

Provide a report to NPL containing all the measured and calculated data including at least the following items:

1. Specimen mass, dimensions and density
2. Measured power
3. Hot and cold face temperatures
4. Thermal conductivity values
5. Mass of oven dried specimen (MFB only)
6. Measurement uncertainty
7. Brief description of the salient features of the apparatus

Each participant is requested to adhere to this protocol and the basic requirements of ISO 8301 or ISO 8302 as far as possible while following the recommended operational procedure of the apparatus.

6 RESULTS

6.1 GUARDED HOT PLATE

The results of the measurements are separated into two sets. The first, shown in Table 8 and Figure 1 and Figure 2, includes all measurements undertaken by NPL on each material. These cover both the total temperature range for each specimen and the density range for the mineral fibre board. The data shown in Figures 1 and 2 were used subsequently for making the necessary temperature and/or density adjustments to all of the other data points from the participants in each intercomparison.

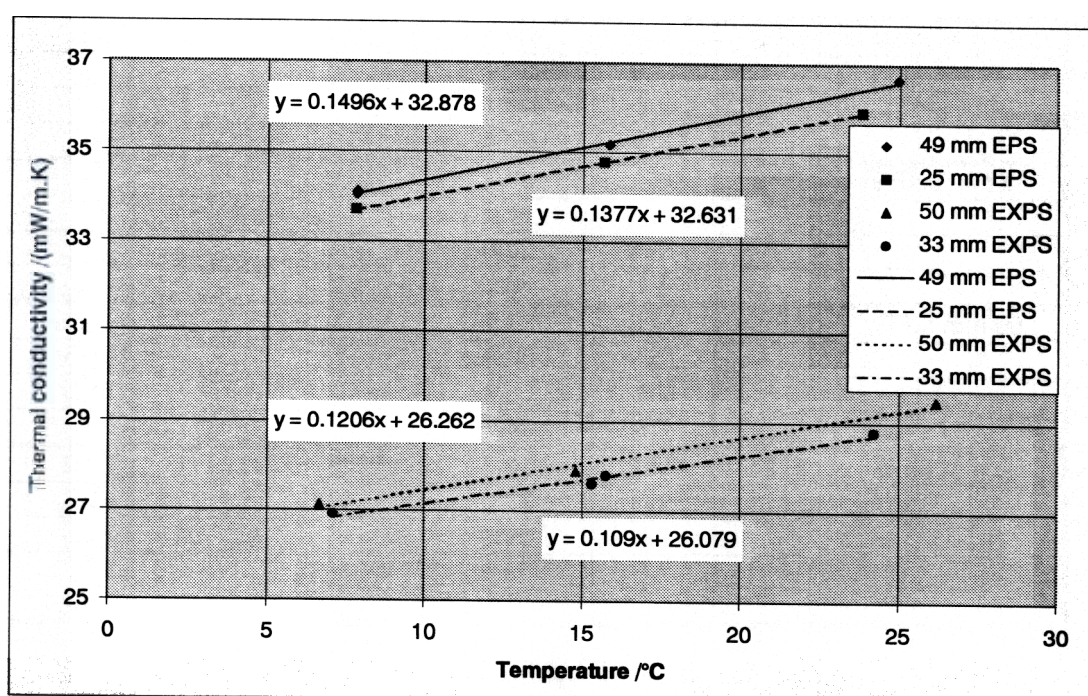


Figure 1. NPL thermal conductivity values for thick and thin EPS and EXPS.

The adjustment procedure was accomplished first by making a temperature correction based on a best-fit straight line obtained through the data as shown in Figure 1 and Figure 2 for the EPS and EXPS, and MFB respectively. The equations for each material are also included in the respective figures.

The thermal conductivity of the MFB was calculated at temperatures of 10°C, 15°C, 19°C and 24°C from the fit in Figure 2. These values were then normalised to a density of 193 kg/m³ and plotted against density to give the percentage variation with density. Using this density correction the raw NPL guarded hot plate results were then normalised to a density of 200 kg/m³ and plotted in Figure 2 to form the baseline for the comparison of all other results. The information obtained from Figure 2 shows that the thermal conductivity of this batch of MFB varies by 0.12% per kg/m³ as shown in Figure 3. Similarly, the relevant values for EPS and EXPS in Figure 1 are used subsequently for all comparison purposes,

Table 8. NPL guarded hot plate results.

Specimen	First test			Repeats		
	Density	Mean test	Thermal conductivity	Density	Mean test	Thermal conductivity
	kg/m ³	/°C	/(mW/m.K)	kg/m ³	/°C	/(mW/m.K)
50 mm EPS	20.8	25.0	36.6			
		15.8	35.			
		7.9	34.1			
		7.9	34.0			
25 mm EPS	20.1	23.9	35.9			
		15.7	34.8			
		7.8	33.7			
50 mm EXPS	32.9	26.2	29.5			
		14.8	27.9			
		6.7	27.1			
		6.7	27.1			
33 mm EXPS	32.6	24.2	28.8			
		15.3	27.6			
		15.8	27.8			
		7.1	26.9			
50 mm MFB	210.3	24.3	37.9	202.6	24.1	37.5
		15.9	36.8		15.9	36.5
		7.9	35.8		8.0	35.5
		7.8	35.7			
30 mm MFB	212.8	23.3	38.2	193.5	23.4	37.2
		15.4	37.2		15.4	36.3
		7.4	36.3		8.3	35.5
		7.3	35.9			

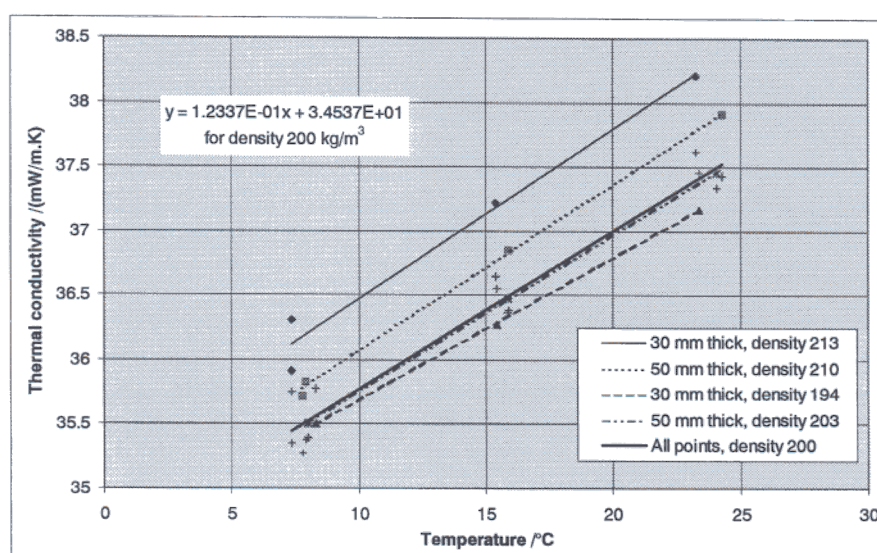
**Figure 2. NPL thermal conductivity values for mineral fibre board.**

Table 9. Guarded hot plate results from each laboratory for thick specimens

Material	Lab.	Density /(kg/m ³)	Mean Temp /°C	Thermal conductivity /(mW/m.K)	% diff from NPL
EPS 49 mm thick	18	20.6	10.0	34.6	0.5
	18		22.6	36.2	-0.2
	19	21.0	10.0	34.0	-0.9
	19		23.4	36.0	-1.0
	20	21.1	23.6	36.3	-0.3
	21	19.5	10.0	36.1	4.9
	22	20.2	11.6	34.4	-0.6
	23	19.8	8.8	33.2	-2.9
EXPS 50 mm thick	18	32.9	9.9	27.1	-1.3
	18		22.9	28.6	-1.5
	19	32.9	10.2	28.1	0.4
	19		23.0	30.0	0.3
	20	32.7	22.9	30.7	-0.6
	21	32.7	10.0	29.9	1.8
	22	32.9	10.5	29.5	0.3
	23	32.9	9.1	27.4	-6.5
MFB 49 mm thick	18	210	9.6	35.4	-2.1
	19	198.6	10.0	34.8	-2.5
	20	213	22.7	37.5	-1.1
	21	203.7	10.0	36.6	2.0
	22	217	10.2	37.0	1.3
	23	202.9	9.2	35.6	-0.6

The second set of data shown in Table 9 and Table 10 provides the individual results of all the other participants identified as laboratories 18 to 23. It includes in the last column the percentage differences from the NPL values derived at each temperature from the least squares fit data in Figure 1 and Figure 2 and allowing for the density adjustment for the mineral fibre board specimens to 200 kg/m³ and for the effects of ageing of the 50 mm thick EXPS, see Discussion.

Table 10. Guarded hot plate results from each laboratory for thin specimens

Material	Lab	Density /(kg/m ³)	Mean Temp /°C	Thermal conductivity /(mW/m.K)	% diff from NPL
EPS 25 mm thick	18	19.7	10.5	34.4	0.9
	19	19.9	10.1	34.0	-0.2
	19		23.1	35.7	-0.3
	21	20.0	10.1	34.6	1.7
	23	20.0	9.3	33.0	-2.7
EXPS 33 mm thick	18	32.5	10.1	26.9	-1.0
	19	32.4	23.0	28.4	-0.7
	21	32.3	10.1	27.9	2.6
	23	32.6	9.4	27.2	0.4
MFB 30 mm thick	18	192.5	9.50	35.30	-0.3
	19	197.2	23	37.20	-0.1
	21	194.0	10.03	35.43	-0.3
	23	208.4	9.4	35.30	-2.1

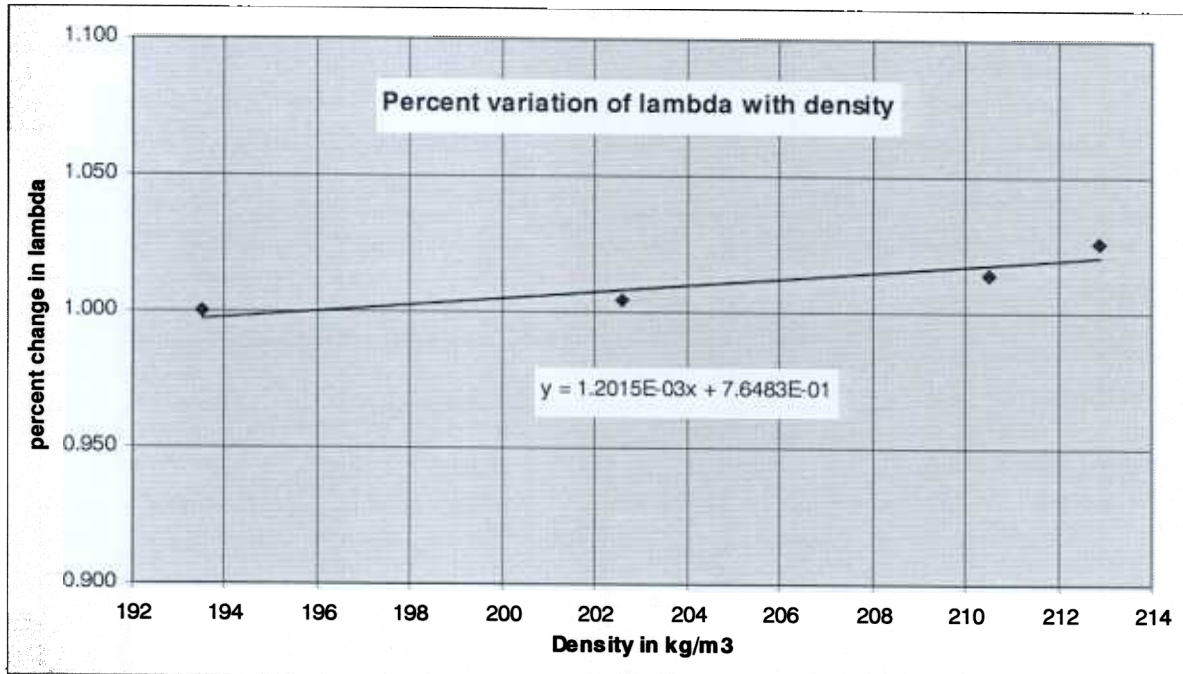


Figure 3. Percentage change in thermal conductivity of rockwool as a function of density.

6.2 HEAT FLOW METER

The heat flow meter results for the thin and thick specimens of EPS, EXPS and Rockwool are tabulated in Table 11 and Table 12, Table 13 and Table 14, and Table 15 and Table 16 respectively. 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 outlined in Section 5.1. For rockwool, a density correction to 200 kg/m³ has also been included. The tables also include the percentage differences in value between the measured values at about 10°C and 23°C and the values obtained using the NPL guarded hot plate data Figure 4 and Figure 5, Figure 6 and Figure 7, and Figure 8 and Figure 9 contain the respective results for the thin and thick EPS, EXPS and rockwool specimens. Each figure contains for comparison the curve fitted to the NPL guarded hot plate measured thermal conductivity values.

Table 11. Heat flow meter results for 25 mm thick expanded polystyrene.**Mean temperature 10°C**

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc λ	% diff.
number	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m.K)	/(mW/m.K)	
1	14.6	25.00	19.70	0.1	20.0	10.1	33.50	34.01	-1.51
2	15.2	25.00		0.2	20.2	10.2	33.23	34.04	-2.38
3	14.4	24.90	20.40	0.1	19.9	10.0	32.59	34.01	-4.17
4	14.3	25.00	20.10	0.5	19.9	10.2	34.50	34.04	1.36
6	13.6	25.00	19.94	0.7	18.7	9.7	35.00	33.97	3.04
7	15.3	25.03	20.20	0.9	20.1	10.5	34.05	34.07	-0.07
8	13.5	25.00	19.70	0.0	20.0	10.0	34.80	34.01	2.33
9	13.3	25.30	20.40	3.2	21.7	12.5	34.30	34.35	-0.13
10	15.4	25.10	20.15	0.4	20.9	10.7	35.30	34.10	3.53
11	14.5	25.00	19.60	-3.0	23.0	10.0	33.50	34.01	-1.49
12	13.2/14.2	24.60	20.45	2.6	18.7	10.6	32.95	34.09	-3.35
13	13.4	24.70	20.50	-2.0	19.7	8.8	32.15	33.85	-5.01
16	17.8	24.91		0.0	20.0	10.0	34.22	34.01	0.62
17	16.1	24.58	20.00	0.0	20.0	10.0	33.89	34.01	-0.36

Mean temperature 24°C

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc λ	% diff.
number	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m.K)	/(mW/m.K)	
2	15.2	25.30		14.3	34.3	24.2	35.79	35.96	-0.48
3	14.4	24.90	20.40	13.3	33.1	23.2	34.35	35.82	-4.11
9	13.3	25.30	20.40	10.0	37.0	23.5	35.35	35.87	-1.44
11	14.5	25.00	19.60	10.0	36.0	23.0	34.90	35.80	-2.51
12	13.1/17.2	24.60	20.05	12.8	34.9	23.8	35.80	35.91	-0.31
13	13.4	24.70	20.50	10.2	37.4	23.8	35.20	35.91	-1.97
13	17.7	24.96	19.90	10.2	37.8	24.0	33.35	35.94	-7.20
14	17.6	24.90	20.00	10.0	37.7	23.9	34.35	35.92	-4.36
15	17.1	26.85		15.5	33.9	24.7	37.30	36.03	3.52
16	17.8	24.91		13.0	33.0	23.0	35.79	35.80	-0.03
17	16.1	24.58	20.00	14.03	34.09	24.06	35.67	35.94	-0.76

Table 12. Heat flow meter results for 50 mm thick expanded polystyrene.**Mean temperature 10°C**

Number	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc λ	% Diff
	number	/mm	(kg/m ³)	/C	/C	/C	/(mW/m. K)	/(mW/m.K)	
	23.4	49.50	20.9	-0.2	20.1	10.0	34.35	34.37	-0.06
2	23.5	49.00		-0.2	19.6	9.7	34.29	34.34	-0.14
3	23.2	49.20	20.1	0.0	20.0	10.0	34.01	34.38	-1.09
4	22.6	50.00	19.8	0.2	20.5	10.3	35.80	34.43	3.98
5	22.1	50.80	19.7			9.9	34.73	34.37	1.06
6	22.4	50.20	20.4	0.5	19.8	10.2	36.40	34.40	5.80
7	23.6	49.70	20.9	0.9	20.7	10.8	34.80	34.49	0.89
8	22.3	50.00	20.0	0.0	20.0	10.0	33.60	34.38	-2.27
9	21.6	50.30	19.7	1.7	21.8	11.8	35.55	34.64	2.63
10	21.5	49.90	19.4	0.6	21.1	10.1	36.15	34.50	4.80
11	23.3	49.60	20.5	-3.0	23.0	10.0	34.40	34.38	0.06
12	22.5/25.4	49.50	19.8	1.9	18.9	10.4	34.15	34.44	-0.83
13	22.2	49.80	19.7	-1.5	19.6	9.1	33.70	34.24	-1.57
16	25.6	49.61		0.0	20.0	10.0	35.78	34.38	4.08
17	24.1	48.90	20.5	0.0	20.0	10.0	34.54	34.38	0.46

Mean temperature 24°C

Number	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc λ	% Diff
	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m. K)	/(mW/m.K)	
2	23.5	49.20		14.0	34.2	24.1	36.67	36.48	0.52
3	23.2	49.20	20.1	13.1	33.0	23.0	35.81	36.32	-1.41
9	21.6	50.30	19.7	8.3	36.9	22.6	36.30	36.26	0.12
11	23.3	49.60	20.5	10.0	36.0	23.0	35.40	36.32	-2.53
12	21.1/25.2	49.65	19.7	12.9	34.9	23.9	36.85	36.45	1.10
13	22.2	49.80	19.7	10.1	37.4	23.8	36.70	36.43	0.74
13	25.9	49.71	20.2	10.2	37.8	24.0	32.85	36.47	-9.92
14	25.1	49.70	20.3	10.0	37.7	23.9	35.95	36.44	-1.36
15	25.1	49.70		14.6	33.9	24.3	37.63	36.50	3.08
16	25.6	49.61		13.0	33.0	23.0	36.77	36.32	1.24
17	24.1	48.89	20.5	14.1	34.1	24.1	36.33	36.48	-0.40

Table 13. Heat flow meter results for 33 mm thick extruded polystyrene.**Mean temperature 10°C**

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc lambda	% diff.
Number	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m.K)	/(mW/m.K)	
1	6.5	32.90	32.5	-0.1	20.0	10.0	26.70	27.17	-1.72
2	5.1	32.50		0.0	20.1	10.2	26.82	27.19	-1.38
3	6.3	32.60	32.4	-0.1	19.9	9.9	26.11	27.16	-3.87
4	6.2	33.00	31.3	-0.5	19.2	9.4	27.50	27.10	1.48
5	2.1	33.50	31.6			9.8	26.90	27.15	-0.91
6	5.8	33.00	32.3	0.6	19.4	10.0	28.07	27.17	3.31
7	5.2	32.58	32.6	0.9	20.9	10.9	27.30	27.26	0.13
8	5.7	33.00	30.4	0.0	20.0	10.0	26.90	27.17	-0.99
9	5.5	33.20	32.3	2.1	21.8	11.9	27.05	27.38	-1.20
10	5.3	33.00	32.6	0.6	21.8	11.2	28.05	27.29	2.77
11	6.4	33.00	31.9	-3.0	23.0	10.0	26.60	27.17	-2.09
12	1.2/6.1	32.50	32.6	2.0	18.6	10.3	26.48	27.20	-2.67
13	5.6	32.70	32.4	-1.2	19.6	9.2	25.95	27.08	-4.19
16	1.2/1	32.64		0.0	20.0	10.0	27.56	27.17	1.44
17	3.2	32.54	32.5	20.1	0.0	10.1	27.24	27.17	0.24

Mean temperature 24°C

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc lambda	% diff.
Number	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m.K)	/(mW/m.K)	
2	5.1	32.60		14.3	34.1	24.2	28.675	28.72	-0.15
3	6.3	32.60	32.4	13.2	33.0	23.1	27.62	28.59	-3.41
9	5.5	33.20		8.7	37.0	22.9	27.75	28.57	-2.87
11	6.4	33.00	31.9	10.0	36.0	23.0	27.6	28.59	-3.45
12	1.1/4.2	33.20	31.9	12.9	34.9	23.9	28.4	28.68	-0.98
13	4.3	32.62	32.4	10.2	37.8	24.0	26.05	28.70	-9.22
13	5.6	32.70	32.4	10.0	37.5	23.8	28.25	28.67	-1.46
	4.4	32.43	32.6	10.0	37.7	23.9	27.1	28.68	-5.50
15	1	32.60		14.8	33.9	24.3	29.35	28.73	2.17
16	1.2/1	32.62		13.0	33.0	23.0	28.86	28.59	0.95
17	3.2	32.56	32.5	34.6	14.6	24.6	28.54	28.76	-0.75

Table 14. Heat flow meter results for 50 mm thick extruded polystyrene.**Mean temperature 10°C**

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc Lambda	% diff
Number	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m.K)	/(mW/m.K)	
1	12.2	50.70	32.7	-0.1	20.1	10.0	27.65	27.46	0.67
2	12.3	50.30		0.0	20.0	10.0	27.47	27.47	-0.01
3	11.8	50.40	32.9	-0.2	19.9	9.9	26.61	27.45	-3.07
4	11.7	50.50	32.3	0.5	19.5	10.0	28.35	27.47	3.20
5	7.2	51.50	32.0			10.0	27.27	27.47	-0.75
6	11.1	50.80	32.5	0.7	20.0	10.4	29.10	27.51	5.78
7	12.4	50.53	32.9	0.9	21.0	11.0	27.90	27.58	1.15
8	11.2	50.00	31.4	0.0	20.0	10.0	28.40	27.47	3.39
9	11.4	51.00	32.7	1.5	21.7	11.6	27.80	27.66	0.50
10	12.5	50.80	32.6	0.6	21.1	10.9	28.75	27.57	4.28
	12.1	50.70	32.5	-3.0	23.0	10.0	27.70	27.47	0.84
12	8.2/11.6	50.20	32.8	1.8	18.9	10.3	27.23	27.50	-1.01
13	11.3	50.70	32.6	-1.1	19.8	9.3	27.35	27.39	-0.14
16	8.2/1	50.40		0.0	20.0	10.0	29.13	27.47	6.05
17	8.1	50.39	32.8	0.1	20.0	10.1	28.83	27.47	4.94

Mean temperature 24°C

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Calc Lambda	% diff
Number	number	/mm	/(kg/m ³)	/C	/C	/C	/(mW/m.K)	/(mW/m.K)	
2	12.3	50.40		13.9	34.1	24.0	29.31	29.16	0.53
3	11.8	50.40	32.9	13.1	33.2	23.1	28.26	29.05	-2.72
9	11.4	51.20	32.7	8.2	37.0	22.6	28.80	28.98	-0.64
12	7.1/10.2	50.40	32.8	12.9	34.9	23.9	29.35	29.14	0.72
13	10.3	50.45	32.7	10.2	37.8	24.0	26.85	29.16	-7.91
13	11.3	50.70	32.6	9.8	37.6	23.7	29.00	29.12	-0.41
14	10.4	50.23	33.1	10.0	37.7	23.9	28.70	29.14	-1.50
15	2	50.30		14.3	33.9	24.1	30.30	29.17	3.88
16	8.2/1	50.40		13.0	33.0	23.0	30.74	29.04	5.87
17	8.1	50.39	32.8	34.1	14.1	24.1	30.30	29.16	3.89

Table 15. Heat flow meter results for 32 mm thick rockwool.**Mean temperature 10°C**

	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Lambda (200)	Calc lambda	% Diff
number	number	/mm	/(kg/m ³)	/C	/C	/C	/(W/m.K)	/(W/m.K)	/(W/m.K)	
1	34.5	31.8	198.0			10.1	34.75	34.83	35.78	-2.65
2	34.6	32.1	211.2			10.1	34.90	34.43	35.78	-3.78
3	34.3	32.4	200.9	-0.1	19.7	9.8	35.10	35.06	35.75	-1.92
4	34.2	31.0	185.2			10.2	36.60	37.25	35.79	4.08
5	31.2	32.5	192.5			9.6	35.13	35.45	35.72	-0.76
6	33.8	32.9	177.0			10.1	36.50	37.51	35.78	4.84
7	34.7	29.9	187.9			11.0	34.95	35.46	35.89	-1.20
8	33.7	30.0	199.4	0	20	10.0	33.70	33.72	35.77	-5.72
9	33.3	32.0	186.0			12.2	34.00	34.57	36.04	-4.07
10	34.8	30.9	193.8			11.1	37.15	37.43	35.90	4.24
11	34.4	32.6	181.3	-3	23	10.0	35.00	35.79	35.77	0.04
12	30.2/34.1	32.3	180.0			10.6	36.30	37.17	35.85	3.69
13	33.6	31.7	209.4			8.9	35.75	35.35	35.64	-0.81
16	30.2/4	31.4	189.6	0.01	20.01	10.0	35.46	35.90	35.77	0.37
17	31.1	32.1	193.8	20.04	0.04	10.0	35.27	35.53	35.78	-0.68

Mean temperature 23°C

	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Lambda (200)	Calc lambda	% Diff
number	number	/mm	/(kg/m ³)	/C	/C	/C	/(W/m.K)	/(W/m.K)	/(W/m.K)	
2	34.6	32.2	210.5			24.0	36.66	36.20	37.50	-3.47
3	34.3	32.4	200.9	13.3	33.1	23.2	36.62	36.58	37.40	-2.19
9	33.3	32.0	186.0			23.1	34.50	35.08	37.39	-6.17
11	34.4	32.6	181.3	10	36	23.0	36.20	37.01	37.37	-0.97
12	30.1/32.2	32.5	192.3	12.8	34.9	23.9	36.40	36.74	37.48	-1.98
12	30.2/34.1	32.2	192.3	12.6	34.9	23.8	36.20	36.53	37.47	-2.49
13	32.4	31.3	210.0			24.0	33.95	33.54	37.50	-10.55
13	33.6	31.7	209.4			23.8	38.40	37.97	37.47	1.32
14	32.3	30.7	209.7			23.9	36.60	36.17	37.48	-3.48
15	32.1	31.5	202.2	15.2	33.9	24.6	38.10	38.00	37.57	1.15
16	30.2/4	31.4	189.6	13.03	33.03	23.0	36.76	37.22	37.38	-0.43
17	31.1	32.1	193.8	34.08	14.04	24.1	36.82	37.09	37.51	-1.10

Table 16. Heat flow meter results for 50 mm thick rockwool.**Mean temperature 10°C**

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Lambda(200)	Lambda calc	% diff
number	number	/mm	(kg/m ³)	/C	/C	/C	/(W/m.K)	/(W/m.K)	/(W/m.K)	
1	38.4	51.40	189.0	0.0	20.1	10.1	35.65	36.12	35.78	0.96
2	38.3	50.90	196.2	-0.1	19.8	9.9	34.95	35.10	35.75	-1.81
3	38.6	51.19	194.2	-0.1	19.9	9.9	34.09	34.33	35.76	-4.01
4	38.7	50.00	199.6	0.3	20.4	10.3	36.55	36.57	35.81	2.11
5	36.1	51.00	201.2			9.9	35.33	35.28	35.76	-1.34
6	39.1	51.80	200.6	0.7	19.7	10.2	38.23	38.20	35.80	6.71
7	38.2	48.68	204.2	0.9	21.0	10.9	34.90	34.72	35.88	-3.23
8	39.2	50.00	188.5	0.0	20.0	10.0	32.90	33.35	35.77	-6.76
9	39.4	51.20	223.1	1.9	21.8	11.8	36.15	35.15	36.00	-2.36
10	38.1	51.20	197.4	0.8	21.6	11.2	34.85	34.96	35.92	-2.67
11	38.5	52.00	195.1	-3.0	23.0	10.0	35.90	36.11	35.77	0.95
12	35.2/38.8	53.00	204.5	1.9	18.7	10.3	36.93	36.73	35.81	2.56
13	39.3	50.40	213.6	-1.5	19.7	9.1	33.95	33.40	35.66	-6.35
16	35.2.2	51.21	203.0	0.0	20.0	10.0	35.77	35.64	35.77	-0.37
17	35.1	51.02	201.7	0.04	20.05	10.04	35.56	35.49	35.78	-0.80

Mean temperature 24°C

Lab	Specimen	Thickness	Density	Mean cold	Mean hot	Mean test	Lambda	Lambda(200)	Lambda calc	% diff
number	number	/mm	(kg/m ³)	/C	/C	/C	/(W/m.K)	/(W/m.K)	/(W/m.K)	
2	38.3	51.00	195.8	14.0	34.1	24.0	36.89	37.08	37.50	-1.13
3	38.6	51.26	194.6	13.1	33.1	23.1	35.27	35.50	37.39	-5.06
9	39.4	51.20	223.1	8.5	37.0	22.7	35.45	34.47	37.34	-7.69
11	38.5	52.00	195.1	10.0	36.0	23.0	36.70	36.92	37.37	-1.23
12	35.2/38.8	51.50	198.2	12.8	34.9	23.8	37.25	37.33	37.48	-0.39
13	37.4	49.99	215.0	10.2	37.8	24.0	33.15	32.55	37.50	-13.19
13	39.3	50.40	213.6	10.4	37.4	23.9	34.85	34.28	37.49	-8.55
14	37.3	48.80	213.2	10.0	37.7	23.9	37.55	36.96	37.48	-1.40
15	37.1	49.90	202.3	14.6	33.9	24.3	37.83	37.73	37.53	0.52
16	35.2/2	51.21	203.0	13.0	33.0	23.0	36.85	36.72	37.38	-1.76
17	35.1	51.02	201.7	14.05	34.09	24.07	37.09	37.02	37.51	-1.31

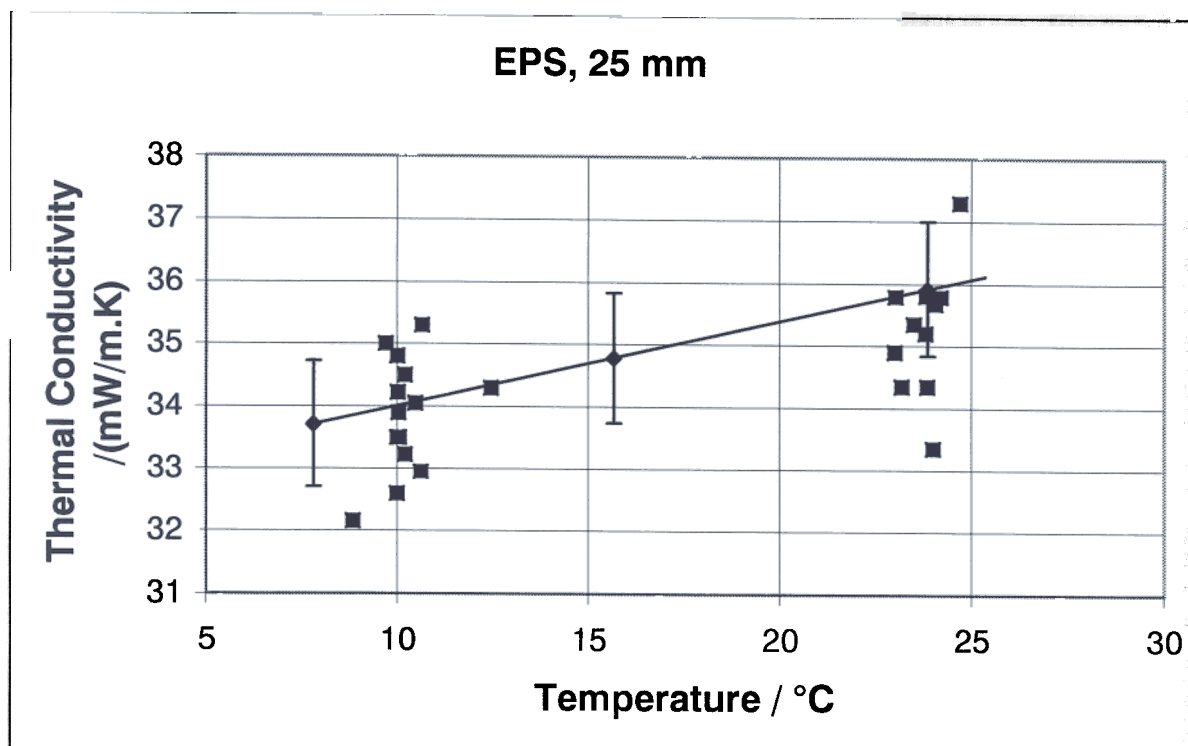


Figure 4. Heat flow meter results for 25 mm thick expanded polystyrene.

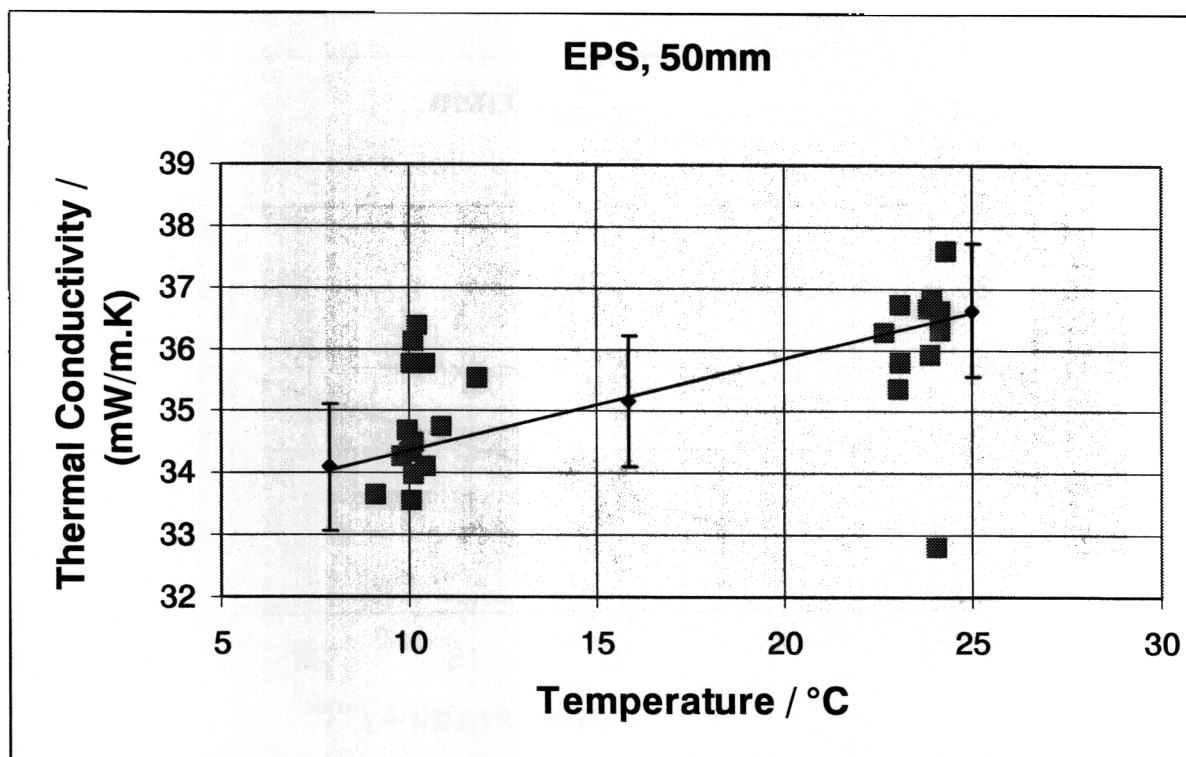


Figure 5. Heat flow meter results for 50 mm thick expanded polystyrene.

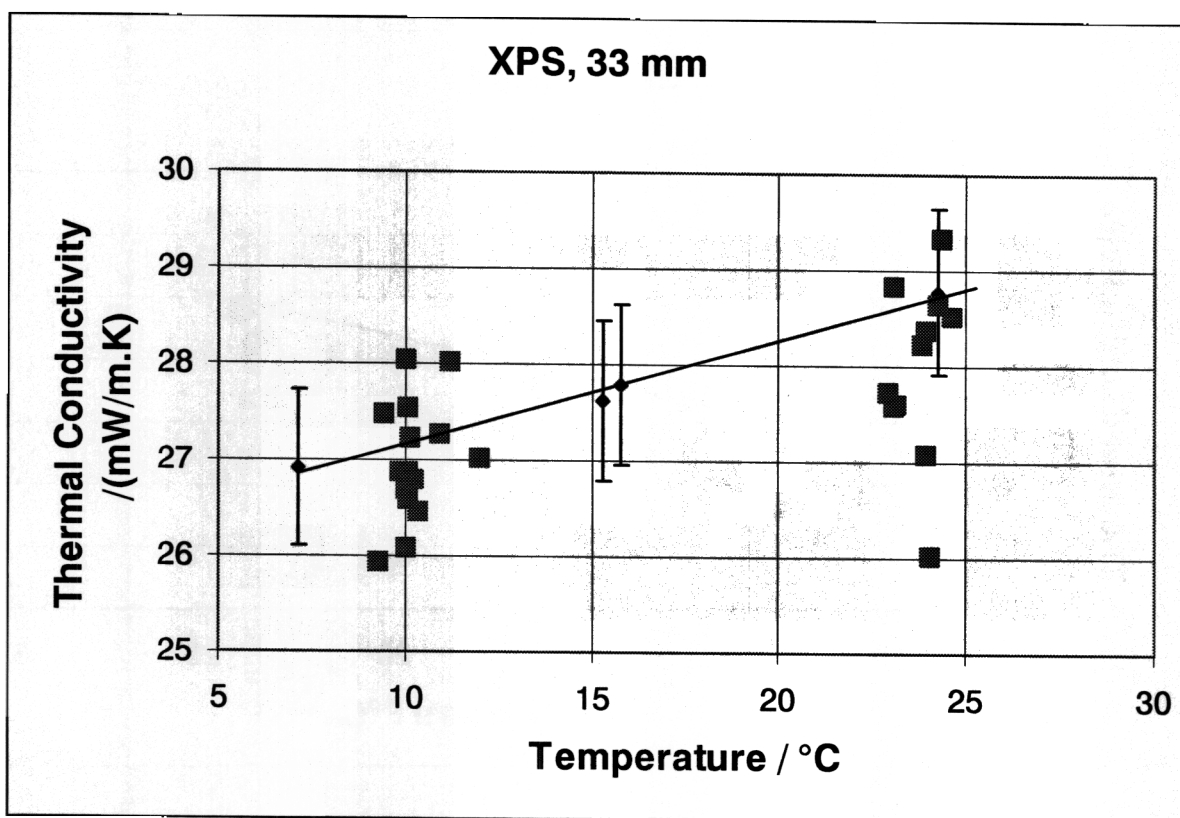


Figure 6. Heat flow meter results for 33 mm thick extruded polystyrene.

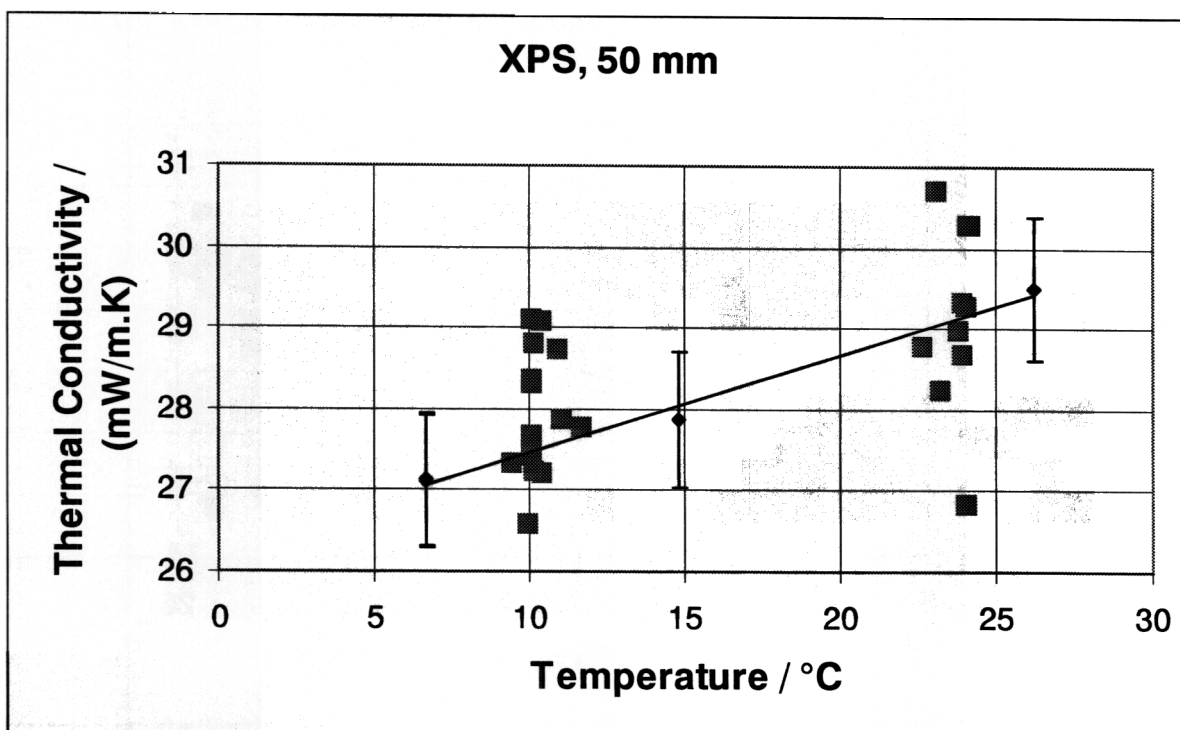


Figure 7. Heat flow meter results for 50 mm thick extruded polystyrene.

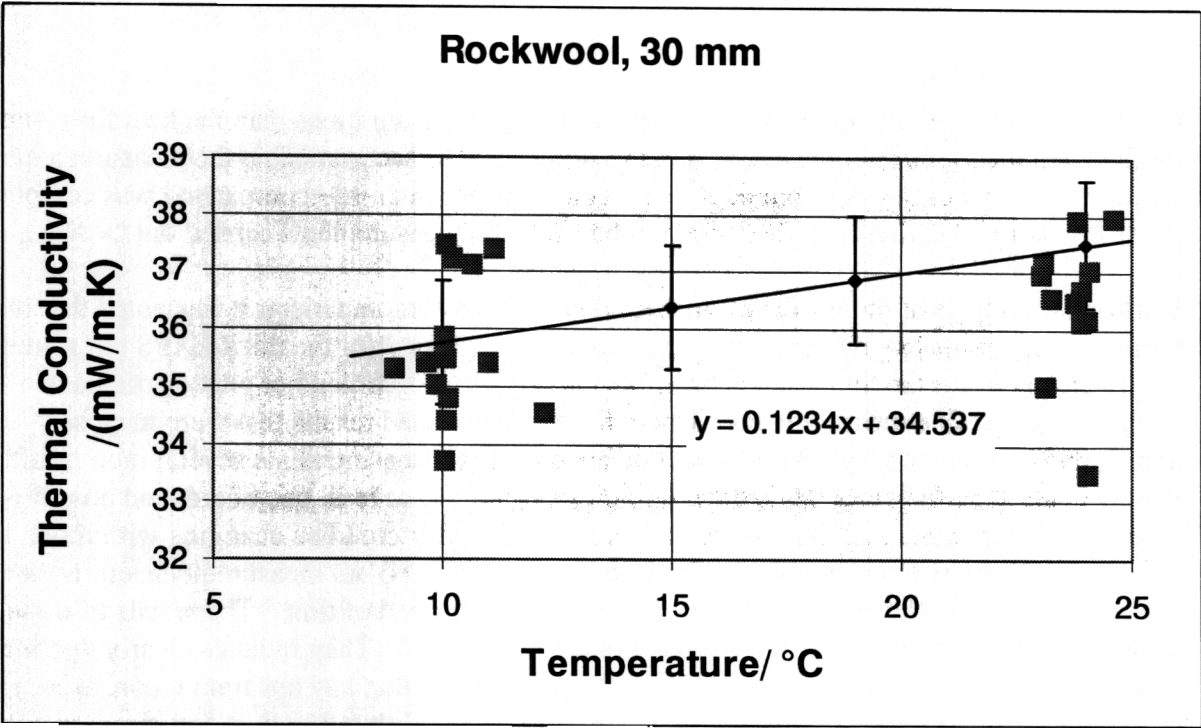


Figure 8. Heat flow meter results for 30 mm thick rockwool normalised to a density of 200kg/m³. 3% error bars shown.

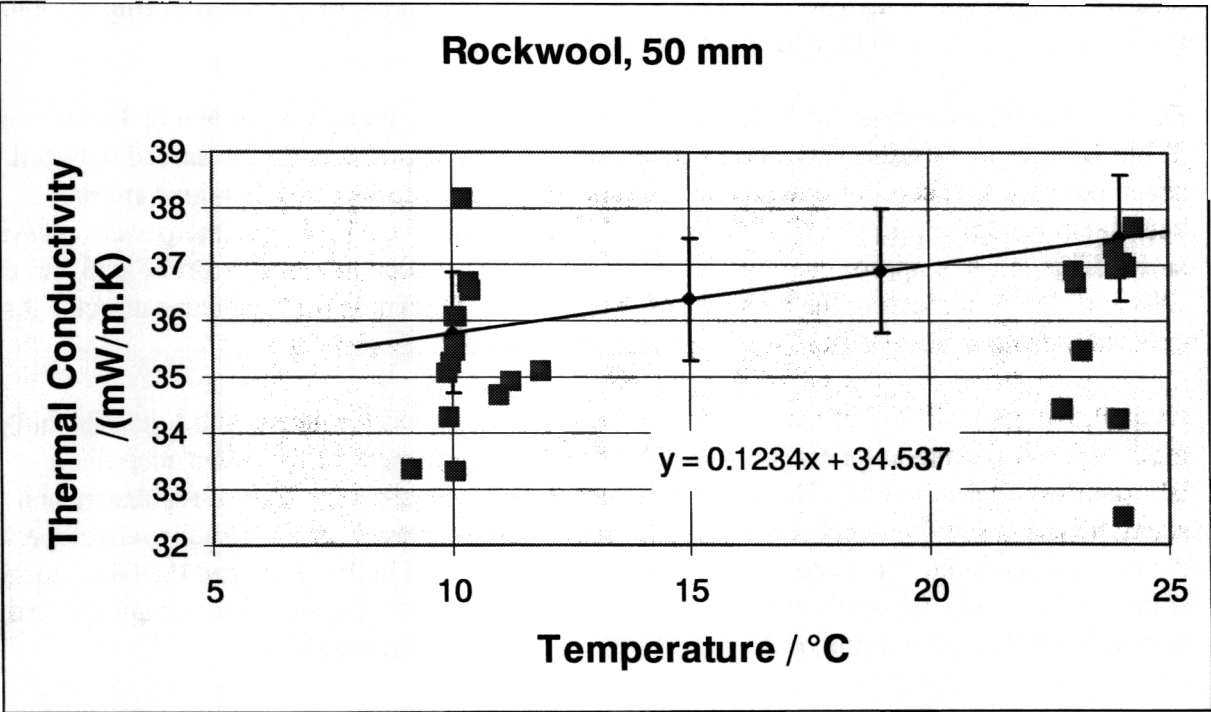


Figure 9. Heat flow meter results for 50 mm thick rockwool normalised to a density of 200kg/m³. 3% error bars shown.

7 DISCUSSION

7.1 GUARDED HOT PLATE

Guarded hot plate measurements have much longer equilibrium times than the heat flow meter method and the organisations involved in the studies had to accommodate the measurements during the course of their normal activities. As a result the later intercomparison was completed much quicker and earlier than the former, other than the measurements carried out by NPL.

During the analysis of the results of the heat flow meter intercomparison it was noted that two participants obtained significantly higher results than expected for the thick EXPS but were in good agreement for the thin specimens of the material. Two guarded hot plate participants carrying out baseline measurements early in the study obtained results that were in close agreement. The former organisations had undertaken their measurements several months after the majority of the participants. Thus the possibility existed that at least one board, and possibly the entire batch of the thick EXPS material differed originally or could be changing with time. As a result, to assist in the analysis of both studies NPL carried out measurements on further specimens cut from the original batch at intervals over a period of time. The results of these measurements are shown in Table 17 and plotted in Figure 10. They indicate clearly that there is a change in thermal property of the thick EXPS with time and that any apparent inconsistency in the guarded hot plate results is probably due to specimen variability rather than any measurement error.

Hence, in order to determine the correct baseline value the dates on which the individual participants undertook the measurements on the material were collated. Then the respective equations provided by Figure 10 were used to obtain the corresponding NPL value at the same date for comparison. The results in Table 9 indicate that, with the exception of a single data point, the differences for the thick EXPS are well within $\pm 2\%$.

Further examination of the collected results for the other five specimens shown in Table 9 and Table 10 indicates similar very good agreement within an approximate $\pm 2\%$ spread between the seven hot plates, except for one isolated data point. In some cases the indications are that agreement is approaching $\pm 1\%$. In addition it is seen that, where both specimens were measured, small differences of approximately 1% or less do occur between the results for the thin and thick EPS and EXPS, indicating the presence of the expected “thickness (or boundary) effect”. As expected, no significant difference is seen for the two MFB specimens.

Overall, the general level of agreement of $\pm 2\%$ that is expected for the standard guarded hot plate method for the temperature range 10 to 25°C has been confirmed for the seven accredited laboratories within the UK. This level of agreement is acceptable for current regulatory and standardisation requirements concerning thermal insulations used for the building envelope within the European Union. Two anomalous data points were found in the study and the laboratories concerned are carrying out further work to identify the possible causes. Also, the unexpected time-dependent behaviour for one of the EXPS materials is being investigated.

Table 17. Variation of the thermal conductivity of the 50 mm thick batch of extruded polystyrene with time

Mean temperature 24 °C		Mean temperature 10°C	
Time	Thermal conductivity	Time	Thermal conductivity
Months	mW/m.K	Months	mW/m.K
3.0	29.22	3.10	27.50
10.3	30.30	10.3	28.83
10.3	30.35		
10.7	30.81	10.6	29.22
10.8	30.79		
14.2	30.74		
14.3	30.73		
14.3	30.74		
15.5	30.93	15.3	29.38

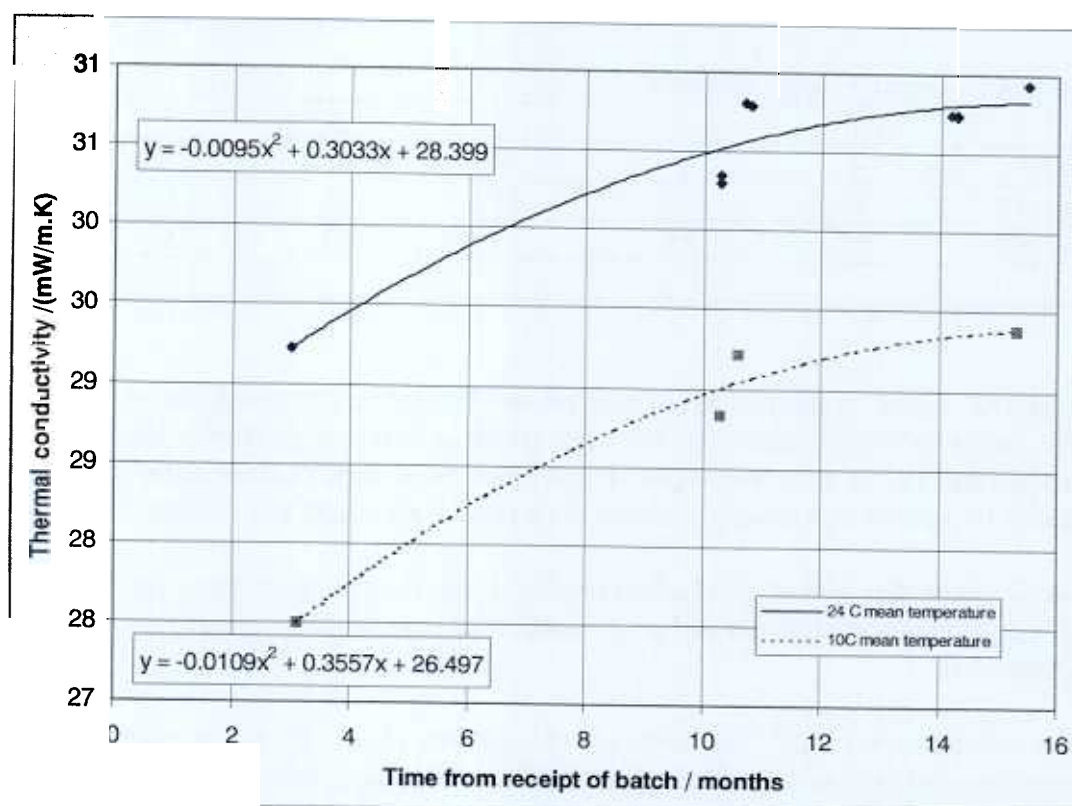


Figure 10. Variation of the thermal conductivity of the 50 mm thick batch of extruded polystyrene with time.

7.2 HEAT FLOW METER

Figure 11, Figure 12 and Figure 13 show the magnitude of the differences from the guarded hot plate baseline values for both thicknesses and temperatures of the EPS, EXPS and Rockwool respectively. An examination of all values for each material indicates that the overwhelming majority is well within $\pm 5\%$ for each. Table 18 summarises this range of agreement. From a total of 154 data points only 20 are outside $\pm 5\%$ while 106 are within $\pm 3\%$ and of the latter 77 are within $\pm 2\%$. If the results from the two non-conforming apparatus are deleted only 11 are outside $\pm 5\%$ while 71 are within $\pm 2\%$. Furthermore the earlier discussion concerning the uncertainty in the values for the board 8 specimens would reduce the number in excess of $\pm 5\%$ to 9.

Table 18. Summary of the deviation of the heat flow meter data points 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						
> ± 5	1	4	1	5	2	6
± 3 to ± 5	6	3	6	4	4	3
Within ± 3	16	17	18	15	16	15
Within ± 2	11	15	14	12	10	10
Excluding non-conforming apparatus						
> ± 5	0	2	0	3	1	4
± 3 to ± 5	6	3	6	6	4	4
Within ± 3	15	17	17	15	16	16
Within ± 2	11	15	13	12	9	9

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 the degree of agreement was found to be essentially within $\pm 3\%$ and in particular in recent comparisons in North America ^(8,9) all results were inside this range.

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

- (a) The existence of a small “thickness effect” is shown clearly by the guarded hot plate measurements on the two cellular plastics. However, these were not exhibited to the same degree by the various heat flow meter apparatus. In a number of cases an effect can be seen but of much greater magnitude than expected or observed in the ghps. Conversely, for

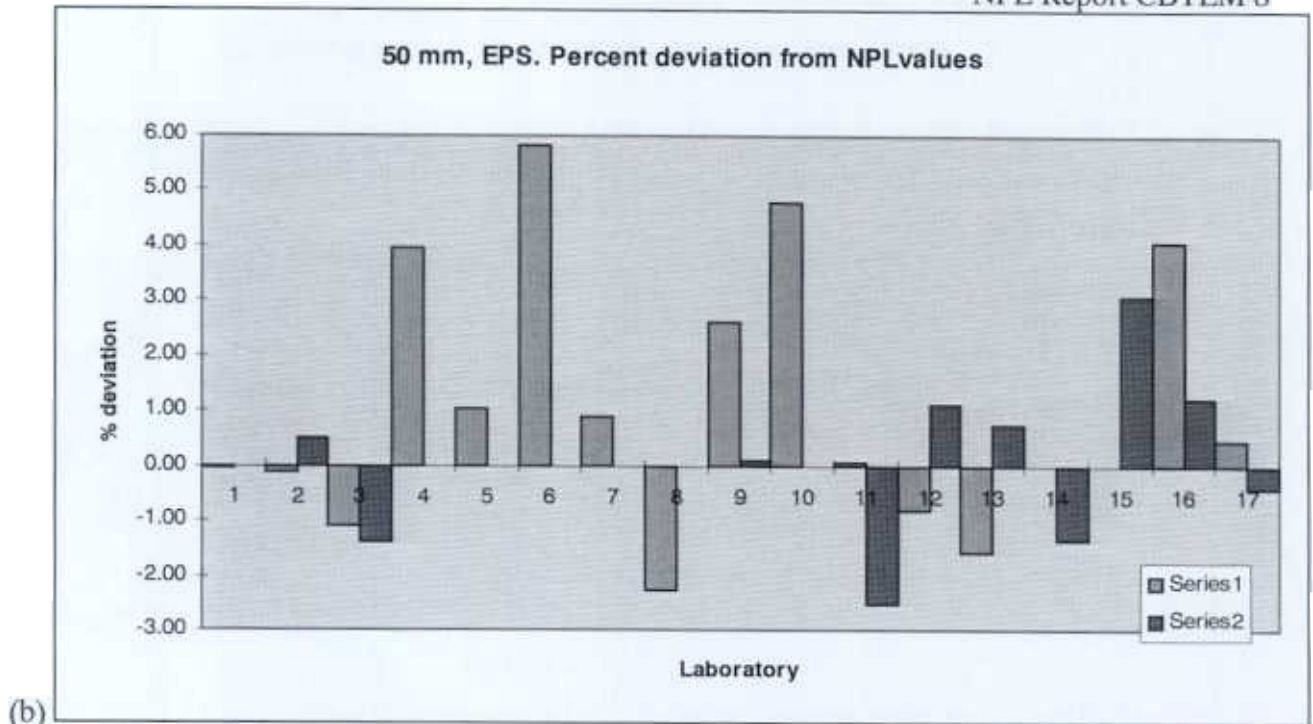


Figure 11. Percent differences from NPL values for 50 mm thick expanded polystyrene results. Series 1 is at a mean temperature of about 10°C and series 2 is at about 23°C.

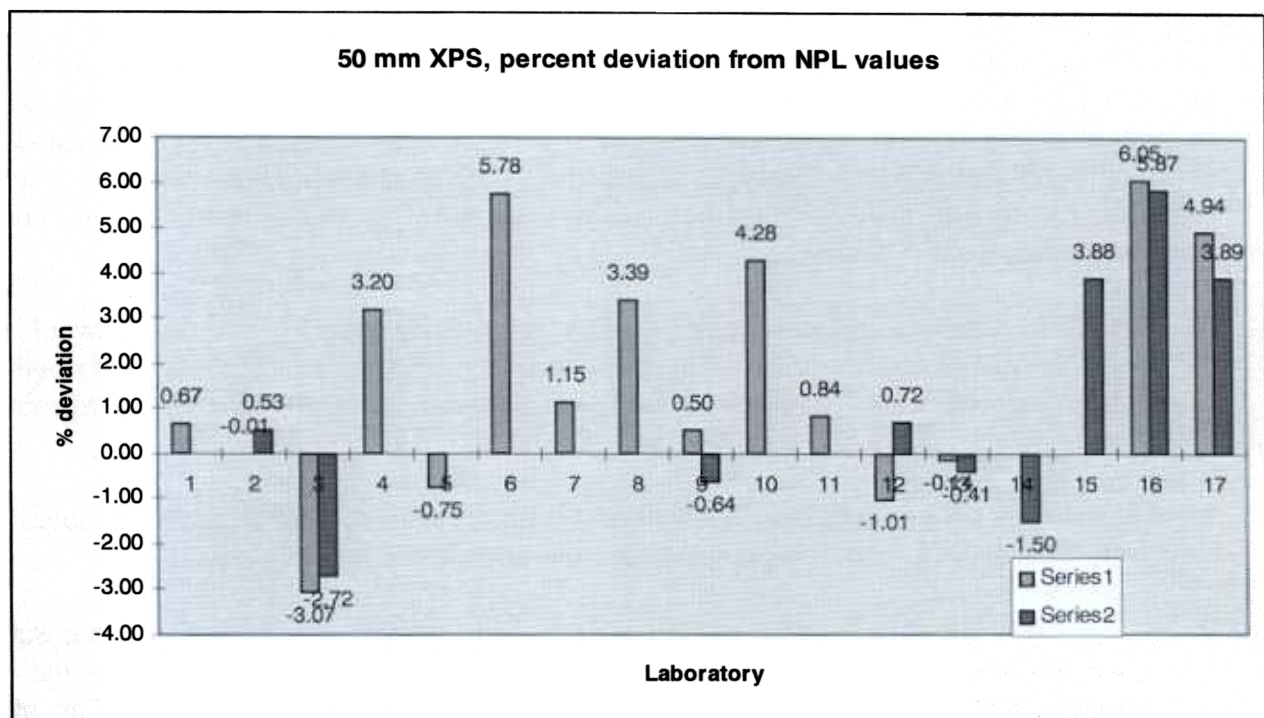


Figure 12. Percent differences from NPL values for 50 mm thick extruded polystyrene results. Series 1 is at a mean temperature of about 10°C and series 2 is at about 23°C.

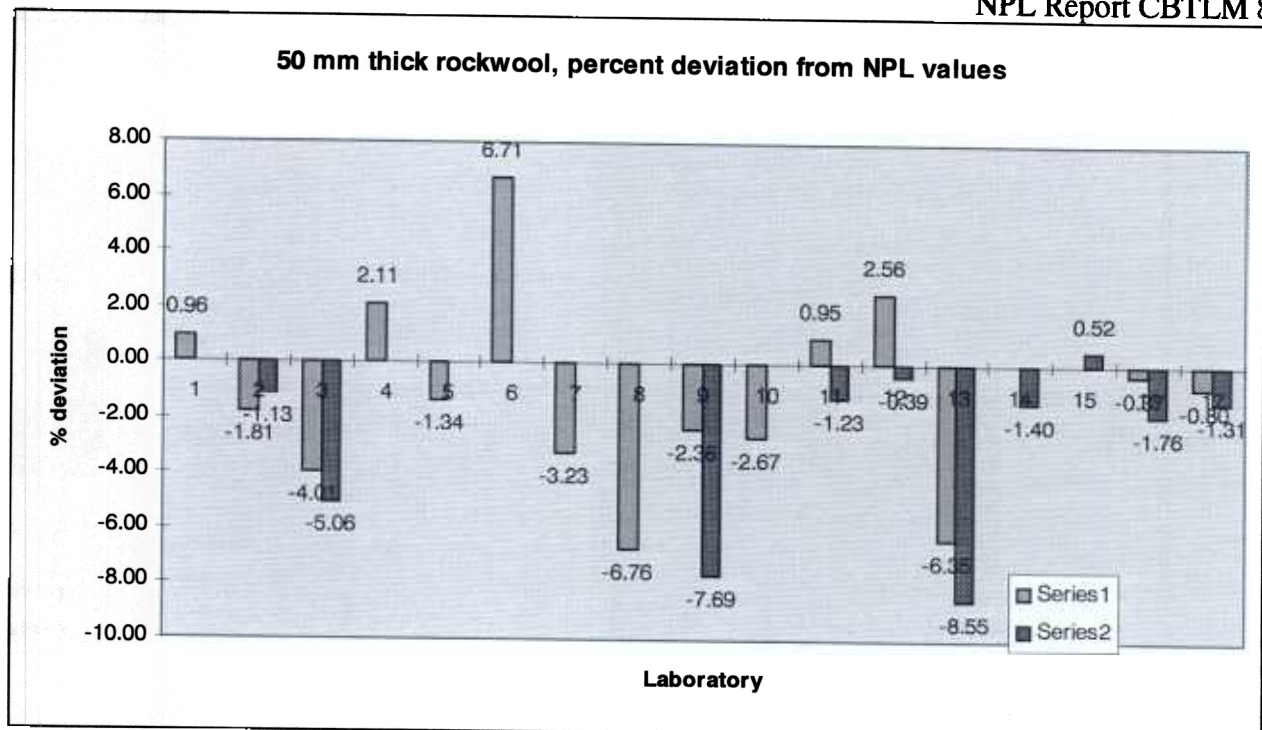


Figure 13. Percent differences from NPL values for 50 mm thick rockwool results at a mean density of 200 kg/m^3 . Series 1 is at a mean temperature of about 10°C and series 2 is at about 23°C .

a significant number of cases the heat flow meter results indicated an effect in the opposite direction, i.e. a lower value for the thicker specimen. Furthermore, for the high-density rockwool material where no effect is expected or observed in the ghps, many of the heat flow meter results indicated significant differences in value between the two thicknesses. In these cases the overall levels of agreement are usually within the generally accepted ± 2 to 3% but significantly different to each other for the two thicknesses.

- (b) In general the overall level of agreement and consistency, especially for the rockwool is less for the thicker than for the thin specimens, even when the results for the two small non-conforming apparatus are removed. This behaviour is apparent for both measurement conditions.

In each case there are two possible individual causes for this apparent inconsistent behaviour. However, dependent on the particular apparatus, they may also be inter-related.

- i) The first cause may be due to insufficient time being allowed for the apparatus to attain equilibrium, especially for the thicker specimens. This could be a major cause for the rockwool material since its density is also some 6 to 10 times greater than that of the other two materials. This combination of greater thickness, especially when combined with the high density, will increase equilibrium times significantly. This factor may not have been appreciated fully, especially by those operators having major experience in measuring only low density materials such as the cellular plastics and/or thin test specimens.

The relevant national and international standards provide adequate guidelines relating to the establishment of equilibrium conditions. It is recommended that operators of heat flow meter apparatus become fully acquainted with these in order to ensure that apparatus operation does conform to the requirements, especially when undertaking tests on specimens that may differ from those normally measured.

- ii) The second cause may be due to effects of apparatus calibration. In all cases in this inter-comparison the apparatus were calibrated with one type of reference material or transfer standard but from different sources. This is a glass fibre board, either moderate density ($\sim 80 \text{ kg/m}^3$) or high density ($\sim 150 \text{ kg/m}^3$), having a thermal conductivity in the range 30.0 mW/m.K to 34.0 mW/m.K over the present temperature range.

Thus the thermal resistance of the transfer standard is only a little lower than that of the thin test specimens. Under these circumstances the heat loss or gain will be similar in the calibration and test modes and thus can be neglected. However, the thermal resistance is significantly lower (by a factor of at least two) than that of the thicker test specimens. Hence for these thick specimens the design of a particular apparatus, especially with respect to guarding and surround insulation, may not be sufficient to maintain the same or similar temperature distributions such that heat loss or gain can be neglected for calibration and test as it is for the thin specimens.

This problem can be overcome or minimised by the use of other reference materials or transfer standards having different thermal resistance values. In this way, the thermal resistance of the calibration specimen can be matched more closely to that of a test specimen and heat loss or gain minimised under the measurement conditions. This problem highlights the existing lack of reference materials both in terms of the range of thermal conductivity values available and the limited thicknesses of current references.

Until additional reference materials in different thicknesses become available, this situation can be resolved only by the use of a certified transfer standard(s) i.e. 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 then ensure that any heat flow meter 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 further. 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 laboratories involved use reference specimens from different calibration source materials. These calibrations were based specifically on reference materials or transfer standards available from either the National Institute of Standards, (NIST), in the USA or the National Physical Laboratory, (NPL), in the United Kingdom. Separately, three apparatus involved the use of a calibration curve supplied by the manufacturers that 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 differences are smaller or larger than those indicated in the present investigation.

A brief initial look at the possible calibration differences has been undertaken during the present intercomparison. Measurements were carried out in the NPL instrument first using the calibration supplied by the manufacturer that was based on the NIST SRM 1450b reference material. The measurements were then repeated using a calibration based on the newly developed and certified European IRMM reference material⁽¹⁰⁾. In developing data for this material, guarded hot plate measurements had been made, over the temperature range 0°C to 40°C, by 6 European standards laboratories, including NPL. The results were most encouraging and provided confidence in their use since all values agreed to within about $\pm 1.0\%$ over the whole temperature range.

Table 19 summarises the results obtained using the two calibrations. They indicate that there is a constant difference 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 required, especially prior to any international comparison of heat flow meter apparatus. To this end, in 1997 NPL had proposed to other national standards organisations in 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 equivalency of calibration of heat flow meter apparatus. The proposal has been accepted and the international comparison is now underway.

Table 19. Heat flow meter values based on two different calibration specimens

Material Identification	Thickness /mm	Thermal conductivity / (mW/m.K)				Difference %	
		Manuf. Calibration (NIST)		NPL calibration (IRMM)			
		10°C	24°C	10°C	24°C	10°C	24°C
EPS thk 24.1	48.88	35.8	37.4	34.5	36.3	2.9	3.0
EPS thin 16.1	24.56	35.0	36.5	33.9	35.7	3.2	2.2
EXPS thk 8.1	50.38	29.7	31.2	28.8	30.3	3.1	3.0
EXPS thin 3.2	32.54	28.0	29.2	27.2	28.5	2.9	2.5
R'wool thk 35.1	51.02	36.6	38.1	35.6	37.1	2.8	2.7
R'wool thin 31.1	32.10	36.4	37.9	35.3	36.8	3.1	3.0

8 CONCLUSIONS

Intercomparisons of seven accredited guarded hot plate apparatus and seventeen heat flow meter apparatus currently in use within the United Kingdom and Ireland has been carried out over the limited temperature range of 10°C to 25°C. Measurements were undertaken on two thicknesses of samples of expanded polystyrene, extruded polystyrene and a high-density mineral fibre board.

The guarded hot plate results indicated that the overall agreement was within $\pm 2\%$ but two anomalous data points were reported. Those for the heat flow meter apparatus indicated that with few exceptions the overall accuracy was within $\pm 5\%$ and that for the majority of heat flow meter apparatus it was $\pm 2\%$ to $\pm 3\%$. Reasons for differences between values due to calibration issues and equilibrium time variations have been discussed together with solutions to reduce the uncertainties.

One thickness of one material was found to have a thermal conductivity that unexpectedly changed with time. However, overall consistency of measurement was found by means of comparison of results of separate measurements by NPL carried out at various times during the total time span of the measurements. No explanation of this anomalous behaviour has yet been found despite consultations with the manufacturers and suppliers of the board.

9 ACKNOWLEDGEMENTS

The contribution by the manufacturers for contributing the materials and the co-operation of their technical representatives, Mr. J. Bowdidge of Rockwool, Mrs. S. Davis of Dow Chemical and Mr. D. Thomsett of Vencel Resil respectively, are recognised and greatly appreciated by all involved in the studies.

10 REPORT ON THE DEBRIEFING MEETING, 20 OCTOBER 1999, NPL.

10.1 INTRODUCTION

At the conclusion of each inter-comparison the individual participants were provided with a copy of the appropriate draft report with a request for comments and suggestions prior to the presentation of a final report encompassing both studies. In addition all participants were invited to a one-day debriefing meeting at which the reports and all comments could be discussed fully to provide conclusions and recommendations. The following is a report of that meeting.

10.2 AGENDA

- 1 Welcome and Introductions
- 2 Summaries of investigations
 - 2.1 Heat flow meter
 - 2.2 Guarded hot plate
- 3 Discussion of major issues
 - 3.1 Materials
 - 3.2 Calibration
 - 3.3 Apparatus size
 - 3.4 Time for equilibrium
- 4 Standards requirements
 - 4.1 Apparatus requirements
 - 4.2 Operational techniques
 - 4.3 Changes to ISO 8301 and/or 8302
- 5 Other issues
- 6 Close of meeting
- 7

ATTENDEES

- | | |
|-----------------------|---------------------------|
| 1. Mike Tanner | Vencel Resil Ltd. |
| 2. Peter Primmer | Marley Bldg Materials |
| 3. John Gearing | Gearing Scientific |
| 4. Arther Charlton | Cape Insulation Products |
| 5. John Denyer | BBA |
| 6. Jon Aseidu-Dompreh | BBA |
| 7. Neil Adam | Superglass |
| 8. Grazyna Mitchner | Celotex Ltd. |
| 9. Robbie Harcourt | Shell Chemicals (UK) Ltd. |
| 10. Rosie Collins | BITS |
| 11. David Salmon | NPL |
| 12. Ron Tye | NPL |
| 13. Clark Stacey | NPL |

Apologies

1. Brian Robson	Nortest
2. Doug Harris	H+H Celcon
3. Michael O'Reilly	Moy Isover
4. Dave Johnstone	Borden Chemical UK Ltd. (Blagden Chemicals)
5. Tony Simpson	Salford University
6. Shona Burns	Stangers
7. Tony Birtchnell	Rockwool Ltd.
8. Norman Heath	Callenders Ltd.
9. Dave Baggett	Owens Corning
10. Rob Foster	Dow Corning
11. David Entwistle	ICI Polyurethanes
12. John Christopher	Isover-British Gypsum
13. Tony Aindow	Owens Corning

The meeting was initially chaired by David Salmon who had to leave the meeting because of ill health and the chair was taken by Ron Tye.

Following the welcome the participants were invited to introduce themselves to the rest of the meeting.

10.3 HEAT FLOW METER INTER-COMPARISON.

Ron Tye presented a summary of the heat flow meter (hfm) inter-comparison by highlighting the objectives, the results and proposed causes or reasons for the apparent discrepancies together with recommendations for solutions to the problems that were identified.

Essentially the objective of the study was to establish the degree of consistency in the measurement of thermal conductivity by all the different types, sizes and forms of hfm apparatus in current use in the UK. Three different types of material in two thicknesses were chosen from a range of common thermal insulation products that were stable and reproducible in property. Hence a broad range of thermal resistance was provided to check performance over a range of thickness and resistance. In addition two low-density products were chosen where a known thickness effect should be seen plus a high-density fibrous product where the thermal conductivity was independent of thickness.

A strict testing and procedural protocol based on ISO8301 was established to avoid individual choice, however it was accepted that the participants could still interpret the standard document in slightly different ways.

In general the results were encouraging indicating that a large majority of the data fell within 5% of the baseline values with over 70% within 3%, the precision level normally attainable with this method. There were two major areas of concern. The performance on the thinner specimens appeared to be better than that obtained on the thicker specimens and more variation and discrepancies were seen for the mineral fibre board than for either of the cellular plastic specimens.

Possible interrelated causes for this behaviour had been suggested and this was left open for later discussion. These included the issues of calibration specimens, equilibrium times and non-conformity in size and design of apparatus. A particularly worrying point relating to the calibration specimen was the discovery by NPL that consistent differences of the order of 2 to 3% were obtained when using the new European certified reference material (Certified to 1%) compared to the use of the manufacturer calibration which was based on a certified transfer standard obtained in the USA.

10.4 GUARDED HOT PLATE INTER-COMPARISON.

David Salmon gave a similar but shorter summary on the guarded hot plate inter-comparison since there was much commonality in the two studies concerning the materials and procedure.

In general, the overall results were very good showing agreement of approximately 2% or better between all the laboratories on all materials. However there were two anomalous data points, one from each of two participants on different materials. These had been investigated by the respective organisations, after discussions with NPL, to try to ascertain the cause. Hopefully procedures would be in place such that the 2% uncertainty level could be maintained in future accreditations.

One interesting feature of this inter-comparison, which assisted in confirming the high performance level of the guarded hot plates, was the discovery of an unexpected and as yet unexplained increase with time in the thermal conductivity of the 50 mm thick extruded polystyrene. This occurred due to the much longer time intervals taken for this study. However NPL carried out measurements on specimens of this batch of material over period of time and consistency of results was maintained when a correction factor for elapsed time before testing was introduced.

The summary was concluded by briefly outlining the objectives and operation of UKAS in relation to its value to the insulation community. In particular, mention was made of the value that could accrue for organisations obtaining UKAS accreditation for their heat flow meter apparatus. However the matter of the relatively high cost was appreciated and obviously a matter for an organisation to consider in the light of forth coming EC legislation requiring companies to produce declared values for their products at designated laboratories.

10.5 DISCUSSION OF MAJOR ISSUES.

The meeting was then opened up for discussion that was wide ranging. The discussion plus the written comments received prior to the meeting are summarised below.

10.5.1 Materials

Concern was expressed by a number of participants that they had difficulty in measuring the thickness of the fibrous material specimens and they were uncertain about the amount of pressure that needed to be applied during a measurement. Little or no concern was expressed on these issues for the cellular polystyrene specimens.

The problem of measuring the specimen thickness was of particular importance since different apparatus measured in-situ thickness in different ways while others had to be set at the externally

measured value. Suggestions were made that this issue should be addressed more specifically within the test method standards. However it was pointed out by the chair that European and International standards existed for the dimensional measurement of specimens that were applicable to all material types. Thus the recommended practice was to use these standardised techniques to determine the specimen thickness and then adjust the separation of the plates to that thickness for subsequent measurement.

The matter of applied pressure on the specimens was also raised with particular concern about the possible effects of contact resistance with different materials. The test method standards provide some guidance but no definitive or quantitative values for the applied pressure. For the present materials the specimen resistance was much greater than any possible contact resistance and therefore they could safely be ignored. It was also pointed out that the “surface condition” of the specimen was part of its thermal resistance and thus the measured value was acceptable providing the thickness was uniform. Contact resistances became of concern when thinner, harder, less compressible, higher thermal conductivity (lower thermal resistance) materials were being measured. Based on the experiences of several participants potential problems could be expected once the thermal conductivity exceeded the order of 0.2 W/m.K to 0.5 W/m.K.

A question was raised concerning the use of a density correction for the mineral fibre board specimens whereas one is not applied for the commonly used glass fibre board reference materials, especially those provided by NPL. However the NPL results indicated that a density correction was necessary. This can be explained by the fact that the density of 200 kg/m³ is considerably higher than the density region where the thermal conductivity does not change with changes in density. For rockwool this is of the order of 80 kg/m³ to 100 kg/m³. A density correction is supplied by NIST for the SRMs 1450b and c but these are bonded high-density fibrous glass with densities of the order of 150 kg/m³ to 160 kg/m³. The fibrous glass standard supplied by NPL and the new European CRM supplied by IRMM have densities in the range 75 kg/m³ to 80 kg/m³ which is at the minimum of the thermal conductivity versus density curve where the conductivity is more or less independent of density.

There was minor concern expressed about the behaviour of the polystyrene materials. The expanded polystyrenes showed no change in properties and the participants had little or no problem with their measurement. Due to the fact that the heat flow meter inter-comparison was undertaken early and rapidly in the history of the programme the effects of the upward drift in the conductivity of the 50 mm thick extruded polystyrene was not apparent. It became of concern later, especially for most of the guarded hot plate participants and two of the heat flow meter participants who joined the programme later than the others. However the additional series of measurements carried out by NPL enabled the effect to be included in the final analysis of the results. The material now appears to be stable but no explanation for this anomalous behaviour is yet available from the manufacturer. Furthermore the thinner material has not shown any tendency to drift and its thermal conductivity remains at the same low level as would be expected for this type of product.

10.5.2 Calibration and verification.

For the heat flow meter in particular adequate reference materials or transfer standards are essential for the basic measurement while they are also required (mandated by the International Standard ISO 8302) for use in the verification of the performance of the guarded hot plate apparatus.

A variety of calibration specimens were used by the participants most of these were the fibrous glass type available from NIST and NPL which were of the order of 25 mm to 37 mm thick. A few also used transfer standards obtained from other sources. It was generally agreed that more were necessary, particularly at the lower end of the thermal conductivity range and also covering a much larger range of thickness. The latter need has been prompted by the increase in the number of organisations now using or planning to use larger apparatus.

For the heat flow meter apparatus it is clear that more precise measurements are possible if a particular apparatus is calibrated using reference materials having thickness and/or thermal resistances covering the range for which the apparatus is designed. In the present study some participants “stacked” two or more reference materials to address this issue. However the stated preference would be to use a thick or thicker reference specimen(s) to avoid any problems, which may be due to contact resistance, however large or small. A further requirement is for a reference material, preferably rigid, having a lower thermal conductivity or much higher thermal resistance for a thickness of 20 mm to 30 mm to enable measurements to be carried out on high resistance evacuated panels.

An associated issue appeared to be the time interval between calibrations of the heat flow meter apparatus. This appeared to vary between days to weeks depending on the user. In general the ISO standard provides information on a required maximum time and allowable drift. It does not appear that a number of the participants calibrate at much shorter intervals and most maintain a detailed record of the value to ensure that any change of drift is within the stated limits. There were suggestions by numerous participants that this issue, and the many others that were discussed, should be contained in a Good Measurement practice or Guide document prepared for use by users of guarded hot plate and heat flow meter apparatus.

10.5.3 Apparatus factors

Most of the current participants were using apparatus of overall dimensions of 305 mm square. However a number of larger apparatus were in use or planned. In general the 305 mm apparatus were used to test specimens up to 50 mm or so thick. However one or two were used for specimens up to 100 mm in thickness. While the basic designs were similar, different sizes of heat flux transducer were installed, different forms of edge guarding were used and calibration was undertaken with different references of one or more thicknesses. Ideally as indicated presumably each apparatus should be calibrated or verified with at least two thicknesses and possibly more depending on its intended use.

An important issue concerned the environment in which the apparatus is operated. Various participants indicated that this was a critical factor in ensuring stability of operation. Some mentioned that draughts from open doors or people walking by were sufficient to cause small but

unacceptable changes. In extreme cases the effects of direct changes such as placing the apparatus near a south-facing window was mentioned as a contributing factor to unsatisfactory and variable performance. For best performance a stable controlled environment is necessary and an apparatus should be running continuously and not intermittently.

10.5.4 Equilibrium time

This factor was mentioned in the report as a possible contribution to the differences and difficulties that participants could have encountered when measuring the high-density fibrous material. However from the inputs of most participants at the meeting it was clear that sufficient time had been allowed for the attainment of equilibrium in testing all specimens. Particular mention was made that times such as overnight or half a day were used for this study and especially for the fibrous material.

Several participants, particularly those measuring at 10°C mean temperature, were concerned that there could be moisture collection in the fibrous material if it was left in the apparatus for a long time. However where specimen drying was carried out there appeared to be little or no change in mass, thus indicating an absence of moisture. In this context it is probably most unfortunate that European Standards require testing of building products to be carried out at 10°C mean temperature where the likelihood of moisture pickup is possible unless additional precautions are taken. Testing at a higher temperature such as 23°C, especially for routine testing purposes, would be highly preferable because of the general absence of moisture under such conditions.

10.5.5 Standards requirements

Based on present experiences there was general satisfaction that the present standards, when used correctly, were sufficient for measurements to be made to the required precision. The results of the present inter-comparison did highlight the major areas, which could lead to errors. However the results gave the operator the means to investigate the various parameters and thereby improve the precision level to within the accepted level of $\pm 2\%$ for the guarded hot plate and $\pm 3\%$ for the heat flow meter. Various issues relating particularly to materials and certain operational procedures were mentioned as items to be included in revised versions of the standard. However following the discussion it appeared that the type of information (some of it already in the materials standards) would be more valuable if it were provided in a Good Practice Guide or similar document.

10.6 CONCLUSIONS

In conclusion, a particular subject of increasing concern amongst the participants is the measurement of loose fill specimens. In particular the preparation and sampling of specimens and differences between those prepared in-situ and those transferred from an external source together with the need for a similar type of reference material. The chairman mentioned that experiences in this field, particularly in North America and Scandinavia, indicate that such measurements should be made on thick (greater than 100mm) specimens in a large 600 mm square or greater apparatus. In both countries the issues of sampling, specimen preparation etc. are covered in appropriate materials standards. In addition it would be most beneficial to have a loose fill reference material, but, providing a thick low-density blanket transfer standard is used for calibration, inter-

comparisons have shown that the normal uncertainty levels of ± 3 to 4 % can be obtained.

Measurements on loose fill materials are thus a stimulus for UK manufacturers and users to obtain larger apparatus.

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