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Validation of the NPL rotatable wall guarded hot box with horizontal heat flow

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Abstract

This report describes measurements carried out to validate the NPL Rotatable wall-guarded hot-box apparatus. The measurements have all been carried out with vertically mounted test elements – that is with horizontal heat flow. The apparatus will be validated with non-horizontal heat flow at another time.

The validation measurements reported were carried out with a 150 mm thick expanded polystyrene (EPS) test element as well as measurements made on 20 mm thick and 60 mm thick glazed calibration panels, which were measured mounted in a 150 mm EPS surround panel, as specified in EN ISO 12567-1 and prEN 12567-2.

The measurements have been designed to show that the apparatus complies with the requirements of EN ISO 8990:1996 and EN 1946-4:2000 and so the requirements of these standards are shown in this report with appropriate data relating to the operation of the rotatable hot box.

The measurements show that the Rotatable wall guarded hot box apparatus meets all the requirements of ISO 8990 and EN 1946-4.

The measurements also confirmed the measurement uncertainty figures that were derived from a detailed uncertainty analysis (also given in this report). The overall measurement uncertainty of thermal conductance measurements made on a homogeneous specimen is estimated to be within ± 3.6 % based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %.

The overall measurement uncertainty of thermal transmittance measurements carried out following the procedures specified in EN ISO 12567-1:2000 is estimated to be within ± 5.5 % based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %.

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1. DESCRIPTION OF THE APPARATUS

The rotatable wall-guarded hot-box (RWGHB) apparatus has been designed and built at the NPL. The principle of this equipment is the same as the original wall-guarded hot-box (see NPL Report QU 91). It retains the advantages of a traditional guarded hot-box but with improved control over the operating environment yet it is more compact than the traditional calibrated hot-box.

The apparatus is designed to make measurements on insulation panels, window and door systems and wall and roof structures, over the conductance range 0.1 to 10 W/m^2.K. The maximum test element size that can be accommodated is 2.4 m x 2.4 m x 0.15 m. The cold-box air temperature can be set between –20 °C and +20 °C and the hot-box air temperature to a maximum of 35 °C. The minimum hot-box temperature is limited by the requirement that the outer wall guard shall be approximately 3 °C above the laboratory air temperature, which is usually held at 18.5 °C ± 1 °C.

In the conventional guarded hot-box the objective of experimentally reducing to zero, the heat loss or gain from the apparatus, other than through the test element, is achieved by surrounding a "metering box" by a "guard box" and controlling the temperature and air flow conditions in the guard box to ensure such heat transfer is minimised. In the wall-guarded hot box, the two-box technique is dispensed with and the heat flow through the apparatus walls is reduced to negligible proportions by actively controlling the temperature of the outside surface of the apparatus to be equal to that of the corresponding zone of the inside wall.

This design change has two main effects; firstly, a much larger test element can be accommodated for a given overall size of apparatus and secondly the specimen edges are now a source of heat loss or gain, as they are no longer in the "guard area". This unwanted heat transfer path is eliminated by using a linear-gradient edge-guard system to establish a temperature gradient across the edge of the specimen, which is closely matched to that in the body of the specimen.

This apparatus has been designed so that it can be fully rotated, enabling the apparatus to be set up at any orientation from cold-box horizontally positioned above the hot-box, through the vertical position, to the hot-box positioned horizontally above the cold box.

A schematic diagram of the apparatus and the associated control systems is shown in Figure 1 and a photograph is shown in Figure 2.

The wall-guard heater system comprises large, self-adhesive, silicone heater pads, fixed evenly to the surface of each of the 6 mm thick aluminium plates that make up the external wall guard. High precision temperature control is achieved by using a thermistor embedded in the top back plate, connected to a bridge circuit as the temperature sensor system. The bottom zone is controlled relative to the top zone by using a differential thermocouple between the top and bottom back plates. The heater system is built as different zones, with the power into each zone being separately controlled to enable their temperatures to be matched as required.

The hot box walls have been lined with a purpose built heat-flow meter (HFM) system to measure the heat flow through them with high sensitivity and precision. This HFM consists of a uniform array of differential thermocouple junctions anchored to thin copper discs attached to the opposite faces of six 2 m x 1 m x 0.02 m panels of rigid insulating board.

Figure 1 Schematic diagram of the rotatable hot box apparatus

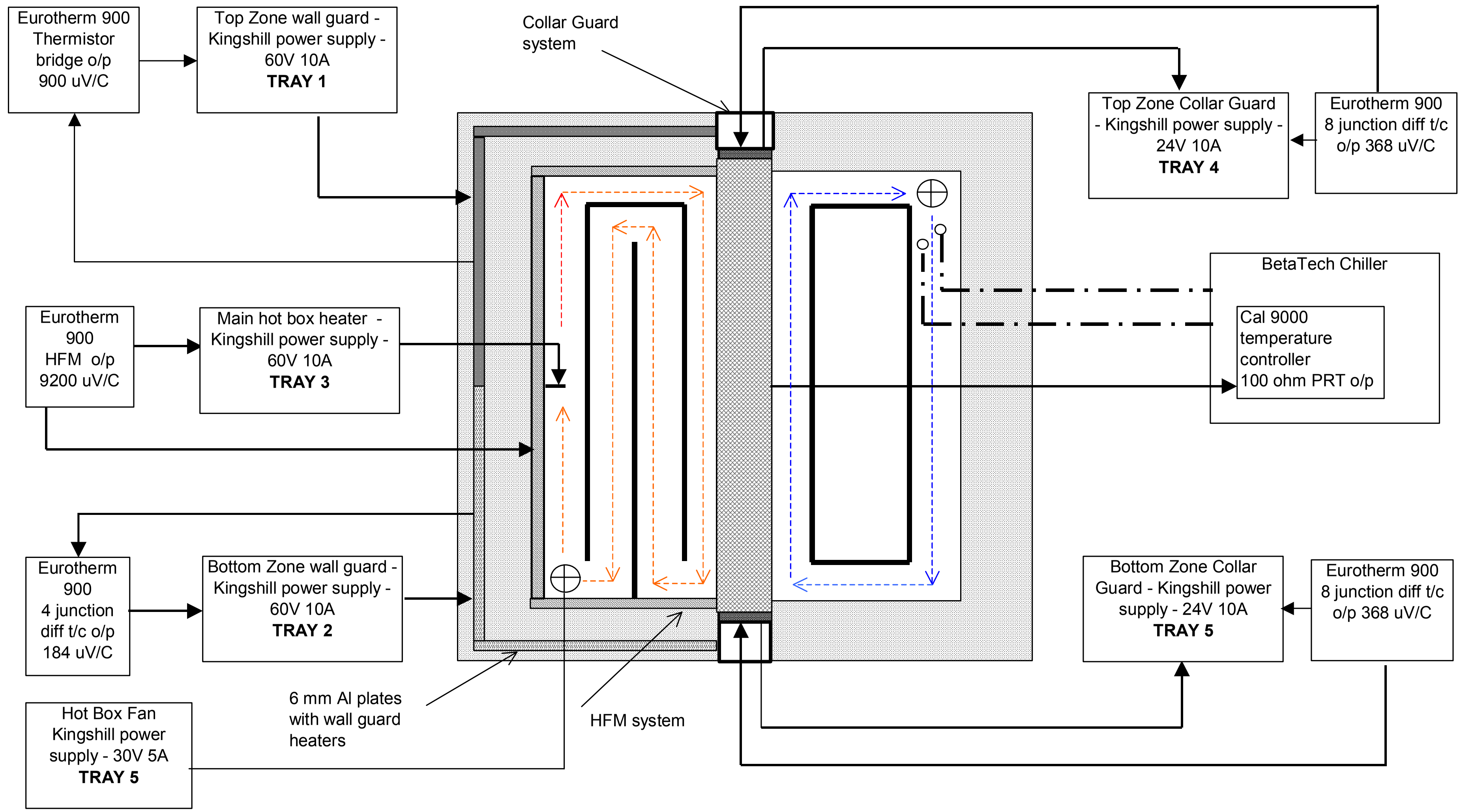


Figure 2 Photograph of the RWGHB in the 45 degree position

The HFM system is clamped to the inside surface of the hot box with fixings which incorporate a thermal break. The output of the heat flow meter system is 6524 µV/°C.

The edge-guard heater system is shown schematically in Figure 1. It consists of four heater plate assemblies, which form a frame around the edge of the entire specimen. They are made from 0.5 mm thick, stainless steel plate against which the specimen or its support panel rests. A strip heater, taped to the back face of the stainless steel plate close to the edge nearest the hot box, is used in conjunction with a 16-way differential thermocouple to raise the edge temperature to that of the face of the specimen or support panel. The opposite edge of this stainless steel plate is firmly clamped to a copper-cooling fin, which protrudes 75 mm into the cold box. The required temperature gradient for effective edge guarding is thus established. Thermocouples attached to the midpoints of the stainless steel plates enable their mean temperatures to be monitored.

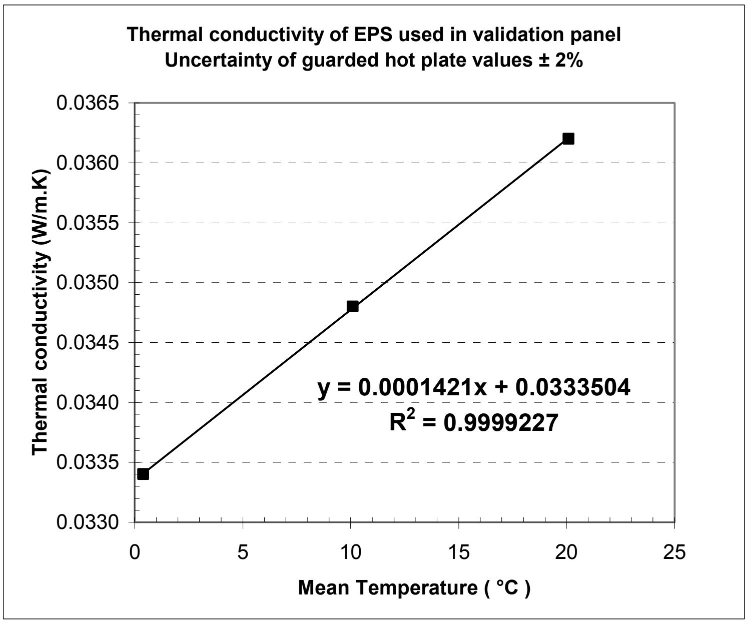
2. CONDUCTION/TRANSMITTANCE VALIDATION MEASUREMENTS

2.1. Test elements used for the validation measurements

2.1.1. A one hundred and fifty mm thick expanded polystyrene test element
A validation panel was made from 0.15 m thick expanded polystyrene (EPS) whose thermal conductivity was measured at three temperatures in the NPL 610 mm guarded hot plate apparatus (see NPL Test Report PP21/E02070019). The uncertainty of those measurements is ± 2%. The thermal conductivity values are shown in Table 1.

Table 1 Thermal conductivity data for the expanded polystyrene

PP21/E02070019	
Temp (°C)	GHP (W/m.K)
0.4	0.0334
10.1	0.0348
20.1	0.0362



2.1.2. Glazed calibration panels (20 mm and 60 mm thick)

The two glazed calibration panels (20 mm thick and 60 mm thick), used to carry out the calibration measurements specified in EN ISO 12567-1:2000, were mounted in a 150 mm thick EPS surround panel (Rothold2) and their thermal conductance measured. The calculated thermal conductance of those glazed calibration panels are given in NPL Test Report PP31/E02020284. Both panels had also been measured the NPL's other Wall Guarded Hot Box, so these measurements also served as an intercomparison between the two apparatuses.

2.1.3. UPVC Double-glazed window system

The U-value of a 1.48 m x 1.23 m UPVC double-glazed window was measured mounted in the surround panel Rothold2 using the procedures specified in BS EN ISO 12567-1:2000. The U-value of that window had previously been measured in the other NPL Wall Guarded Hot Box mounted in surround panel 10, also following the procedures specified in BS EN ISO 12567-1:2000.

2.2. Precision of measurements of the 150 mm thick EPS validation panel

The thermal conductance of the 150 mm thick validation panel was measured in the RWGHB at standard temperature conditions (approximately warm air temperature of 23 °C and cold air temperature of +3 °C) and compared with the thermal conductance calculated from the thermal conductivity of the material used and the measured thickness. The result of that measurement is given in Table 2. The agreement is excellent and would be consistent with a hot-box measurement uncertainty of < ± 2%.

Table 2 Comparison of RWGHB measurements with calculated values for 150 mm thick EPS

Specimen number	Hot Box power	Top CG diff t/c	Bottom CG diff t/c	Thermistor	HFM	Surface temp diff	Mean temperature	Conductance uncorrected for HFM o/p	Conductance corrected for HFM o/p (using 0.00363 W/µV)	Predicted conductance value	Difference of cor. Conductance from predicted conductance	Main heater control mode
	W	µV	µV	µV	µV	°C	°C	W/m².K	W/m².K	W/m².K	%	
R01D	26.467	8	2	24355	-107	19.28	11.85	0.2371	0.2406	0.2351	2.3	Manual

2.3. Measurements of the two glazed calibration panels

2.3.1. Accuracy, repeatability and intercomparison using the 20 mm thick GCP.
This panel was measured at three different air temperature differences as required by BS EN ISO 12567-1:2000, then removed and at a later date replaced mounted flush with the cold side of the surround panel and the measurements required by prEN 12567-2 were carried out at the same temperature conditions. The results of the two measurements made in the

Rotatable Hot box, at the standard temperature conditions are compared with the calculated thermal conductance and with the conductance value measured with the other Wall Guarded Hot Box in Table 3. For more details of these measurements see NPL Report CBTLM 26.

Table 3 Thermal conductance values of the 20 mm thick glazed calibration panel

TT206	Rotable Hot Box		WGHB	
Mean temperature °C	Measured conductance 40 mm from warm side °C	Measured conductance flush with cold side °C	Measured conductance (W/m2.K)	Calculated conductance (W/m2.K)
11.3	2.368	2.394	2.433	2.443

Glazed Calibration Panel 20 mm thick

Note[1]
Calculated thermal conductance and uncertainty of TT206 are given in NPL Test Report PP31/E02020284
Note[2]
Boundary loss of 1.74 Watts used to calculate thermal conductance

% difference (Measured Rotate - Calculated)	= -3.1	This figure would indicate uncertainty of Rotate measurements is just better than	± 2%
% difference (Measured Rotate - Measured WGHB)	= -2.7	Equivalent to both apparatus having uncertainties of	± 1.9%
% difference (Measured Rotate(h) - Measured Rotate(v))	= -1.1	Repeatability	

The results show excellent agreement with the Wall Guarded Hot Box and the calculated thermal conductance values and repeatability of about 1%.

2.3.2. Accuracy and intercomparison using the 60 mm thick GCP

This panel was measured at three different air temperature differences as required by BS EN ISO 12567-1:2000. The results of the measurements made in the Rotatable Hot box, at the standard temperature conditions are compared with the calculated thermal conductance and with the conductance value measured with the other Wall Guarded Hot Box in Table 4. The measurement uncertainties estimated from these measurements are broadly in line with those derived from the uncertainty analysis – see section 5.

Table 4 Thermal conductance values of the 60 mm Glazed Calibration Panel

TT207	**RHB**	**WGHB**	
Mean temperature °C	Measured conductance 40 mm from warm side °C	Measured conductance (W/m2.K)	Calculated conductance (W/m2.K)
12.75	0.621	0.672	0.655

Glazed Calibration Panel 57 mm thick

Note[1]
Calculated thermal conductance and uncertainty of TT206 are given in NPL Test Report PP31/E02020284

% difference (Measured Rotate - Calculated)	= -5.2	This figure would indicate uncertainty of Rotate measurements is just better than	± 4.9%
% difference (Measured Rotate - Measured WGHB)	= -7.6	Equivalent to both apparatus having uncertainties of	± 5.4%

2.4. Measurements made with the UPVC double glazed window

After carrying out the calibration measurements of the surround panel Rothold2 as specified in BS EN ISO 12567-1:2000, measurements were made of a 1.48 m x 1.23 m UPVC double glazed window. This window had been previously measured in the other Wall Guarded Hot Box as specified in BS EN ISO 12567-1:2000. The results of these two measurements are shown in Table 5.

Table 5 U-value of UPVC window (WGHB & Rotatable hot box)

Apparatus	Surround panel	Standardized U-value W/m^2.K
Wall Guarded Hot Box	Holder 10	1.750
Rotatable Hot Box	Rothold2	1.723
Difference %	1.5	

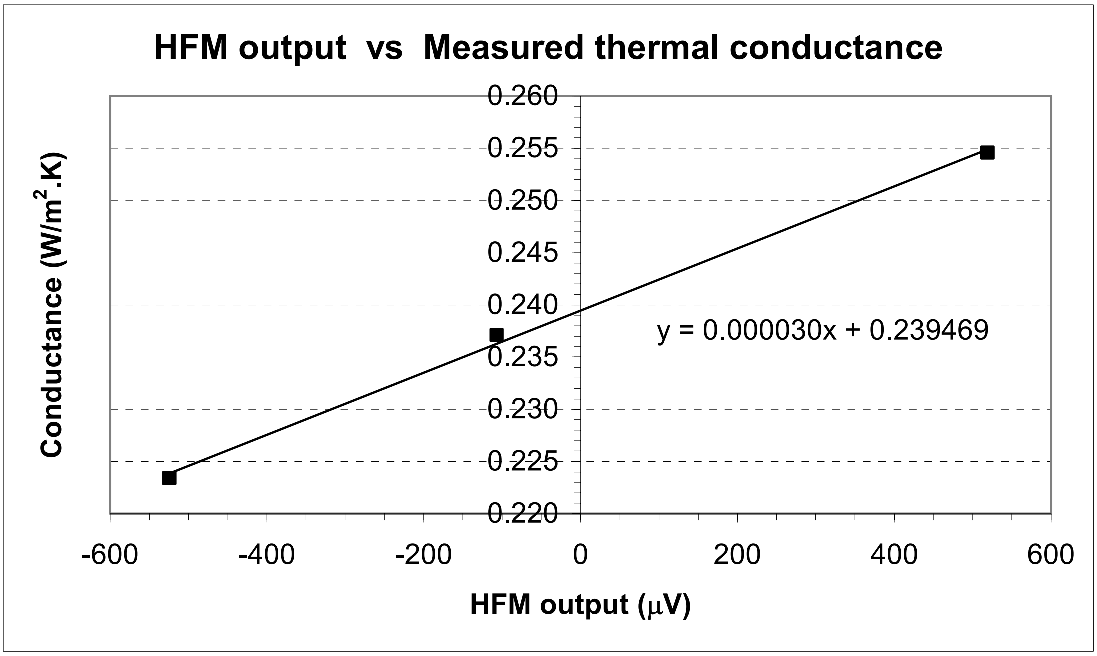
2.5. Effect of Wall guard HFM offsets

Two further measurements of the 150 mm thick EPS validation panel were carried out with the main heater set to give HFM off sets of + 500 µV and then –500 µV. The results are shown in Table 6 and Figure 3

Table 6 Effect on measured thermal conductance of HFM offset

Specimen number	Hot Box power W	Top collar guard differential thermocouple output µV	Bottom collar guard differential thermocouple output µV	Thermistor bridge output µV	Heat Flow Meter (HFM) output µV	Surface temperature difference °C	Mean temperature °C	Conductance - uncorrected for HFM output W/m^2.K
R01D	26.467	8	2	24355	-107	19.28	11.85	0.2371
R01F	24.545	7	2	24355	-524	18.97	11.71	0.2234
R01G	28.976	8	3	24356	519	19.67	12.12	0.2546

Figure 3 Graph of thermal conductance vs HFM offset



The average power (loss or gain) into the hot box for a 1 μV offset of the HFM has been calculated from this data to be + 0.00363 W/μV.

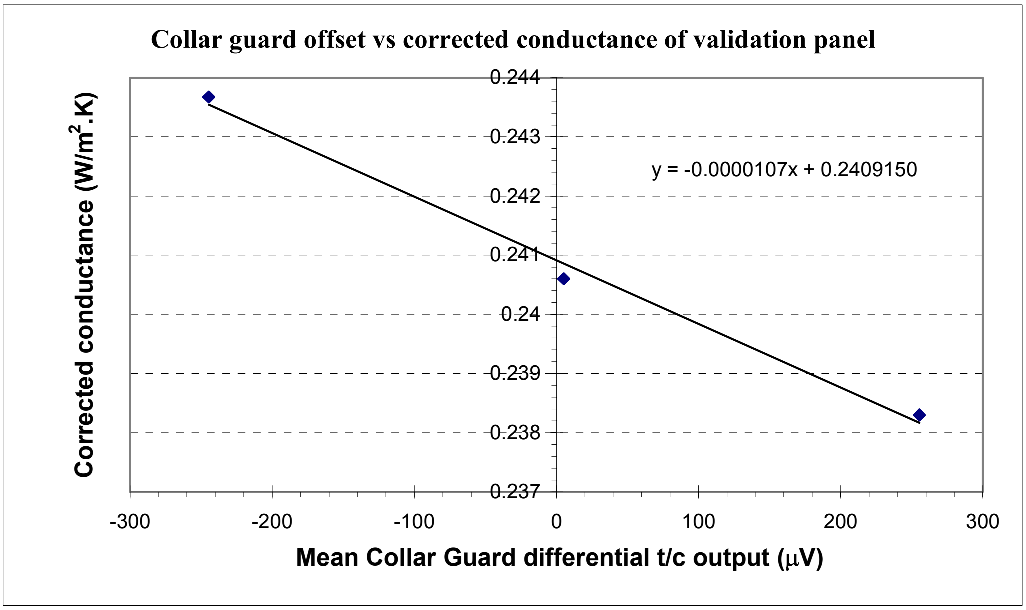
2.6. Effect of Collar Guard differential thermocouple offset

Two further measurements of the 150 mm thick EPS validation panel were carried out with the Collar Guard heaters set to produce collar-guard differential thermocouple offsets of + 250 μV and -250 μV. The results are shown in Table 7 and Figure 4.

Table 7 Effect of collar guard differential offset

Specimen number	Hot Box power W	Top CG diff t/c μV	Bottom CG diff t/c μV	Mean CG diff t/c μV	Thermistor μV	HFM μV	Surface temp diff °C	Mean temperature °C	Conductance uncorrected for HFM o/p $W/m^2.K$	Conductance corrected for HFM o/p (using 0.00363 W/μV) $W/m^2.K$	
R01B	26.651	259	252	256	24355	1	19.32	11.87	0.2383	0.2383	to determine effect of a +ve collar guard offset
R01D	26.467	8	2	5	24355	-107	19.28	11.85	0.2371	0.2406	HFM, CG offsets = 0 - Manual power - this is the "base" reading
R01E	27.230	-242	-247	-245	24355	-9	19.33	11.83	0.2434	0.2437	to determine effect on the measured conductance of a -ve collar guard offset

Figure 4 Collar Guard differential t/c vs thermal conductance



The average power loss or gain caused by a offset of the collar guard differential thermocouple was calculated from this data to be - 0.00120 W/µV.

2.7. Effect of temperature difference on measured thermal conductance

Two further measurements of the 150 mm thick EPS validation panel were carried out with both the Collar Guard differential thermocouples and the HFM outputs set to zero but with different temperature differences across the specimen surface. The results are shown in Table 8 and Figure 5.

Table 8 Effect on thermal conductance of surface temperature difference

Specimen number	Hot Box power W	Top CG diff t/c µV	Bottom CG diff t/c µV	Thermistor µV	HFM µV	Surface temp diff °C	Mean temperature °C	Conductance uncorrected for HFM o/p W/m².K	Conductance corrected for HFM o/p (using 0.00363 W/µV) W/m².K
R01D	26.467	8	2	24355	-107	19.28	11.85	0.2371	0.2406
R01H	35.203	8	3	26112	44	25.14	11.92	0.2419	0.2408
R01J	42.608	9	3	27601	-58	30.20	11.86	0.2438	0.2450

Figure 5 Graph of surface temperature difference vs hot box power

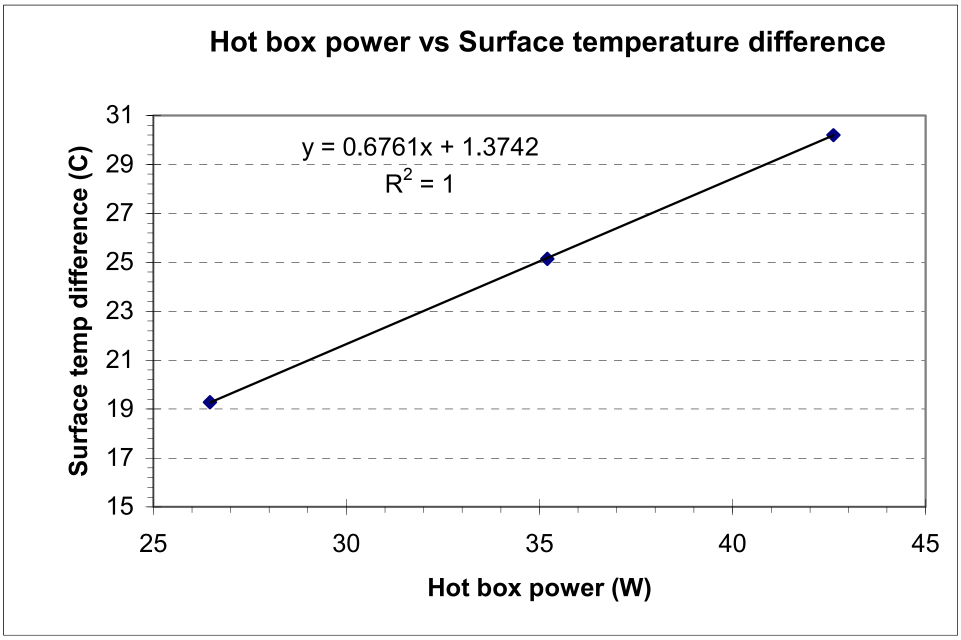
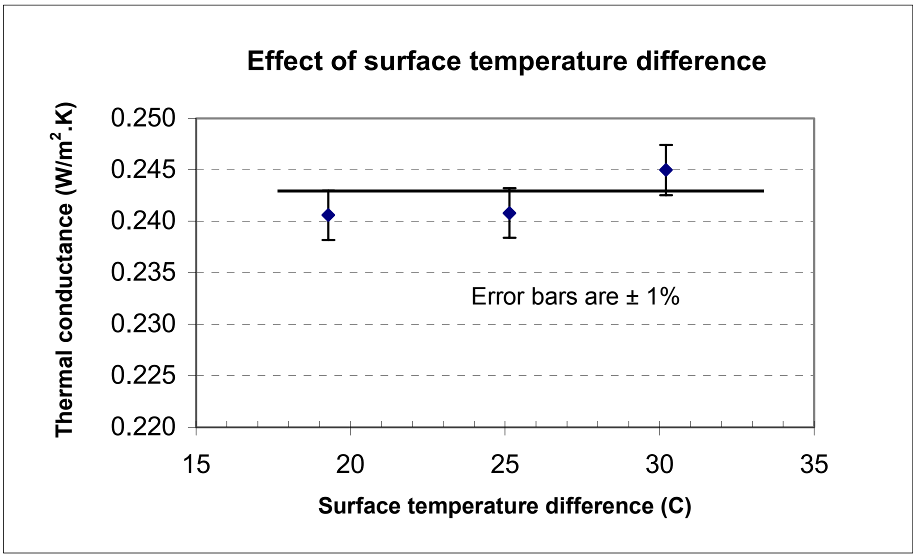


Figure 5 shows that the relationship between power and temperature difference to be linear. The measured thermal conductance values plotted against surface temperature are shown in Figure 6. The values are the same to within ± 1%.

Figure 6 Thermal conductance vs surface temperature difference



2.8. Temperature stability of the hot and cold air

The apparatus was run for 45 hours after it had reached thermal equilibrium (with both the HFM output and the collar guard differential thermocouple in balance). The stability of the hot and cold air temperatures and the air temperature difference are shown in Figure 7, Figure 8 and Figure 9 respectively.

Figure 7 Stability of the warm air temperature

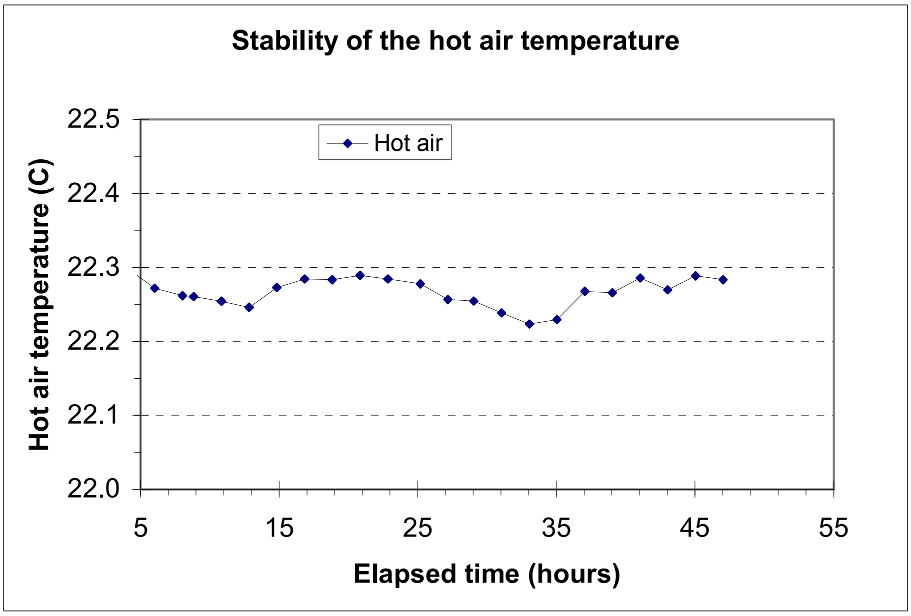


Figure 8 Stability of the Cold Air temperature

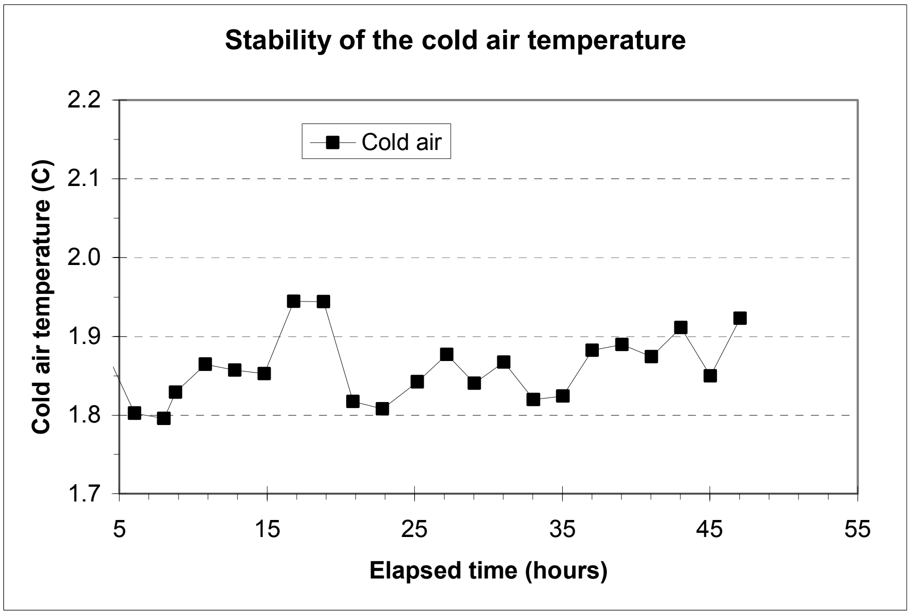


Figure 9 Stability of the air temperature difference

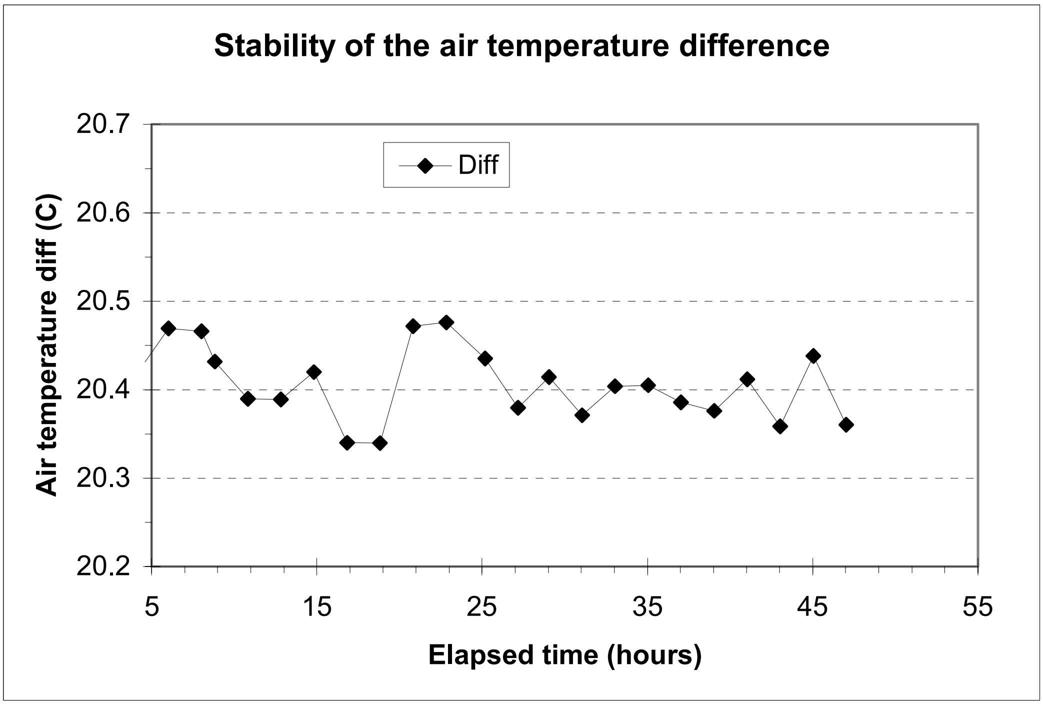


Figure 9 shows that that the maximum variation in the air temperature difference over 40 hours is 0.14 °C which is 0.07% of the air to air temperature difference.

2.9. Temperature uniformity – natural convection in warm chamber

The air, surface and baffle temperatures for the hot and cold sides are shown in Figure 10 and Figure 11 and the distribution of the temperature differences are shown in Figure 12.

Figure 10 Uniformity of the hot air temperature (no fan)

HOT SIDE TEMPERATURES °C

Hot Air = 22.30

						Max spread	% of air to air temp
	24.18	24.13	24.18	24.14	24.21	0.08	0.40
	22.90	22.85	22.89	22.91	22.89	0.05	0.26
	22.05	22.05	22.04	22.05	22.04	0.01	0.07
	21.41	21.38	21.42	21.41	21.42	0.04	0.20
	20.96	20.97	20.98	20.97	20.99	0.03	0.15
Max spread	3.23	3.15	3.20	3.17	3.22		
Gradient (°C/m)	1.68	1.64	1.67	1.65	1.68		

Hot Baffle = 21.92

					Max spread	% of air to air temp
	23.03	23.04	23.09	23.14	0.11	0.54
	22.19	22.14	22.15	22.17	0.05	0.23
	21.47	21.46	21.45	21.47	0.03	0.13
	20.98	20.96	20.96	21.01	0.05	0.23
Max spread	2.05	2.08	2.13	2.14		

Hot Surface = 21.58

					Max spread	% of air to air temp
	22.81	22.92	22.97	23.03	0.22	1.10
	21.80	21.75	21.75	21.78	0.05	0.23
	20.94	20.89	20.89	20.90	0.05	0.26
	20.41	20.39	20.40	20.42	0.02	0.12
Max spread	2.39	2.52	2.57	2.61		

Figure 11 Uniformity of the cold air tempertaure (4.1 m/s air speed)

COLD SIDE TEMPERATURES

Cold Air **1.99**

						Max spread	% of air to air temp 1.99
	2.06	1.94	1.91	1.94	2.06	0.15	0.74
	2.07	1.95	1.90	1.94	2.05	0.16	0.80
	2.06	1.96	1.91	1.95	2.05	0.15	0.74
	2.08	1.96	1.92	1.95	2.06	0.16	0.79
	2.09	1.96	1.94	1.96	2.07	0.16	0.77
Max spread	0.04	0.02	0.03	0.02	0.03		
Gradient (°C/m)	0.02	0.01	0.02	0.01	0.01		

Cold Baffle **2.05**

					Max spread	% of air to air temp
	2.13	2.00	2.01	2.11	0.13	0.62
	2.14	2.00	1.99	2.11	0.15	0.72
	2.11	1.99	1.98	2.10	0.13	0.66
	2.10	1.97	1.99	2.10	0.13	0.65
Max spread	0.04	0.03	0.03	0.02		

Cold Surface **2.31**

					Max spread	% of air to air temp
	2.25	2.45	2.49	2.34	0.24	1.19
	2.26	2.40	2.43	2.27	0.17	0.83
	2.21	2.33	2.37	2.23	0.16	0.79
	2.14	2.32	2.28	2.17	0.18	0.89
Max spread	0.12	0.13	0.21	0.17		

Figure 12 Uniformity of the air temperature difference

TEMPERATURE DIFFERENCES

Air to Air **20.31**

						Max spread	% of air to air temp 20.31
	22.12	22.18	22.27	22.20	22.15	0.15	0.74
	20.83	20.90	20.98	20.96	20.84	0.15	0.75
	19.98	20.09	20.12	20.10	19.99	0.14	0.69
	19.33	19.42	19.50	19.46	19.36	0.17	0.85
	18.86	19.01	19.04	19.01	18.91	0.18	0.90
Max spread	3.26	3.17	3.23	3.19	3.24		
Gradient (°C/m)	1.70	1.65	1.68	1.66	1.69		

Baffle to Baffle 19.87

					Max spread	% of air to air temp
	20.90	21.04	21.08	21.03	0.18	0.88
	20.05	20.15	20.16	20.06	0.11	0.54
	19.36	19.47	19.47	19.38	0.11	0.56
	18.88	18.98	18.97	18.91	0.11	0.52
Max spread	2.03	2.05	2.11	2.12		

Surface to Surface 19.20

					Max spread	% of air to air temp
	20.55	20.47	20.48	20.69	0.23	1.11
	19.54	19.35	19.32	19.51	0.22	1.06
	18.73	18.57	18.52	18.67	0.21	1.05
	18.28	18.08	18.12	18.25	0.20	0.99
Max spread	2.28	2.39	2.36	2.45		

These distributions show that the vertical air temperature gradient (even with natural convection) is less than 2 °C/m and that the air and baffle uniformity is always better than 1% of the air to air temperature difference.

2.10. Temperature distribution in warm chamber -using the hot box fan

When the hot box fan is used to increase the air flow in the warm box then the vertical gradient in the warm air reduces to < 0.05 ^{o}C/m. This is shown in Figure 13.

Figure 13 Temperature distribution in the warm chamber with the fan on

HOT SIDE TEMPERATURES °C

Hot Air = 23.39

						Max spread	% of air to air temp
	23.40	23.43	23.47	23.40	23.38	0.09	0.41
	23.39	23.41	23.44	23.39	23.37	0.07	0.32
	23.38	23.39	23.42	23.38	23.35	0.07	0.31
	23.38	23.40	23.42	23.37	23.34	0.08	0.36
	23.35	23.39	23.40	23.35	23.33	0.06	0.29
Max spread	0.05	0.05	0.07	0.04	0.04		
Gradient (°C/m)	0.03	0.03	0.04	0.02	0.02		

Hot Baffle = 23.19

					Max spread	% of air to air temp
	23.26	23.28	23.25	23.23	0.04	0.19
	23.20	23.20	23.18	23.17	0.03	0.14
	23.17	23.22	23.17	23.14	0.08	0.36
	23.15	23.15	23.11	23.07	0.08	0.39
Max spread	0.10	0.12	0.14	0.17		

Hot Surface = 22.79

					Max spread	% of air to air temp
	23.07	23.04	22.98	22.99	0.09	0.40
	22.87	22.85	22.77	22.82	0.10	0.47
	22.75	22.74	22.64	22.63	0.12	0.56
	22.63	22.63	22.55	22.56	0.08	0.39
Max spread	0.44	0.41	0.44	0.43		

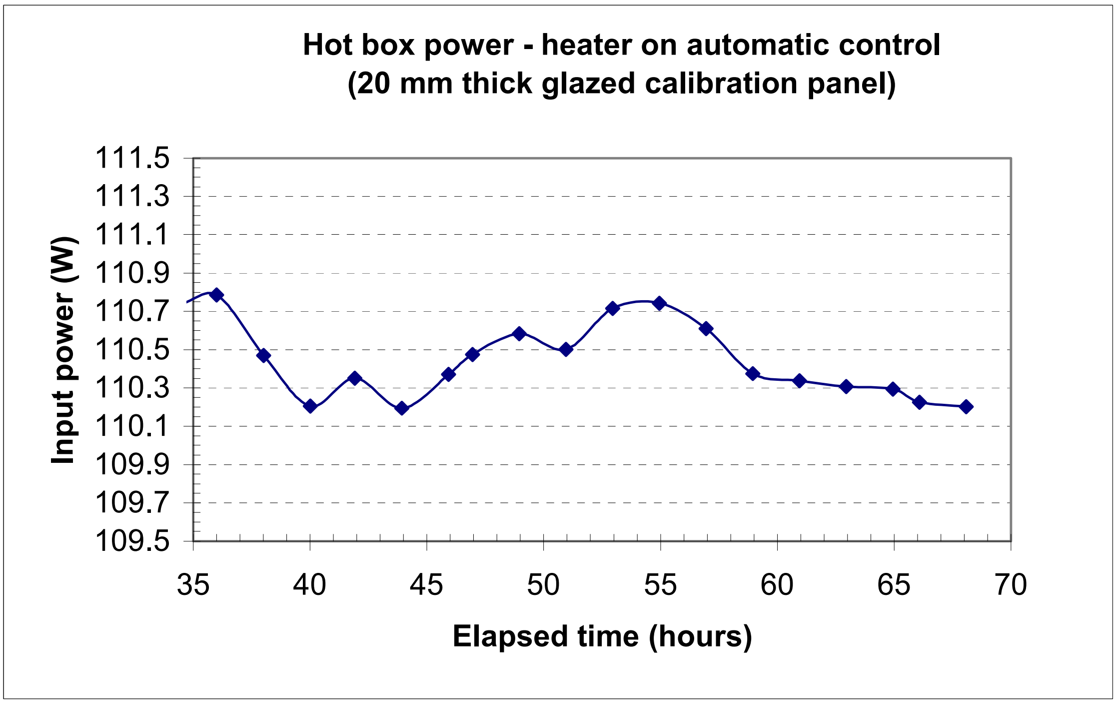
2.11. Stability of input power

This was monitored whilst measuring the 20 mm thick glazed calibration panel required by BS EN ISO 12567-1. There are two different situations of interest

With the hot box heater power under control of the temperature controller
With the hot box power set “Manually” – that is set by the controller at one output voltage.

In both cases the hot box fan was switched on at the normal speed required to produce the standard surface coefficient. The stability of the hot-box, input power when it is controlled by the temperature controller, with the objective of keeping the output of the HFM system at zero, can be seen in Figure 14.

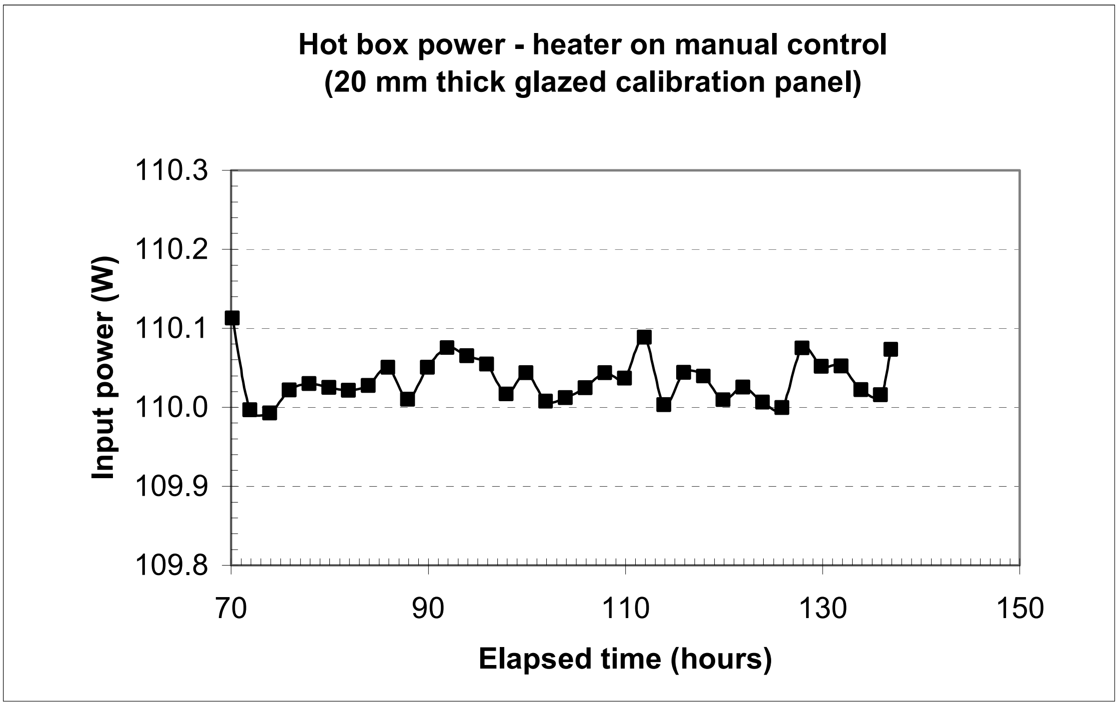
Figure 14 Stability of the hot box input power - temperature controller in use



The maximum variation over the 33 hours was 0.5% of the average power

The hot box power was then switched to manual control. This effectively sets the output voltage to a constant value. The stability of the hot box input power when the hot box heater output voltage is fixed, can be seen in Figure 15.

Figure 15 Stability of the hot box power when under manual control



In this situation, the maximum variation in the net input power over 70 hours is about 0.1%.

2.12. Hot box fan power measurement check

The 150 mm thick EPS validation panel was measured with and without the hot box fan. The thermal conductance values are shown in Table 9

Table 9 Effect of hot box fan power on measurements of EPS

Specimen number	Hot box fan	Hot Box power W	Fan power W	Top CG diff t/c µV	Bottom CG diff t/c µV	Mean CG diff t/c µV	Thermistor µV	HFM µV	Surface temp diff °C	Mean temperature °C	Conductance uncorrected for HFM o/p W/m2.K	Conductance corrected for HFM o/p (using 0.00363 W/mV) W/m2.K	
R01D	no fan	26.467	0.000	8	2	5	24355	-107	19.28	11.85	0.2371	0.2406	HFM, CG offsets = 0 - Manual power - this is the "base" reading - calc value = 0.2352 W/.m^2.K. Difference (Calc - meas) = -2.3%
R01M	fan 9v	18.782	9.791	4	2	3	24355	2	20.65	12.44	0.2391	0.2390	Hot box fan switched on 9V - Hot box power on AUTO - calculated conductance = 0.2357 W/.m^2.K. Difference (Calc - meas) = 2.0%

The figures in Table 9 show that although the hot fan contributes about 30% of the power in one measurement and 0% of the power in the other, the measured conductance values differ by < 0.5%. This shows that the measurement of the hot box fan power is sufficiently precise to ensure that it does not influence the measured values.

3. THERMOCOUPLE CHECKS

Two batches of Type T, Grade 1 thermocouple wire are used in this apparatus. The NPL temperature section has calibrated both batches. The results of which are given in NPL Test Report PM04/E01050106. To ensure that no systematic errors were being introduced into the temperature difference measurements when using these two batches, extra checks were carried out. Thermocouples from these different batches were mounted in the copper block system designed for checking the thermocouple calibration in-situ. The thermocouples under test were monitored through the hot box instrumentation system and the temperatures calculated using the equations calculated from the NPL calibrations. These are the equations used in the Rotatable software (ROT_LOG7). The results are shown in Table 11.

A hot box thermocouple and a cold box thermocouple were taped between two pieces of brass plate and placed in the cold box. The readings from each thermocouple (through the scanning/logging system) were recorded when the cold box was at a stable low temperature. The results are shown in Table 10. The agreement is excellent.

The results in Table 11 show that the agreement (at temperatures below 45 °C) between the two batches of wire is better than 0.02 °C which is 0.1% of a 20 °C temperature difference.

Table 10 Comparison of output of hot & cold thermocouples

Thermocouple ID (Hot or Cold box) (Connector block ID) (Scanner Card & channel number)	**Temperature** **°C**	**Difference between the two thermocouples** **°C**
Cold Box RHS 1 (1!23)	2.641	
Hot Box LHS 20 (4!26)	2.659	0.018

4. AIR VELOCITY MEASUREMENTS

The air flow velocity in the Hot box can be controlled by altering the gap between the baffle and the test element (or surround panel) from 50 mm to 420 mm and by altering the speed of an axial fan covering the whole box width powered by a DC motor. The air flow velocity in the cold box can be controlled by altering the gap between the baffle and the test element (or surround panel) from 50 mm to 450 mm and by altering the speed of an axial fan covering the whole box width, powered by an AC motor mounted outside the cold box. The air velocities measured (with the same fan motor settings) when the warm air was at 23 °C and the cold air was 3 °C, are given in Table 12.

Table 11 Results of the thermocouple checks

Brown/white thermocouples					Blue/white thermocouples (°C)					Difference Blue-Brown
Tc 1 (°C)	Tc 2 (°C)	Tc 3 (°C)	Tc 4 (°C)	Average (°C)	Tc 1 (°C)	Tc 2 (°C)	Tc 3 (°C)	Tc 4 (°C)	Average (°C)	(°C)
		2.17	2.17	2.17		2.18	2.16	2.18	2.17	0.003
		6.30	6.31	6.31		6.30	6.31	6.31	6.31	0.003
		8.81	8.82	8.82		8.81	8.82	8.82	8.82	0.001
19.72	19.73	19.73	19.73	19.73	19.71	19.72	19.72	19.72	19.71	-0.015
45.62	45.54	45.48	45.50	45.54	45.61	45.57	45.56	45.49	45.56	0.019
54.74	54.64	54.58	54.61	54.64	54.72	54.69	54.66	54.58	54.66	0.018
59.63	59.49	59.42	59.44	59.49	59.59	59.55	59.52	59.41	59.52	0.025

Table 12 Measured air flow velocities

Heat flow direction	Hot box air velocity (m/s)	Cold box air velocity (m/s)
Horizontal	0.29	4.1
Vertical	0.32	4.6

5. UNCERTAINTY ANALYSIS

A sensitivity analysis of all the measurement parameters was carried out for two situations:-

- Conductance and transmittance measurements of the 150 mm thick expanded polystyrene specimen (see Table 13)
- U-value measurement as specified in BS EN ISO 12567-1:2000 (see Table 14)

This data and other experimental data were used to carryout a measurement uncertainty analysis following the methodology set out in the ISO publication - *ISO Guide to the expression of uncertainty in measurement (ISBN 92-67-10188-9)* and the UKAS publication *M3003 The expression of uncertainty and confidence in measurement*. .The resulting uncertainty budget and estimate of measurement uncertainty for the 150 mm sample can be seen in Table 15and

Table 16 and for EN 12567-1 measurements of a window or door mounted in a surround panel in Table 17 and Table 18.

Table 13 Sensitivity data for 150 mm EPS measurement

Source of error	Value used	Units	Change	% Change in thermal conductance	% Change in thermal transmittance
Hot air	22.34	°C	Change by 0.3	0.0	-0.3
Hot surface	21.57	°C	Change by 0.3	-1.5	-0.4
Hot baffle	21.99	°C	Change by 0.3	0.0	-0.8
Cold air	1.84	°C	Change by 0.3	0.0	1.4
Cold surface	2.17	°C	Change by 0.3	1.6	0.1
Cold baffle	1.91	°C	Change by 0.3	0.0	0.3
Specimen area	5.7876	m^2	Change by 1	-14.7	-14.6
Baffle emissivity	0.94		Change by 0.1	0.0	-0.1
Surf emissivity	0.9		Change by 0.1	0.0	-0.1
Heater volts	11.8	Volts	Change by 10%	8.7	8.6
Heat amps res	0.1	Ω	Change by 10%	-7.9	-7.8
Heat amps volts	0.196	Volts	Change by 10%	8.7	8.6
Fan volts	7	Volts	Change by 10%	1.3	1.3
Fan amps res	0.1	Ω	Change by 10%	-1.2	-1.2
Fan amps volts	0.05	Volts	Change by 10%	1.3	1.3
Power	26.62	Watts	Change by 1	3.8	3.7
Conductance	0.237	$W/m^2.K$			
Transmittance	0.227	$W/m^2.K$			

Table 14 Sensitivity data for measurements to BS EN ISO 12567-1:2000

Test element	Source of error	Value		Change plus	% change in U-value	
Window	Specimen area	1.827	m^2	1	35.750	minus
Thick Cal	Specimen area	1.825	m^2	1	19.663	plus
Window	Heater volts	21.100	Volts	10%	12.999	plus
Window	Heat amps res	0.099	Ω	10%	12.999	plus
Window	Heat amps volts	0.344	Volts	10%	12.999	plus
Thin Cal	Cold surf	4.419	°C	1	6.679	plus
Thick Cal	Heater volts	14.140	Volts	10%	6.193	minus
Thick Cal	Heat amps res	0.099	Ω	10%	6.193	minus
Thick Cal	Heat amps volts	0.231	Volts	10%	6.193	minus
Thick Cal	Holder area	3.963	m^2	1	5.091	plus
Thin Cal	Hot surf	18.158	°C	1	4.899	minus
Window	Cold air	2.626	°C	1	4.284	plus
Thick Cal	Cold air	3.637	°C	1	3.619	minus
Thin Cal	Cold air	2.694	°C	1	3.485	minus
Window	Hot baffle	21.824	°C	1	3.113	minus
Thin Cal	Hot baffle	21.922	°C	1	2.704	plus
Thin Cal	Conductance (thin change only)	2.400	$W/m^2.K$	5%	2.700	plus
Thick Cal	Hot baffle	22.609	°C	1	2.396	plus
Window	Hot air	23.173	°C	1	1.898	minus
Thick Cal	Cold surf	4.143	°C	1	1.408	plus
Thick Cal	Cold surround	3.866	°C	1	1.382	minus
Thin Cal	Hot air	23.284	°C	1	1.331	plus
Thick Cal	Hot surround	22.502	°C	1	1.330	plus
Window	Fan volts	7.007	Volts	10%	1.311	plus
Window	Fan amps res	0.100	Ω	10%	1.311	plus
Window	Fan amps volts	0.050	Volts	10%	1.311	plus
Thin & Thick	Conductance – thin ↑ & thick ↓	2.4 & 0.66	$W/m^2.K$	5%	1.300	minus
Thin & Thick	Conductance – thin ↑ & thick ↑	2.4 & 0.66	$W/m^2.K$	5%	1.200	plus
Window	Cold baffle	2.814	°C	1	0.942	plus
Thick Cal	Hot air	23.166	°C	1	0.813	plus
Thin Cal	Cold baffle	2.867	°C	1	0.660	minus
Thick Cal	Fan volts	7.007	Volts	10%	0.620	minus
Thick Cal	Fan amps res	0.100	Ω	10%	0.620	minus
Thick Cal	Fan amps volts	0.050	Volts	10%	0.620	minus
Thick Cal	Cold baffle	3.719	°C	1	0.315	minus
Thick Cal	Hot surf	21.346	°C	1	0.165	minus
Thin Cal	Hot reveal	20.227	°C	1	0.136	plus
Thick Cal	Hot reveal	21.891	°C	1	0.107	plus
Window	Cold reveal	3.236	°C	1	0.106	plus
Thick cal	Conductance – thick ↑	0.660	$W/m^2.K$	5%	0.100	minus
Thin Cal	Cold reveal	3.192	°C	1	0.097	minus
Thin Cal	Baffle emissivity	0.980		0.1	0.028	minus
Window	Hot holder	22.159	°C	1	0.028	minus
Window	Cold holder	2.884	°C	1	0.028	minus
Thin Cal	Reveal emissivity	0.950		0.1	0.027	plus
Thin Cal	Specimen surf em	0.880	°C	0.1	0.026	plus
Thick Cal	Specimen surf em	0.880		0.1	0.019	plus
Thin Cal	Heater volts	21.164	Volts	10%	0.018	plus
Thin Cal	Heat amps res	0.099	Ω	10%	0.018	plus
Thin Cal	Heat amps volts	0.345	Volts	10%	0.018	plus
Thin Cal	Fan volts	7.014	Volts	10%	0.018	plus
Thin Cal	Fan amps res	0.100	Ω	10%	0.018	plus
Thin Cal	Fan amps volts	0.050	Volts	10%	0.018	plus
Thick Cal	Cold reveal	3.847	°C	1	0.015	minus
Thick Cal	Baffle emissivity	0.980		0.1	0.012	plus
Window	Baffle emissivity	0.980		0.1	0.008	plus
Window	Reveal emissivity	0.950		0.1	0.004	minus
Thick Cal	Reveal emissivity	0.950		0.1	0.002	plus
Thin Cal	Hot surround	22.361	°C	1	0.000	
Thin Cal	Cold surround	2.943	°C	1	0.000	
Thin Cal	Specimen area	1.825	°C	1	0.000	
Thin Cal	holder area	3.963	m^2	1	0.000	
Thin Cal	Holder thickness	149.670	m	1	0.000	
Thick Cal	Holder thickness	0.150	m	1	0.000	
Window	Holder area	3.960	m^2	1	0.000	
Window	Holder thickness	0.150	m	1	0.000	
Window	Specimen surf em	0.880		0.1	0.000	
Window	Hot surf	n/a	°C	1		
Window	Hot reveal	n/a	°C	1		
Window	Cold surf	n/a	°C	1		

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Table 15 Uncertainty analysis - plain sample (Part 1)

Parameter	Source of uncertainty	Row ID
Assumed transmittance	Change this to the appropriate value	a
Assumed conductance	This is dependent on the U-value and assumes total surface resistance =0.17 m² .K/W	b
		c
Heater power VOLTS	Voltage across the heater (2 x DVM calb. error)	d
Heater power AMPS	Voltage across the heater I monitoring resis. (2 x DVM calb. error) (heater res = 6 ohms)	e
Heater power AMPS	Resistance of the heater current monitoring resistance (2 x calibration error)	f
		g
Fan power VOLTS	Voltage across the fan motor (2 x DVM calb. error)	h
Fan power AMPS	Voltage across the fan current monitoring resistance (2 x DVM calb. error)	I
Fan power AMPS	Fan current monitoring resistance (2 x calibration error)	j
		k
Emissivity of baffles	Painted with matt black paint - assumed to be 0.94	l
Emissivity specimen	Assumed to be 0.9	m
		n
Area	Aperture = 2.405 m x 2.405 m (assume worse case error in measuring dimensions ± 5 mm)	o
		p
Absolute Temp error	T/c calb. ± 0.1°C + sampling ± 0.2°C + Cropico offset 0.25	q
		r
Air temp hot side	(Mean of 25 t/cs -cal ± 0.2°C) + assume ISO block variation of 0.1°C + 0.1°C non-representative	s
Air temp cold side	Average of 25 t/cs T/c cal ± 0.2 C Assume ISO block variation of 0.1 C	t
		u
Surface temp hot side	Average of 16 t/cs T/c cal ± 0.2 C Assume ISO block variation of 0.1 C	v
Surface temp cold side	Average of 16 t/cs T/c cal ± 0.2 C Assume ISO block variation of 0.1 C	w
		x
Baffle temp Hot	Average of 16 t/cs T/c cal ± 0.2 C Assume ISO block variation of 0.1 C	y
Baffle temp cold	Average of 16 t/cs T/c cal ± 0.2 C Assume ISO block variation of 0.1 C	z
		a1
Spurious heat loss/gains	Imbalance across the HFM of hot box walls due to 100 µV offset @ 0.00363 Watts per µV	b1
		c1
Spurious heat loss/gains	Due to temperature imbalance at collar guard offset of 100 µV @ 0.0012 Watts per µV	d1
		e1
Repeatability	Assume 1.5%	f1
		g1
		h1
$u_c(V_H)$	Combined uncertainty of measured value with hot box fan ON	i1
U	Expanded uncertainty measured value with hot box fan ON	j1
$u_c(V_H)$	Combined uncertainty of measured value with hot box fan OFF	k1
U	Expanded uncertainty measured value with hot box fan OFF	l1
	[1] These values are the effect on conductance/transmittance of changing the value by 1 unit - calculated using the spreadsheet "Results sheet used to check errors"	

Table 16 Uncertainty analysis - plain sample (Part 2)

Row ID	error ±	units	typical value	units	value ± units	Probability distribution	divisor	Conduct c1[1]	Cond. ui(VH) ± W/m² .K	Trans c1[1]	Trans. ui(VH) ± W/m² .K	v_i v_{eff}	Conductance % error	Transmittance % error
a			0.227	W/m² .K										
b			0.236	W/m² .K										
c														
d	0.06	%	11.80	volts	0.007080	rectangular	1.7321	1.746E-02	7.136E-05	1.656E-02	6.770E-05	∞		
e	0.06	%	0.1960	volts	0.000118	rectangular	1.7321	1.051E+00	7.136E-05	9.971E-01	6.770E-05	∞		
f	0.4	%	0.10	ohms	0.000400	rectangular	1.7321	1.873E+00	4.325E-04	-1.777E+00	-4.104E-04	∞		
g														
h	0.06	%	7.00	volts	0.004200	rectangular	1.7321	4.453E-03	1.080E-05	4.226E-03	1.025E-05	∞		
I	0.06	%	0.10	volts	0.000060	rectangular	1.7321	6.235E-01	2.160E-05	5.916E-01	2.049E-05	∞		
j	0.4	%	0.10	ohms	0.000400	rectangular	1.7321	-2.834E-01	-6.545E-05	-2.689E-01	-6.210E-05	∞		
k														
l	0.1	-	0.94	-	0.1	rectangular	1.7321	0.000E+00	0.000E+00	1.905E-03	1.100E-04	∞		
m	0.1	-	0.90	-	0.1	rectangular	1.7321	0.000E+00	0.000E+00	2.074E-03	1.197E-04	∞		
n														
o	0.5	%	5.79	m²	0.028938	rectangular	1.7321	-3.493E-02	-5.836E-04	-3.316E-02	-5.539E-04	∞		
p														
q	0.55	ºC	10	ºC	0.550000	rectangular	1.7321	9.000E-04	2.858E-04	9.000E-04	2.858E-04	∞		
r														
s	0.3	ºC	22.64	ºC	0.30	rectangular	1.7321	0.000E+00	0.000E+00	-2.616E-03	-4.530E-04	∞		
t	0.3	ºC	1.84	ºC	0.30	rectangular	1.7321	0.000E+00	0.000E+00	1.030E-02	1.784E-03	∞		
u														
v	0.3	ºC	21.57	ºC	0.30	rectangular	1.7321	1.204E-02	2.085E-03	-3.046E-03	-5.275E-04	∞		
w	0.3	ºC	2.17	ºC	0.30	rectangular	1.7321	1.241E-02	2.150E-03	6.398E-04	1.108E-04	∞		
x					0.00									
y	0.3	°C	22.00	°C	0.30	rectangular	1.7321	0.000E+00	0.000E+00	-6.331E-03	-1.097E-03	∞		
z	0.3	°C	1.91	°C	0.30	rectangular	1.7321	0.000E+00	0.000E+00	2.342E-03	4.057E-04	∞		
a1														
b1	0.363	W	26.60	Watts	0.363000	rectangular	1.7321	8.907E-03	1.867E-03	8.451E-03	1.771E-03	∞		
c1														
d1	0.12	W	26.60	Watts	0.120000	rectangular	1.7321	8.907E-03	6.171E-04	8.451E-03	5.855E-04	∞		
e1														
f1	0.0036	W/m2.K	0.24	W/m² .K	0.003600	rectangular	1.7321	1.000E+00	2.078E-03	1.000E+00	2.078E-03	∞		
g1														
h1														
i1						normal			0.004217		0.003666	∞		
j1						normal(k=2)			0.008434		0.00733	∞	3.6	3.2
k1						normal			0.004216		0.003666	∞		
l1						normal(k=2)			0.008433		0.00733	∞	3.6	3.1

Table 17 Uncertainty analysis for measurements to EN 12567-1 – (Part 1)

Parameter	Source of uncertainty	Row ID
Assumed transmittance		
Thin calibration panel		a
Hot air temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	b
Hot surface temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	c
Hot baffle temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	d
Cold air temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	e
Cold surface temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	f
Cold baffle temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	g
Thick calibration panel		h
Hot surround temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	I
Hot air temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	j
Hot surface temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	k
Hot baffle temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	l
Cold surround temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	m
Cold air temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	n
Cold surface temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	o
Cold baffle temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	p
Panel area	Assume measurements accurate to ±2 mm equivelent to 0.3%	q
Surround area	Assume measurements accurate to ±2 mm equivelent to 0.3%	r
Heater voltage	Voltage across the heater (2 x DVM calb. error)	s
Heater amps - volts across Res	Volts across the heater I monitoring resis. (2 x DVM calb. error) (heater res = 6 ohms)	t
Heater amps - Resistor	Resistance of the heater current monitoring resistance (2 x calibration error)	u
Fan voltage	Voltage across the fan motor (2 x DVM calb. error)	v
Fan amps - volts across Res	Voltage across the fan current monitoring resistance (2 x DVM calb. error)	w
Fan amps - Resistor	Fan current monitoring resistance (2 x calibration error)	x
Window measurement		y
Hot air temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	z
Hot baffle temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	a1
Cold air temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	b1
Cold baffle temperature	Calibration of t/cs are ± 0.2 °C & 0.1°C measurement & sampling error	c1
Panel area	Assume can be measured to ± 2 mm (samre as calibration panel)	d1
Heater voltage	Voltage across the heater (2 x DVM calb. error)	e1
Heater amps - volts across Res	Volts across the heater I monitoring resis. (2 x DVM calb. error) (heater res = 6 ohms)	f1
Heater amps - Resistor	Resistance of the heater current monitoring resistance (2 x calibration error)	g1
Fan voltage	Voltage across the fan motor (2 x DVM calb. error)	h1
Fan amps - volts across Res	Voltage across the fan current monitoring resistance (2 x DVM calb. error)	j1
Fan amps - Resistor	Fan current monitoring resistance (2 x calibration error)	k1
Absolute Temperature error	T/c calb. ± 0.2°C+sampling±0.2°C+ fit± 0.1°C=assume 0.008 W/m2.K per 1 C	l1
Spurious heat loss/gains HFM	Heat flow due to temp. imbalance across the hot box walls of 100 uV @ 0.00363W/u	m1
Spurious heat loss/gains CG	Heat flow due to temp. imbalance at collar guard of 100 uV @ 0.0012 W/uV	n1
Repeatability	This has been shown by experiment to be better than 1.5%	o1
Effect of Cal. Panel errors[1]	Effect of varying the cond. to the extremes of their uncertainty in opposite directions.	p1
$u_c(V_H)$	Combined uncertainty direct measured transmittance plus hot box fan	q1
U	Expanded uncertainty direct measured transmittance plus hot box fan	u1

Table 18 Uncertainty analysis for measurements to EN 12567-1 – (Part 2)

Row ID	error ±	units	typical value	units	value ± units	Probability distribution	divisor	c1 sensitivity	ui(VH) ± W/m² .K	v_i v_{eff}	
			1.7	W/m² .K							
a											
b	0.3	°C	24.00	°C	0.30	rectangular	1.7321	0.0228	0.003949	∞	
c	0.3	°C	19.00	°C	0.30	rectangular	1.7321	0.0839	0.014531	∞	
d	0.3	°C	23.00	°C	0.30	rectangular	1.7321	0.0463	0.008019	∞	
e	0.3	°C	3.00	°C	0.30	rectangular	1.7321	–0.0597	-0.010334	∞	
f	0.3	°C	5.50	°C	0.30	rectangular	1.7321	0.1143	0.019803	∞	
g	0.3	°C	4.00	°C	0.30	rectangular	1.7321	–0.0113	-0.001956	∞	
h											
I	0.3	°C	22.50	°C	0.30	rectangular	1.7321	0.0224	0.003884	∞	
j	0.3	°C	23.00	°C	0.30	rectangular	1.7321	0.01271	0.002201	∞	
k	0.3	°C	21.50	°C	0.30	rectangular	1.7321	–0.0031	-0.000534	∞	
l	0.3	°C	22.50	°C	0.30	rectangular	1.7321	0.0016	0.000276	∞	
m	0.3	°C	3.80	°C	0.30	rectangular	1.7321	–0.0239	-0.004143	∞	
n	0.3	°C	3.60	°C	0.30	rectangular	1.7321	–0.0639	-0.011068	∞	
o	0.3	°C	4.10	°C	0.30	rectangular	1.7321	0.0238	0.004126	∞	
p	0.3	°C	3.70	°C	0.30	rectangular	1.7321	–0.0059	-0.001022	∞	
q	0.3	%	1.820	m^2	0.0055	rectangular	1.7321	0.3366	0.001061	∞	
r	0.6	%	3.960	m^2	0.0238	rectangular	1.7321	0.0872	0.001195	∞	
s	0.06	%	15.500	volts	9.300E-03	rectangular	1.7321	-0.1060	-0.00064	∞	
t	0.06	%	0.254	volts	1.524E-04	rectangular	1.7321	-0.1060	-0.00064	∞	
u	0.4	%	0.100	ohms	4.000E-04	rectangular	1.7321	-0.1060	-0.00424	∞	
v	0.06	%	7.000	volts	4.200E-03	rectangular	1.7321	-0.0106	-0.00006	∞	
w	0.06	%	0.055	volts	3.300E-05	rectangular	1.7321	-0.0106	-0.00006	∞	
x	0.4	%	0.100	watts	4.000E-04	rectangular	1.7321	-0.0106	-0.00042	∞	
y											
z	0.3	°C	23.00	°C	0.30	rectangular	1.7321	–0.0325	-0.005627	∞	
a1	0.3	°C	22.00	°C	0.30	rectangular	1.7321	–0.0533	-0.009230	∞	
b1	0.3	°C	2.50	°C	0.30	rectangular	1.7321	0.0733	0.012702	∞	
c1	0.3	°C	2.80	°C	0.30	rectangular	1.7321	0.0161	0.002795	∞	
d1	0.3	%	1.82	m^2	0.0055	rectangular	1.7321	–0.6120	-0.001929	∞	
e1	0.06	%	21.00	volts	0.0126	rectangular	1.7321	0.2218	0.001614	∞	
f1	0.06	%	0.10	volts	0.0001	rectangular	1.7321	0.2218	0.000008	∞	
g1	0.4	%	0.34	ohms	0.0014	rectangular	1.7321	0.2218	0.000176	∞	
h1	0.06	%	7.00	volts	0.0042	rectangular	1.7321	0.0221	0.000054	∞	
j1	0.06	%	0.10	volts	0.0001	rectangular	1.7321	0.0221	0.000001	∞	
k1	0.4	%	0.05	ohms	0.0002	rectangular	1.7321	0.0221	0.000003	∞	
l1	0.5	ºC	10	ºC	0.500000	rectangular	1.7321	0.0080	0.00231	∞	
m1	0.363	watts	62.00	Watts	0.363000	rectangular	1.7321	0.0161	0.00338	∞	
n1	0.12	watts	62.00	Watts	0.120000	rectangular	1.7321	0.0161	0.00112	∞	
o1	0.0255	W/m² .K	1.70	W/m² .K	0.025500	rectangular	1.7321	1.0000	0.01472	∞	
p1	0.0459	W/m² .K	1.70	W/m² .K	0.045900	rectangular	1.7321	1.0000	0.02650		
q1						normal			0.047146	∞	
u1						normal(k=2)			0.0943	∞	5.5

6. REQUIREMENTS IN EN ISO 8990 AND EN 1946-4

A list of the requirements specified in EN ISO 8990:1996 is given in Figure 16, Figure 17, Figure 18 and Figure 19, with the appropriate data for the Rotatable wall guarded hot-box. A list of the requirements specified in EN 1946-4:2000 is given in, Figure 20 and Figure 21 with the appropriate data for the rotatable wall guarded hot box. The table showing the requirements of EN 1934 has been omitted as there is no intention to measure masonry in this apparatus.

7. CONCLUSIONS

The measured data show that the NPL Rotatable wall guarded hot box apparatus meets the requirements of both EN ISO 8990 and EN 1946-4.

The sensitivity of the measured values to the various thermal balances required has been determined.

The detailed measurement uncertainty analysis showed that the overall measurement uncertainty of thermal conductance measurements made on a homogeneous specimen is estimated to be within ± 3.6 % based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %. This has been confirmed by comparison between the results of the thermal conductance measurements on the 150 mm thick EPS specimen obtained with the hot box and the guarded hot plate apparatus.

The detailed measurement uncertainty analysis showed that the overall measurement uncertainty of thermal transmittance measurements carried out following the procedures specified in EN ISO 12567-1:2000 is estimated to be within ± 5.5 % based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %. This has been confirmed by comparison of the results of the thermal conductance measurements on the 20 mm and 60 mm thick glazed calibration panels from the Rotatable hot box with the thermal conductance values calculated from thermal conductivity and thickness measurements.

The results of the measurements made of the 20 mm and 60 mm glazed calibration specimens in both the Wall Guarded Hot Box and the Rotatable hot box are also compatible with both apparatus having a measurement uncertainty of ± 5.5%.

The measured U-value of a UPVC double glazed window using the procedures specified in EN ISO 12567-1:2000 obtained in the Wall Guarded Hot Box and the Rotatable Hot box agreed to 1.5%.

The repeatability of the apparatus was shown to be 1.1%

Figure 16 Requirements of EN ISO 8990 (Part 1)

ISO 8990 Clause	Type of box	Requirement in BS EN ISO 8990	NPL Rotatable Wall Guarded Hot Box
2.9.3.2	Both	The metering box walls SHALL be calibrated……	Measured as 0.00363 Watts per μV
2.9.3.3		The flanking loss f_4 shall cover the range of specimen thickness's to be tested.	Thickness at Edge is always 150 mm. Flanking loss is always neglible when collar guard is in balance(-0.0012 W/μV)
2.9.3.2	Both	The corrections ARE determined by measurements on calibration panels	Yes on 150 mm thick expanded polystyrene (EPS) and on 20 mm and 60 mm thick glazed calibration panels TT206 and TT207 whose thermal conductance values are given in NPL Test cetrtificate:
2.9.3.3	CHB	The flanking corrections SHOULD BE determined by measurements on calibration panels with same thickness and	Yes - thickness at the edge is always 150 mm
1.6.1.2	GHB	Metering area is from centre of nose for thick specimen to the inner periphery of the nose when the specimen thickness tends	N/a
1.6.1.2	CHB	Metering area is the inner periphery of the metering box.	Yes (Internal aperture of the hot box has been measured as 5.7876 m^2.
1.6.1.2	Both	The ratios of specimen side/specimen thickness and guard width/specimen thickness are governed by the same principles as for the guarded hot plate.	Thickness limited to those that can be mounted in the 150 mm EPS holder panel
2.2	Both	Emissivity of surfaces seen by the specimen can be high or low.	High (Black originally and also sprayed with Matt black paint)
2.2	Both	Low emissivity surfaces unsuitable for permeable specimens.	n/a
2.3.1	GHB	Error in evaluating metering box losses should not affect the determination of the specimen heat flow by more than 0.5%.	With the validation panel that required only 26.5 Watts the error in measuring the output from the heat HFM would need to be 36 μV to cause an error of 0.5%. The HFM output however can be measured to within +/- 2 μV.
2.3.1	Both	Box walls should be thermally uniform.	Yes they are.
2.3.1	Both	The box walls can be made from panels of cellular plastic or a sandwich with a core of cellular plastic and a suitable facing.	Mainly EPS with plywood facings
2.3.1	Both	The box walls, perimeter seal and specimen shall form an air and water vapour tight enclosure to avoid errors due to air and moisture transfer.	Yes they do.
2.3.1	GHB	In the Guarded Hot Box configuration, the metering box is held against the specimen to provide an air tight joint. The width of the gasket on the nose on the box shall not exceed 2 % of the metering width or 20 mm.	n/a
2.3.2	Both	Variations in air temperature across the air flow parallel to specimen surface shall not exceed 2 % of the air to air temperature difference from hot to cold side.	0.9% at worst
2.3.2		Any air temperature gradients along the air flow shall not exceed 2 K/m.	Gradient in hot-box without hot box fan = 1.68 °C/m. With hot box fan on gradient drops to 0.04 °C/m

Figure 17 Requirements of EN ISO 8990 (Part 2)

ISO 8990 Clause	Type of box	Requirement in BS EN ISO 8990	NPL Rotatable Wall Guarded Hot Box
2.4	GHB	The relationship between the metering area size and the guard area size and edge insulation shall be such that when testing a homogenous specimen of maximum expected resistance and thickness, the predicted error on specimen heat flow caused by peripheral heat loss f_5 shall be smaller than 0.5% of the metered heat flow f_1. A procedure to quantify this error can be found in ISO 8302.	The collar guard system keeps these peripheral heat losses very small. The sensitivity to the collar guard differential thermocouple offset is 0.0012 W/°C. The total power used when measuring the Validation panel is 26 Watts and the offset can be measured to with +/- 2 μV. That represents an error of < 0.1%.
2.4	GHB	The requirements as to emissivity, shielding of heaters, and temperature stability are in principle the same for the guard box as for the metering box. Temperature uniformity should be such that the influence on imbalance error will be smaller than 0,5% of the heat flow through the metered area of the specimen.	No guard Box
2.6	Both	The chamber walls should be constructed to reduce the load of the refrigeration equipment and PREVENT moisture condensation.	Yes they are.
2.6	Both	Air velocities should be adjustable to meet the required surface coefficient of heat transfer of the test and should be measured	Air velocity in both the hot and cold boxes are adjusted by variable speed fans and by adjusting the gap between the specimen and the baffle. Max air velocity in the cold box is 5 m/s
2.7	Both	Surface temperatures of the equipment "seen" by the specimen shall be investigated to calculate the mean radiant temperature.	The radient temperatures are measured by 16 thermocouples on both the hot and cold baffles
2.7	Both	The number of sensors for air temperature and surface temperature measurement shall be at least two per square meter and not less than nine, unless other information on the temperature distribution is available.	2.8 thermocouples per square metre are used for a specimen filling the aperture. 4.5 thermocouples per square metre are used on a door and 4.9 thermocouples per square metre used on a window.
2.7.1	Both	Surface temperature measurements shall be made with sensors chosen and applied to the surface in such a way that the sensors do not change the temperature at the measuring point.	Thermocouples made from 0.2 mm diameter wire are used throughout.
2.7.1	Both	For very inhomogeneous specimens [determination of the average surface temperature] is not possible: in this case specimen thermal resistance, R_s, cannot be measured, as only the transmittance, U, based on the environmental temperature difference across the specimen, can be defined.	Thermal transmittance is always calculated from environmental temperatures.
2.7.1	Both	As a guideline to compare non-homogeneous and very inhomogeneous specimens the following is proposed. Local differences in surface temperature caused by inhomogeneities exceeding 20% of the mean surface-to-surface temperature difference SHOULD be taken as evidence of such inhomogeneity.	Agreed
2.7.2	Both	Air temperature sensors shall be radiation-shielded, unless it is shown that the difference between shielded and unshielded ones is so small that the accuracy requirements are met.	Cold air t/cs shielded. However with small diameter wire - effect of radiant heat exchange is neglible and therefore shielding is unnecessary..

Figure 18 Requirements of EN ISO 8990 (Part 3)

ISO 8990 Clause	Type of box	Requirement in BS EN ISO 8990	NPL Rotatable Wall Guarded Hot Box
2.7.2	Both	In natural convection, temperature sensors **shall be placed** outside the boundary layer, its thickness being a few centimetres in most cases. In turbulent flow the boundary layer thickness may exeed 0.1 m	They always are: Baffle to specimen distance kept greater than 40 mm and air thermocouples placed halfway between them.
2.7.2	Both	In forced convection, turbulent fully developed flow shall exist between the specimen and the baffle, and sensors shall be placed to detect bulk air temperatures (temperature of adiabatic mixing).	It is: Baffle to specimen distance kept greater than 40 mm and air thermocouples placed halfway between them.
2.7.3	GHB	Thermopiles used for monitoring heat flow **through the metering** box walls shall have junctions mounted in the same way as described for surface temperature sensors and with at least one pair of junctions per 0.25 m^2 surface (4 junctions per m^2)..	The junction density in the wall heat flow meter system is 14 junctions per m^2.
2.7.3	GHB	Similar requirements apply to the thermopile used in the Guarded Hot Box for monitoring imbalance heat flow, 2 in the surface of the specimen between metering and guard area, except that at least one pair of junctions per 0,5 m of perimeter of metered area is required.	n/a
2.7.5	Both	At steady-state, the controllers shall keep any random temperature fluctuations and long-term drifts within 1% of the air-to-air temperature difference over the specimen for at least two consecutive test periods.	When the air-to-air temperature difference is 20 °C the maximum warm air fluctuation in **40 hours** was 0.07 °C; the maximum cold air fluctuation was 0.14°C and maximum fluctuation in temperature difference was 0.14°C which is 0.35%, 0.7% and 0.7% respectively.
2.7.5	Both	...the control system for the guard box temperatures shall not introduce additional errors on imbalance heat flow rate greater than 0.5% of f_1.	N/a
2.8	Both	Temperature differences shall be measured with an accuracy of +1% of air-to-air temperature difference from hot to cold side.	Error in measuring air temperature difference is estimated to be +/-1%.
2.8	Both	Absolute temperature measurement shall be made with an accuracy of +5% of the air-to-air temperature difference.	Thermocouple wire has been calibrated - uncertainty of the calibration is +/- 0.1°C and the Cropico CJC unit is always within +/- 10 mV = 0.25 °C so worst case uncertainty is +/- 0.35°C = 1.8 % of the air-to-air temperature difference
2.8	Both	The output from balancing thermopiles, power input to heaters, fans, etc. shall be measured with such accuracy that added error in the measurement of the specimen heat flow, ϕ_1 due to instrumentation accuracy will be smaller than 1.5%	Instrumentation accuracy is a very minor source of error.
2.9.1	Both	After completion of the construction, an initial check of performance shall be made	Yes - these have been carried out with:
		Estimated uncertainty of EPS thermal conductivity measurement was ± 2%	1) 150 mm thick EPS validation panel R01 which was measured to 2.3% of it's calculated thermal conductance
		Estimated uncertainty of thermal conductance determination was ± 5%	2) Glazed calibration panel TT206 which was measured to within 4.5% of its calculated thermal conductance value.
		Estimated uncertainty of thermal conductance determination was ± 5%	3) Glazed calibration panel TT206 which was measured to within 4.1% of its calculated thermal conductance value.

Figure 19 Requirements of EN ISO 8990 (Part 4)

ISO 8990 Clause	Type of box	Requirement in BS EN ISO 8990	NPL Rotatable Wall Guarded Hot Box
2.7.2	Both	In natural convection, temperature sensors **shall be placed** outside the boundary layer, its thickness being a few centimetres in most cases. In turbulent flow the boundary layer thickness may exeed 0.1 m	They always are: Baffle to specimen distance kept greater than 40 mm and air thermocouples placed halfway between them.
2.7.2	Both	In forced convection, turbulent fully developed flow shall exist between the specimen and the baffle, and sensors shall be placed to detect bulk air temperatures (temperature of adiabatic mixing).	It is: Baffle to specimen distance kept greater than 40 mm and air thermocouples placed halfway between them.
2.7.3	GHB	Thermopiles used for monitoring heat flow **through the metering** box walls shall have junctions mounted in the same way as described for surface temperature sensors and with at least one pair of junctions per 0.25 m^2 surface (4 junctions per m^2)..	The junction density in the wall heat flow meter system is 14 junctions per m^2.
2.7.3	GHB	Similar requirements apply to the thermopile used in the Guarded Hot Box for monitoring imbalance heat flow, 2 in the surface of the specimen between metering and guard area, except that at least one pair of junctions per 0,5 m of perimeter of metered area is required.	n/a
2.7.5	Both	At steady-state, the controllers shall keep any random temperature fluctuations and long-term drifts within 1% of the air-to-air temperature difference over the specimen for at least two consecutive test periods.	When the air-to-air temperature difference is 20 °C the maximum warm air fluctuation in **40 hours** was 0.07 °C; the maximum cold air fluctuation was 0.14°C and maximum fluctuation in temperature difference was 0.14°C which is 0.35%, 0.7% and 0.7% respectively.
2.7.5	Both	...the control system for the guard box temperatures shall not introduce additional errors on imbalance heat flow rate greater than 0.5% of f_1.	N/a
2.8	Both	Temperature differences shall be measured with an accuracy of +1% of air-to-air temperature difference from hot to cold side.	Error in measuring air temperature difference is estimated to be +/-1%.
2.8	Both	Absolute temperature measurement shall be made with an accuracy of +5% of the air-to-air temperature difference.	Thermocouple wire has been calibrated - uncertainty of the calibration is +/- 0.1°C and the Cropico CJC unit is always within +/- 10 mV = 0.25 °C so worst case uncertainty is +/- 0.35°C = 1.8 % of the air-to-air temperature difference
2.8	Both	The output from balancing thermopiles, power input to heaters, fans, etc. shall be measured with such accuracy that added error in the measurement of the specimen heat flow, ϕ_1 due to instrumentation accuracy will be smaller than 1.5%	Instrumentation accuracy is a very minor source of error.
2.9.1	Both	After completion of the construction, an initial check of performance shall be made	Yes - these have been carried out with:
		Estimated uncertainty of EPS thermal conductivity measurement was ± 2%	1) 150 mm thick EPS validation panel R01 which was measured to 2.3% of it's calculated thermal conductance
		Estimated uncertainty of thermal conductance determination was ± 5%	2) Glazed calibration panel TT206 which was measured to within 4.5% of its calculated thermal conductance value.
		Estimated uncertainty of thermal conductance determination was ± 5%	3) Glazed calibration panel TT206 which was measured to within 4.1% of its calculated thermal conductance value.

Figure 20 Requirements of EN 1946-4 Annex A.1.1

EN 1946-4:2000

Annex A (normative)
Limits for equipment performance and test conditions

A.1 A.1.1 Clause in EN 8990	Calibrated and guarded hot box Accuracy and repeatability, stability, uniformity Description	Accepted value	NPL value
2.3.1	maximum error allowed in the measurement of the specimen heat flow rate caused by the metering box losses	0,5 %	0.03%
2.3.2	maximum Variation allowed in air temperature across the air flow parallel to specimen surface	2%	0.40%
2.3.2	maximum air temperature gradients allowed along the air flow	2 **K**/m	1.7 °C/m
2.3.2	maximum error allowed in the measurement of the specimen heat flow rate caused by the measurement of shaft power	0,5 %	N/a
2.4	maximum error allowed in the measurement of the specimen heat flow rate caused by heat flow rate at the edge of the specimen	0,5 %	<0.1%
2.4	maximum imbalance error due to non-uniformity of temperature as a percentage of the heat flow rate through the metered area of the specimen	0,5 %	N/a
2.7.1	maximum difference allowed in surface temperature as percentage of mean surface-to-surface temperature difference for inhomogeneous specimens	20%	Specific to test
2.7.5	required short-term and long-term stability of the temperature as a percentage of the temperature difference over the specimen	1%	0.70%
2.7.5	maximum allowed additional imbalance heat flow rate error due to the controllers {of the guard box}	0,5 %	N/a
2.8	Required accuracy in the measurements of temperature differences between heating and cooling unit as a percentage of the air-to-air temperature difference	±1 %	±1 %
2.8	maximum equivalent level of uncertainty of the instrument in temperature measurements	0,05 **K**	< 0.03 K
2.8	required accuracy in the measurement of absolute temperatures as a percentage of air-to-air temperature difference	**±** 5 %	1.80%
2.8	maximum error allowed in the measurement of specimen heat flow rate due to instrumentation accuracy	1,5 %	<1%
3.5	maximum allowed difference between two subsequent measurement periods for resistance, transmittance, power and temperature	1%	<1%

Figure 21 Requirements of EN 1946-4 Annex A.1.2 & A.1.3 & A.1.4

A.1.2	**Equipment design requirements**		
Clause in ISO 8990	**Description**	**Accepted value**	**NPL value**
1.6.1.1	maximum allowed heat flow rate through the metering box walls as a percentage of the total power input	10%	<0.7%
2.2	recommended minimum total hemispherical emissivity for any surface in contact with the specimen	0,8	0.9
2.3.1	maximum width of the gasket on the nose on the metering box as a percentage of the metering width	2%	N/a
2.3.1	maximum width of the gasket on the nose on the metering box	20 mm	N/a
2.6	recommended range of air velocity in simulating natural conditions for building component	0,1 m/s to 10 m/s	0.1 to 5 m/s
2.7.1	maximum thermocouple diameter when measuring air and surface temperature	0,25 mm	0.2 mm
2.7.1	recommended length of the adjoining wire of the junctions in thermal contact with the surface	100 mm	50 mm
2.7.3	maximum surface area to be covered by one pair of junctions	0,25 m^2	0.07 m^2
2.7.3	minimum distance between two pairs of junctions along the perimeter of the metered area	0,5 m	N/a

A.1.3	**Acceptable specimen characteristics**		
Clause in ISO 8990	**Description**	**Accepted value**	**NPL value**
2.7.1	maximum allowed difference in surface temperature as percentage of mean surface-to-surface temperature difference for inhomogeneous specimens	20%	Specific test

A.1.4	**Acceptable testing conditions**		
Clause in ISO 8990	**Description**	**Accepted value**	**NPL value**
3.4	recommended range of mean test temperature	from 10 °C to 20 °C	Agreed
3.4	recommended minimum temperature difference	20 °C	Agreed

Figure 22 Requirements of EN ISO 12567-1 (Part 1)

A.3	Determination of thermal transmittance of doors and windows by hot box method		
A.3.1	**Accuracy and repeatability, stability, uniformity**		
Clause in EN12567-1	**Description**	**Accepted value**	**NPL value**
5.1	The operation of the hot box shall be in according to EN ISO 8990:1996 requirements	n/a	See Figs 17 to 20
A.3.2	**Equipment design requirements**		
Clause in EN12567-1	**Description**	**Accepted value**	**NPL value**
5.2	minimum required thickness of the surround panel	100 mm	150 mm
5.2	maximum allowed thermal conductivity of the surround panel	0,04 W/(m x K)	0.0335 W/m.K
5.2	maximum allowed thermal conductivity for a material that bridges the aperture	0,04 W/(m x K)	N/a
5.2	minimum required emissivity of the surfaces of the surround panel and baffle plates	0,8	0.9
5.3	recommended minimum distance of the aperture from the inside surfaces of the cold and hot boxes	200 mm	> 200 mm
5.3	minimum required surface area for the aperture contact with the enclosed insulating material	1 m^2	> 1 m^2
5.5	minimum number of positions to be used to measure surface temperature on the surround panel	8	12
5.5	minimum distance of temperature sensors from the edge of calibration panel	100 mm	205 mm
5.5	maximum thermocouple diameter when measuring surface temperature	0,3 mm	0.2 mm
5.5	minimum required emissivity of the outer surface of any adhesive or adhesive tape used to fix thermocouples	0,8	0.9
5.5	minimum distance between the baffle and the warm face of the surround panel	150 mm	150 mm
5.5	minimum distance between the baffle and the cold face of the surround panel	50 mm	100 mm
5.5	minimum allowed air speed	1,5 m/s	4.1 m/s

Figure 23 Requirements of EN ISO 12567-1 (Part 2)

A.3.3	Acceptable specimen characteristics		
Clause in EN12567-1	Description	Accepted value	NPL value
4	maximum allowed tolerance of the projected area of the specimen as percentage of the surround panel aperture	0,5 %	< 0.3%
5.3	recommended height for test specimens for standardized test application for windows	1480 mm	Yes
5.3	recommended width for test specimens for standardized test application for windows	1230 mm	Yes
5.3	recommended height for test specimens for standardized test application for doors	2000 mm	Yes
5.3	recommended width for test specimens for standardized test application for doors	1000 mm	Yes
5.4	recommended thicknesses for the calibration panel	20 mm; 60 mm	Yes Yes
C.1.1	approximate density of the expanded polystyrene of the core material of the calibration panel	28 kg/m ^{3}	Yes
C.1.1	required thickness of the two pieces of float glass in	4 mm	Yes
5.4	required mean temperature range to measure the thermal conductance of calibration panels	from 5 °C to 15 °C	Yes

A.3.4	Acceptable testing conditions		
Clause in EN12567-1	Description	Accepted value	NPL value
5.4	required distance from the warm face of the surround panel when mounting the calibration panel in the surround panel	40 mm	Yes
5.5	minimum number of Position to be used to measure surface temperature on the calibration panel	9	Yes
6.2.1.1	required steps in mean air temperatures for calibration measurements	± 5 °C	Yes
6.2	required mean temperature at which each calibration panel shall be measured	10 °C	Yes
6.2.1.1	required environmental temperature difference between hot and cold sides	20 K ± 2 K	Yes
6.2.1.1	required total surface thermal resistance for the calibration panel	0,17 ± 0,01 $m^2 \cdot K/W$	Yes
6.3	required approximate mean air temperature at which measurement of test specimen shall be done	10 °C	Yes