Report on hot box measurements using the procedures specified in ISO/CD 12567 and CEN/TC 89 WI 26 part 2 03.1995 on two glazed, calibrated, reference panels (1.48 m x 1.23 m).

Ray Williams & David Hall

December 1995

NPL Report QM115
December 1995

Report on hot box measurements using the procedures specified in ISO/CD 12567 and CEN/TC 89 WI 26 part 2 03.1995 on two glazed, calibrated, reference panels (1.48 m x 1.23 m).

Ray Williams & David Hall
Centre for Quantum Metrology
National Physical Laboratory
Teddington, Middlesex, UK TW11 0LW

ABSTRACT

This report outlines the principles of draft CEN standard procedures for measuring the U-value of windows and window components in a hot box. The constructional details of the glazed calibration panels, required by those standards, are described and the methods used to calculate their thermal performance are given. Details of the hot box measurements made with those panels, as specified in the draft CEN standards, are included. The graphs produced from these data, required for any subsequent hot box measurements of window systems to achieve the following; normalise the U-value to standard surface resistances, derive the heat flux density through the test element and to calculate the environmental temperatures, are also included. Finally, the sensitivity to the calibration measurement results, of subsequent U-value measurements, are discussed.

ISSN 1361-4045

National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

Approved on behalf of Managing Director, NPL
by Dr J R Gott, Director, Centre for Quantum Metrology

CONTENTS

LIST OF SYMBOLS

Symbol	Physical Quantity	Unit
A	Area	m^2
F	Fraction	-
θ	Celsius temperature	°C
Φ	Heat flow rate	W
q	Density of heat flow rate	W/m^2
R	Areal thermal resistance	$m^2.K/W$
H	Heat exchange coefficient	$W/m^2.K$
h	Surface coefficient of heat transfer	$W/m^2.K$
d	Thickness	m
C	Conductance	$W/m^2.K$

Subscript	Symbol
Convection (air)	a
Baffle	b
Calibration	c
Exterior (cold)	e
Interior (hot)	i
Surround panel	sur
Total	t
Radiant	r
Input	in
Measured	m

1 PRINCIPLE OF THE NEW DRAFT CEN STANDARDS

1.1 THE CEN STANDARDS

There are draft CEN standards for U-value measurements of the following:-

• A glazed unit	prEN 1098 (BS 6993 Part 2)
• A window frame section	CEN/TC 89 N 216 E rev. 02.1995
• A whole glazed window assembly	CEN/TC 89 WI 26 Part 2 03.1995

These standards use a new method to derive a number of important parameters; a method that relies totally on hot box measurements of glazed, calibrated reference panels

1.2 THE FEATURES OF THE NEW METHODOLOGY

The objective of this approach is to enable the following operations to be carried out without measuring the surface temperature of the test element.

- normalise the measured U-value to a standard total surface resistance value
- calculate the boundary loss around the window edges
- calculate the environmental temperature on the hot and cold sides

1.3 AN OUTLINE OF THE NEW METHODOLOGY

The CEN measurement approach is the same for all three standards. The method involves the following steps:-

i) Making at least two glazed, calibrated reference panels with the following approximate dimensions.

   - 4 mm glass / 12 mm insulation / 4 mm glass
   - 4 mm glass / 50 mm insulation / 4 mm glass
   - For whole window systems the recommended size of panel is 1.48 m x 1.23 m
   - For insulated glazing panels the recommended panel size is 1.2 m x 1.2 m.

ii) The thermal conductance of these panels must be calculated by measurements of the thermal conductivity of the insulation material and the thickness of the panel and/or insulation material.

iii) Three U-value measurements must then be made of each glazed reference panel, as described in the standard.

iv) From these measurements the following graphs are produced:-

- Total surface resistance vs heat flux density. This is used to normalise the measured U-value to the standard surface resistance of 0.17 m^2.K/W.

- Holder panel coefficient vs the mean temperature of the holder panel for the two calibrated reference panels. This is used to derive the total power through the holder panel needed to calculate the power through the test element.

- Convective fraction vs heat flux density for the hot and cold sides. This is used to calculate the environmental temperatures of the hot and cold sides.

2 FABRICATION OF THE CALIBRATION PANELS

2.1 CALIBRATION PANEL SIZES

This report describes the measurements carried out on panels measuring 1.48 m x 1.23 m, required when making hot box measurements of whole-window systems.

2.2 FIXING THE GLASS TO THE EPS

Each panel is made from a sheet of Expanded Polystyrene (EPS) material sandwiched between two sheets of 4 mm thick, toughened glass. The EPS is fixed to the glass using Araldite (glue) 2019, at 36 points, equally distributed over the EPS surface. Each adhesion point is approximately 35 mm in diameter.

2.3 THICKNESS MEASUREMENTS OF THE CORE MATERIAL AND FINISHED PANEL

The thickness of the 1.48 m x 1.23 m pieces of EPS selected and of the finished glazed panel, were measured at 32 places, by placing them on a large surface-table and measuring down onto their top surface from a purpose-built gantry using a depth gauge. The base-line was established by measuring down to the surface table in the same way. This is referred to as method A. For the purpose of calculating heat transfer through the panel, the gap between the glass sheets is assumed to be full of EPS. The results of these measurements are given in Table 1 for TT083 and Table 2 for TT084. The uncertainty of each measurement is estimated as ± 0.2 mm so the total uncertainty of the thickness measurement is estimated as ± 0.3 mm. This is ± 2.5% for the 12 mm panel and ± 0.6% for the 60 mm panel.

A more precise, yet inexpensive, method for measuring the thickness of the glazed panel has been devised. This requires a plywood board 1000 mm long x 300 mm wide and 25 mm thick in which a 660 mm long, 30 mm wide slot has been cut along the centre. A Linear Displacement Transducer (with a resolution of 0.02 mm) was mounted at the entrance to the slot on one side and a ball bearing fixed in position opposite it. This "micrometer" was calibrated using 19 mm and 20 mm slip gauges. This is referred to as method B. The thickness of panel TT083 was measured (in 63 positions) when in both the vertical and horizontal position. The average thicknesses measured were within 0.1 mm of each other. The summary of the measurements carried out with the panel in the vertical position, using this method, is also given in Table 1. The value obtained using method B has been used in the calculations that follow.

Table 1: Summary of thickness measurements for TT083

Mean thickness (mm) of the EPS core and of the glazed panel TT083		
Method A		
EPS average thickness	=	11.53
Standard deviation	=	0.16
Minimum thickness	=	11.22
Maximum thickness	=	11.73
Glass thickness (at edges)	=	4.00
Method A		
Glazed panel average thickness	=	20.01
Standard deviation	=	0.18
Minimum thickness	=	19.76
Maximum thickness	=	20.29
Average Air Gap	=	0.24 (per side)
Thickness assumed for the EPS core	=	12.01 ± 0.3
Method B		
Glazed panel average thickness	=	19.69
Standard deviation	=	0.26
Minimum thickness	=	19.07
Maximum thickness	=	20.08
Average Air Gap	=	0.08 (per side)
Thickness assumed for the EPS core	=	11.69 ± 0.1
Thickness taken for the EPS core	=	11.69 ± 0.1 mm

Table 2: Summary of thickness measurements for TT084

Mean thickness (mm) of the EPS core and of the glazed panel (TT084)		
EPS average thickness	=	59.69
Standard deviation	=	0.18
Minimum thickness	=	59.47
Maximum thickness	=	60.04
Glazed panel average thickness	=	67.98
Standard deviation	=	0.17
Minimum thickness	=	67.69
Maximum thickness	=	68.19
Average air gap	=	0.15 (per side)
Glass thickness (at edges)	=	4.00
Thickness assumed for the EPS core	=	59.98 ± 0.3 mm

2.4 THERMAL CONDUCTIVITY MEASUREMENTS OF THE CORE MATERIAL

The thermal conductivity of the 12 mm thick EPS material used in TT083 was measured in the NPL Standard 305 mm x 305 mm guarded hot plate apparatus. The two specimens required were cut from the same sheet as the material that was used in TT083 and then machined flat to within 0.2 mm, the flatness specified in BS 874 Part 2 Section 2.1.

Table 3 Thermal conductivity of the EPS material used in TT083

Thermal Conductivity of Expanded Polystyrene used in TT083 Thickness in GHP = 11.56 mm		
Mean specimen temperature (°C)	Temperature Difference (°C)	Thermal conductivity W/(m.K)
-0.13	16.40	0.0313
7.60	15.90	0.0322
17.10	15.30	0.0332

The thermal conductivity values shown in Table 3 are, however, about 4% higher than would be expected for material of this density. Other thermal conductivity measurements made on EPS from this batch, gave the values shown in Table 4. Previous measurements made on four different 11 mm thick EPS sheets, taken from another batch, gave values that were within about 1% of one another. See Table A9 and Graph A10 in the Appendix. It was therefor decided to assume that the values in Table 3 were not representative of the material actually used in the panel TT083. This decision is supported by the previous good agreement obtained between conductance values measured in the hot box and the predicted conductance obtained for 15 different calibration panels measured over a five year period. It should also be noted, that the U-values for a whole-window system, derived from these values using the CEN method are not sensitive to the calculated conductance of the thin panel. See section 7.

Table 4: Thermal conductivity of the EPS material used in TT083

Thermal Conductivity values for the EPS sheet from the same batch used in TT083[1] Thickness in GHP = 11.56 mm		
Mean specimen temperature (°C)	Temperature Difference (°C)	Thermal conductivity W/(m.K)
3.3	16.67	0.0303
10.3	16.40	0.0311
20.0	15.90	0.0321

[1] These values were obtained for a sheet of EPS from the same batch as in TT083 used in the SM&T Project 3032. The identification numbers of the two thermal conductivity specimens is QM179 A & B.

The thermal conductivity of the 59 mm thick EPS material was measured in the NPL 610 mm x 610 mm Guarded Hot Plate Apparatus. The single specimen was machined flat to within 0.2 mm, the flatness specified in BS 874 Part 2 Section 2.1. These results are shown in Table 5.
The uncertainty of the λ measurements on the 11.6 mm thick EPS is estimated as ± 3% at the 95% confidence level. This figure is larger than normally quoted for the NPL 305 mm Guarded Hot Plate Apparatus (±1.5%) to account for the increased errors that result from the unusual thinness of the specimens. The uncertainty of the measurements on the 59 mm thick material is estimated as ± 2% at the 95% confidence level.

Table 5: Thermal conductivity of the EPS material used in TT084

Thermal Conductivity of Expanded Polystyrene used in TT084 Thickness in GHP = 59.52 mm		
Mean specimen temperature (°C)	Temperature Difference (°C)	Thermal conductivity W/(m.K)
4.80	15.90	0.0339
11.90	16.30	0.0349
19.90	16.40	0.0358

2.5 CALCULATION OF CALIBRATION PANEL CONDUCTANCE

The thermal conductivity of the EPS at each experimental mean temperature was calculated from the data in Tables 4 and 5. The thickness of EPS in each panel was assumed to be the same as the average gap between the two sheets of glass. The thermal conductivity of glass was taken to be 1 W/m.K. The calculations are shown in Table A1 in the Appendix.

3 THE HOT BOX MEASUREMENTS

3.1 EXPERIMENTAL DETAILS

The hot box measurements were carried out in the NPL Wall Guarded Hot Box, which is described in some detail in NPL Report QU 91. The instrumented panels were mounted in a 150 mm thick EPS holder panel and the thermal properties measured in the NPL WGHB in the normal way. The panels were mounted 25 mm from the cold face of the holder panel as shown in Figure 1.

The hot and cold surface temperatures of the panels are measured by nine thermocouples on each face. The thermocouples were placed in the centre of squares of equal area. The thermocouples are made from 0.2 mm diameter PTFE coated wire. The thermocouples have been calibrated in the following manner. Five 1.2 m long thermocouples were cut at equal distances along each reel of wire used. These five thermocouples were calibrated by the NPL Temperature Section and an equation derived from all five sets of data. The thermocouples used in the WGHB have had the PTFE insulation removed for at least 50 mm from the hot junction. The thermocouples are fixed to the glass surface with paper masking tape, after first smearing the bare wire with ZnO loaded silicone grease. The portion of wire in contact with the glass is always fixed horizontally.

Additional thermocouples were used to measure the holder-panel reveal temperature in the hot box.

Three measurements were made with different heat flux densities as specified in CEN/TC 89 WI 26 Part 2 03.1995.

3.2 THE MEASUREMENT RESULTS

Six sets of measurement data were obtained, each being the average of five sets of readings taken every two hours, after equilibrium had been reached. The results are shown in Tables A2, A3, A4 and A5 in the Appendix.

4 CALCULATION OF THE CEN CALIBRATION DATA

The detailed calculations for the holder panel heat transfer coefficients and total surface resistances can be seen in Table A6 in the Appendix. The calculations and data used to calculate the Hot and Cold side convective fractions can be seen in Tables A7 and A8 in the Appendix.

A summary of the important measurement parameters are presented in Table 6, together with the values which are derived from them and used to plot the graphs required by the CEN draft standards.

These graphs are as follows:-

Graph 1 Heat Flux Density vs Total Surface resistance

Graph 2 Holder Panel Heat Transfer Coefficient vs Holder panel Mean temperature.

Graph 3 Convective Fraction for the Hot and Cold sides vs different heat flux densities.

FIGURE 1 **Specimen Mounting Details**

Table 6: Summary of measured and calculated values

	Calibration Panel TT083			Calibration Panel TT084		
d[m] thickness [m]	0.02001			0.06798		
A area of panel [m^2]	1.827			1.846		
Test number	1	2	3	1	2	3
$\theta_{c.mean}$ {mean panel temperature} [°C]	14.53	11.20	6.49	15.32	10.70	4.74
Cold temperatures - measured						
$\theta_{a.e}$ {air} [°C]	8.17	2.51	-5.73	8.00	-0.64	-12.06
$\theta_{b.e}$ {baffle} [°C]	8.21	2.58	-5.64	8.04	-0.58	-11.98
$\theta_{c.e}$ {cal panel} [°C]	9.56	4.37	-3.12	8.43	0.01	-11.08
$\theta_{sur.e}$ {reveal - estimated} [°C]	8.43	2.88	-5.22	8.29	-0.20	-11.4
Hot temperatures - measured						
$\theta_{a.i}$ {air} [°C]	23.28	22.97	22.69	23.62	23.42	23.33
$\theta_{b.i}$ {baffle} [°C]	22.33	21.55	21.12	23.09	22.65	22.29
$\theta_{c.i}$ {cal panel} [°C]	19.50	18.03	16.10	22.21	21.39	20.56
$\theta_{sur.i}$ {reveal} [°C]	21.36	20.57	19.57	22.06	21.14	20.22
Φ_{in} {Hot box power - measured} [W]	55.90	76.38	105.38	23.58	36.55	53.14
v_i {air flow hot} [m/s]						
v_e {air flow cold] [m/s]						
$C(\theta_{c.mean})$ {Calc conductance} [$W/m^2.K$]	2.640	2.610	2.569	0.585	0.576	0.563
q_c {power cal panel - calc.} [W/m_2]	26.27	35.66	49.37	8.063	12.30	17.82
$h_{r.i}$ {radiant sur coef- hot} [$W/m^2.K$]	4.875	4.819	4.759	4.969	4.936	4.904
$h_{r.e}$ {radiant sur coef- cold} [$W/m^2.K$]	4.136	3.903	3.580	4.108	3.746	3.301
$h_{a.i}$ {convective coef- hot} [$W/m^2.K$]	3.508	3.945	4.054	3.042	3.432	3.785
$h_{a.e}$ {convective coef- cold} [$W/m^2.K$]	22.89	22.90	22.35	22.40	22.28	21.12
$F_{a.i}$ {Convective fraction - hot}	0.419	0.450	0.460	0.380	0.410	0.436
$F_{a.e}$ {Convective fraction - cold}	0.847	0.854	0.862	0.845	0.856	0.865
R_{tc} {Total res. cal.panel} [$m^2.K/W$]	0.174	0.168	0.168	0.185	0.180	0.177
H_{sur} {Surround panel coef} [W/K]	0.550	0.575	0.559	0.592	0.610	0.605

Graph 1 **Heat Flux Density vs Total Surface resistance**

Graph 2 Holder Heat Transfer Coefficient vs Holder Mean temperature.

Graph 3 Convective Fraction vs Heat flux densities.

6 UNCERTAINTIES

6.1 WGHB MEASUREMENTS

An error analysis of this equipment is presented in NPL Report QU 91, page 8. The uncertainty in the measurement of conductance of a double-glazed panel mounted in a holder requiring a boundary loss correction is +5.5% to -6.5% at the 95% confidence level. This uncertainty is confirmed by the results of the measurements on fifteen homogeneous reference panels of different constructions with thermal conductances ranging from 0.6 to 6.8 W/m^2K. The measured thermal conductance of those panels were all within ± 5% of the value calculated from thermal conductivity data measured with the NPL guarded hot-plate apparatus. The uncertainty of the guarded hot-plate measurements was ±3% or better.

6.2 PREDICTED CONDUCTANCE OF THE INSTRUMENTED PANELS

The uncertainty of the thermal conductivity measurement is ± 3% and the uncertainty of the thickness measurement is estimated as ± 3 mm which is ± 2.5% for the thin panel and ± 0.6% for the thick panel. The total uncertainty is therefore estimated as ± 4% for the thick panel and ± 6% for the thin panel.

7 DISCUSSION

The holder-panel heat-transfer coefficient is plotted against the holder-panel mean temperature for the thick and thin panels respectively in Graph 2. This shows the coefficient for the thick panel to be higher than the coefficient for the thin panel, an unexpected result. However, the calculated holder-panel heat-transfer coefficient is very sensitive to changes in the calculated calibration-panel conductance. For instance a 1% change in the conductance of the 20 mm thick calibration panel, produces a 6% change in the holder-panel heat-transfer coefficient. This is highlighted by the error bars in Graph 2 which show the variation of holder panel heat transfer coefficient for a change in the predicted thermal conductance of both calibration panels of ± 5%, the possible uncertainty in their predicted conductances.

Fortunately the thickness of any window frames likely to be measured using the data from these panels will usually be about 70 mm, about the same as that of the thick panel whose conductance is known with more precision and is not so critical. It can be shown that even if the heat transfer coefficient for the thin panel was increased by 42%, the calculated U-value of a window system (with a U-value of 2.5) only increases by 0.25%.

The most important effect of the calculated conductance value of the thin panel is in correcting the measured U-values to the standard total surface resistance value. By increasing the calculated conductance by about 5% the standardised U-value of a window with a U-value of 2.5 $W/m^2.K$, will increase by about 1.8%.

Finally some of the outer "glue spots" on the cold side of the calibration panels have delaminated. This did not happen with the other calibration panels of this type that have been made at the NPL. It is almost certainly due to the larger size and the large temperature difference across the panel and the low temperatures -15°C that required by this procedure. The overall thicknesses of the panels, however, do not seem to have been effected. In future an adhesive system that retains its flexibility to these low temperatures must be used.

8 CONCLUSIONS

i) It is important that the thermal conductance of the calibration panels is determined as precisely as is practically possible. This means:-

- Measuring the thickness of the panel to a precision of ± 0.2mm (± 2% for 12 mm thick panel and 0.5% for 60 mm thick panel). This is not a simple task for these large panels and it is important for a suitable practical method to be identified.

- Measuring the thermal conductivity of the EPS material to a precision of ± 3.5%. This is a fairly demanding requirement for the thin material.

ii) There appears to be a possibility that the thermal properties of EPS with the same density can vary by as much as 4%. This needs to be investigated further to understand why and how likely it is to occur. It would be useful if a simple sorting test could be developed that could be used to ensure different pieces of EPS had similar properties. For example the measurement of light transmission.

iii) The density of EPS can also vary from place to place over a 2.4 m x 1.2 m sheet. Therefore it is important to use EPS with as high a density as possible where the thermal conductivity vs density curve is fairly flat.

iv) Even though the holder-panel heat-transfer coefficient is sensitive to the calculated conductance of the calibration panel (see Graph 2), the uncertainty in the calculated value of the power through the test element is actually always the same as the uncertainty in the conductance of the calibration panels. This uncertainty figure, however, includes many other sources of error, not necessarily identified in the simpler method, which have now effectively been calibrated out.

v) A better adhesive system must be identified for use with any future panels.

Table A1 Calculation of the thermal conductance of the calibration panels

Table A2 **Hot box measured values TT083**

Table A3 **Hot box measured values TT083**

Table A4 **Hot box measured values TT084**

Table A5 **Hot box measured values TT084**

Table A6 Calculations of total surface resistance and holder panel coefficients

Table A7 Calculation of convective fraction - Part 1

Table A8 **Calculation of convective fraction - Part 2**

Table A10 Thermal Conductivity of EPS material

Material details	Thickness (mm)	Density (kg/m^3)	λ @ 10°C (W/m.K)
QM179A and QM179B **SM&T 3032 project TT0??**	11.57	26.7	0.0311 & 0.0309
QM178A and QM178B **DOE project TT083**	11.56	26.9	0.0325 4.3% higher than SM&T
QM177A and QM177B **TT082 Instrumented Panel**	11.52	21.3	0.0318
QM169 **TT072 Glazed calibration panel**	10.19	20.0	0.0329
QM170 **TT074 Glazed calibration panel**	10.67	20.03	0.0330
QM166 **TT077 Glazed calibration panel**	10.30	20.08	0.0328
QM167 **TT076 Glazed calibration panel**	10.77	20.13	0.0327
QM166 & QM167 Combined to make a 21 mm thick specimen	21.07	20.10	0.0339 3.3% higher individual
LA 36 TT073 Glazed calibration panel	56.19	19.39	0.0355 8.2% higher than QM166
LA 37 TT075 Glazed calibration panel	56.26	19.34	0.0356 8.5% higher than QM166
LA 43 Glazed cal panel DOE project TT084	59.52	24.36	0.0346 6.5% higher than QM178
LA 48 Glazed cal panel SMT Project TT0??	59.15	26.10	0.0343 10.3% higher than QM179

Table A9 Thermal Conductivity values of EPS material

Graph A10 Thermal Conductivity vs Density for EPS material