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An evaluation of the effect of high performance spacer bars on the thermal performance of a range of window systems.

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Abstract

In this project the U-value of seventy-eight window systems were calculated by the Centre for Window and Cladding Technology using the procedures specified in BS EN ISO 10077-1, BS EN ISO 10077-2 and BS EN 673 standards and the U-value of twelve of those window systems have been measured by the National Physical Laboratory using the procedures specified in BS EN ISO 12567-1. The window systems included five types of frame, three types of glazing unit and six types of spacer bar. The improvement to the overall U-value resulting from the use of the high performance spacer bars is reported and the linear thermal transmittance (Ψ) and frame U-value (U_f) values are also given. The measured values are shown to largely support the calculated U-values and some reasons for the observed differences are explored.

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Approved on behalf of Managing Director, NPL
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CONTENTS

1 INTRODUCTION 7
2 DETAILS OF THE MEASUREMENT AND CALCULATION METHODS .. 7
2.1 Description of the NPL Wall-Guarded Hot Box 7
2.2 Description of the measurement procedures specified in BS EN ISO 12567-1 . 9
2.3 Standards and software used for the U-value calculations 9
3 THE WINDOW SYSTEMS 10
3.1 The frames 10
3.2 The Insulated Glazing Units 10
3.3 The spacer bar systems 10
4 THE MEASURED U-VALUES 11
5 THE CALCULATED U-VALUES 11
6 DISCUSSION 18
6.1.1 Problems 18
6.1.2 Relationships between the calculated and measured U-values 18
6.1.3 Relationships between the calculated and measured surface temperatures. 20
6.1.4 Main observations 20
6.1.4.1 Variation in real IGU thickness. 21
6.1.4.2 Depth of secondary sealant in the IGU 21
6.1.4.3 Air gaps between secondary sealant and glass edge 21
6.1.4.4 Depth of penetration of the IGU in the frame. 22
7 CONCLUSIONS 22
ANNEX 1 – LIST OF PROJECT PARTNERS 24
ANNEX 2 WINDOW FRAME DRAWINGS 25
ANNEX 3 GLAZING UNIT SPACER BAR DETAILS 30
ANNEX 4 THERMAL CONDUCTIVITY DATA 31
ANNEX 5 DETAILED MEASUREMENT DATA 32

LIST OF TABLES

Table 1 Description of the window systems to be evaluated 8
Table 2 Measured and calculated U-values 12
Table 3 Measured surface temperatures 14
Table 4 Simulation results for all the window systems 15
Table 5 Summary of the average Ψ, U_f and U_w values for the PVC-U windows 16
Table 6 Summary of the average Ψ, U_f and U_w values for the aluminium windows 16
Table 7 Summary of the average Ψ, U_f and U_w values for the softwood window 17
Table 8 Comparison of calculated and measured surface temperatures 17
Table 9 Relationships between the measured and calculated U-values 19
Table 10 Effect on window U-value of the different spacer bars 20
Table 11 IGU thickness at 10 °C mean temperature 21
Table 12 Measurement details TT294 32
Table 13 Measurement details TT298 33
Table 14 Measurement details TT299 34

Table 15 Measurement details TT300 35
Table 16 Measurement details TT301 36
Table 17 Measurement details TT302 37
Table 18 Measurement details TT303 38
Table 19 Measurement details TT304 39
Table 20 Measurement details TT306 40
Table 21 Measurement details TT307 41
Table 22 Measurement details TT309 42
Table 23 Measurement details TT308 43
Table 24 Measurement details TT310 44

LIST OF FIGURES

Figure 1 Positions of the surface thermocouples during the U-value measurements 13
Figure 2 Air gap at IGU edge 21
Figure 3 Position of insulation panel in frame 22
Figure 4 Section drawings of the softwood window 25
Figure 5 Section drawings of the 3 Chamber PVC-U window 26
Figure 6 Section drawings of the 5 Chamber PVC-U Frame 27
Figure 7 Section drawings of the aluminium frame - 5 mm fill and debridge 28
Figure 8 Section drawings of the aluminium window 23 mm polyamide thermal break 29
Figure 9 Spacer bar details 30

1 INTRODUCTION

Funding for this project came from the DTI Partners in Innovation (Pii) scheme, the Glass and Glazing Federation, who coordinated the project, and a number of Industrial Partners. The names of the partners are given in ANNEX 1 – LIST OF PROJECT PARTNERS

The objective of the project was to evaluate the improvement in thermal performance of fifteen window systems (comprising five frame types with three insulated glazing unit (IGU) types) that resulted from using different spacer bar systems in the IGUs. To evaluate those systems, the following measurements and calculations were carried out:-

a) The U-value and linear thermal transmittance (Ψ) values of the seventy-eight window systems shown in Table 1 have been calculated by the Centre for Window and Cladding Technology (CWCT) using the procedures specified in BS EN ISO 10077-2 and BS EN 673.

b) The U-value of twelve of the systems (Table 1) has been measured by the National Physical Laboratory (NPL) using the procedures specified in BS EN ISO 12567-1.

The systems for which the U-values were that were calculated and measured are listed in Table 1 and described in more detail in Section 4.

2 DETAILS OF THE MEASUREMENT AND CALCULATION METHODS

2.1 Description of the NPL Wall-Guarded Hot Box

The thermal transmittance measurements were made in the NPL Wall Guarded Hot Box, described in NPL Report QU 91. Where relevant, the equipment and measurement procedures are in accordance with the requirements of BS EN ISO 8990:1996. The main features of the equipment are summarised below:

- The interior dimensions of the hot box are 1.95 m x 1.95 m.
- All surfaces “seen” by the test element are matt black.
- There are nine air temperature sensors, 75 mm from the holder panel face, positioned at the centres of squares of equal areas in front of the window in both the hot and cold boxes.
- The net heat flow direction is horizontal.

This facility is accredited by UKAS to comply with BS EN ISO 8990 and to carry out measurements of windows to the procedures specified in BS EN ISO 12567-1.

Table 1 Description of the window systems to be evaluated

GGF Pii Project Evaluating warm edge technology				≤ Calculated		
IGU Details	**Spacer type**	**Wood frame**	**PVC-U 3 Chamber**	**PVC-U 5 Chamber**	**Aluminium 5 mm fill and debridge**	**Aluminium 23 mm Polyamide**
U-value = 1.7 W/m^2.K	Al. Standard type	≤	≤	≤	≤	≤
Gap = 16 mm	Azon - Warmlight	≤	≤	≤	≤	≤
Fill = Air	Swiggle	≤	≤	≤	≤	≤
Coating = Pilk K	TPS	≤	≤	≤	≤	≤
	Swiss spacer	-	≤	-	-	-
(ε_n =0.15)	Super spacer	≤	≤ & Measure	≤	≤	≤
U-value = 1.4 W/m^2.K	Al. Standard type	≤	≤ & Measure	≤	≤	≤
Gap = 16 mm gap	Azon - Warmlight	≤	≤ & Measure	≤	≤	≤
Fill = Air	Swiggle	≤	≤ & Measure	≤	≤	≤
Coating = Optitherm SN	TPS	≤	≤ & Measure	≤	≤	≤
	Swiss spacer	-	≤ & Measure	-	-	-
(ε_n =0.04)	Super spacer	≤ & Measure	≤ & Measure	≤ & Measure	≤ & Measure	≤ & Measure
U-value = 1.16 W/m^2.K	Al. Standard type	≤	≤	≤	≤	≤
Gap =16 mm gap	Azon - Warmlight	≤	≤	≤	≤	≤
Fill = 90% Argon	Swiggle	≤	≤	≤	≤	≤
Coating = Optitherm SN	TPS	≤	≤	≤	≤	≤
	Swiss spacer	-	≤	-	-	-
(ε_n =0.04)	Super spacer	≤	≤ & Measure	≤	≤	≤

2.2 Description of the measurement procedures specified in BS EN ISO 12567-1

The measurement procedure specified in BS EN ISO 12567-1 is an air-to-air method requiring no surface measurements of the window being tested. The procedure requires a schedule of measurements to be made on two different thickness of calibration panels, at three different temperature conditions. The calibration panels comprised a core of expanded polystyrene sandwiched between sheets of 4 mm thick float glass. The thermal conductivity of the expanded polystyrene was measured in the NPL standard guarded hot plate apparatus and the average thickness of the calibration panels was measured. From these data, the thermal conductance of each calibration panel was determined.

From the data obtained for the measurements on the calibration panels, three graphs are produced, which are used to carry out the following:

- Calculation of the heat flux density through the holder panel, including any boundary loss around the reveal.
- Calculation of the hot and cold environmental temperatures.
- Correction for the change in surface resistance that results from changing the heat flux density, from the value used to establish the air flow conditions that produced a total surface resistance of 0.17 $(m^2 \cdot K)/W$ with the thin calibration panel, to the heat flux density used when measuring the window.

Windows are mounted in a 150 mm thick expanded polystyrene holder panel as specified in BS EN ISO 12567-1:2000 and the measurements carried out at the temperature conditions specified (environmental temperature difference of 20 ± 1 K).

Thermal transmittance values quoted are the mean of five sets of readings taken at two-hourly intervals. Equilibrium is assumed when the maximum difference between the five thermal transmittance values is less than 1 %.

2.3 Standards and software used for the U-value calculations

- The procedures specified in EN ISO 10077-1 were used to calculate the whole window U-value from its component parts.
- The procedures in BS EN 673 were used to calculate the centre of glazing (COG) U-value.
- The procedures in BS EN ISO 10077-2 were followed when using the FEA software tool to calculate the U-value of the frame sections.
- The FEA Software used was Physibel BISCO.

- When using the BISCO software, two different methods of dealing with radiant heat transfer are possible. The values shown in this report are those obtained using the “simple” method, which is that specified in BS EN ISO 10077-2.

- The FEA Software complies with the requirements of BS EN ISO 10022-1, as required by BS EN ISO 10077-2.

3 THE WINDOW SYSTEMS

3.1 The frames

All the window frames were of the same design, vertically divided with one side-hung casement next to a fixed light. The windows all measured 1.48 m high x 1.23 m wide. The following frames types were used:-

- Softwood – See Annex 1 Figure 4
- PVC-U 3 chamber - See Annex 1 Figure 5
- PVC-U 5 chamber – See Annex 1 Figure 6
- Aluminium – 5 mm fill and debridge thermal break – See Annex 1 Figure 7
- Aluminium – 23 mm polyamide thermal break - See Annex 1 Figure 8

3.2 The Insulated Glazing Units

Three types of glazing unit were used:

- 4mm float glass / 16 mm air filled gas gap / 4 mm Pilkington K
- 4mm float glass / 16 mm air filled gas gap / 4 mm Optitherm SN
- 4mm float glass / 16 mm argon filled gas gap / 4 mm Optitherm SN

3.3 The spacer bar systems

Six types of spacer bar systems were used – See Annex 1 Figure 9.

- Standard desiccant-filled aluminium spacer bar
- Azon Warmlight
- Tremco Swigglestrip
- TPS
- Swiss spacer
- EdgeTech Superspacer

4 THE MEASURED U-VALUES

The measured U-values, for the window systems identified in Table 1, are shown in Table 2, along with the calculated U-values. For each measurement, a table giving the measurement details has also been included (ANNEX 3).

It is important to note that when comparing the measured U-values of windows of the same size, measured in the same surround panel, with the same temperature difference across them, it is the apparatus repeatability that is of importance. The repeatability of the NPL Hot Box apparatus is 1.2 %. Consequently, any real difference between windows that is greater than about 1.5%, should be measurable.

To aid analysis of the correlation between the measured and calculated values, the surface temperatures of the hot and cold surfaces were recorded at five positions on the window during each test (Figure 1). The surface temperatures for all of the measured windows are shown in Table 3.

5 THE CALCULATED U-VALUES

The U-values of the windows that have been both measured and calculated are shown in Table 2. All the simulation results are shown in Table 4. A summary of the linear thermal transmittance value (Ψ) and frame U-value (U_f) are given in Table 5 for the PVC-U windows, Table 6 for the aluminium windows and Table 7 for the soft-wood window.

It should be noted that the measured and calculated results in Table 2 use the calculated results for an aluminium window with a 5 mm fill and debridge thermal break that was 50 mm deep (the same as was tested) whereas the results in Table 4 for all the calculated values include the results for a 70 mm deep window of that type. This resulted from wrong drawings being supplied.

The minimum warm surface temperatures that were calculated for the measured window systems are shown with the equivalent measured surface temperatures in Table 8.

A detailed description of all the calculated U-values, linear thermal transmittance values and minimum surface temperatures are given in the CWCT report 441/GGF/03.

Table 2 Measured and calculated U-values

Frame material	Technical description	Depth -hot to cold (mms)	Gas fill type	Gas gap (mms)	Coating	Spacer bar	Measured U-value $W/m^2.K$	Calculated U-value CEN $W/m^2.K$	Diff. $\frac{(C - M)}{M}$ %
PVC-U	3 Chamber	62	Air	16	Opti/SN	Al.	1.72	1.82	5.6
PVC-U	3 Chamber	62	Air	16	Opti/SN	Warmlight	1.65	1.73	5.0
PVC-U	3 Chamber	62	Air	16	Opti/SN	Swiggle	1.71	1.71	0.1
PVC-U	3 Chamber	62	Air	16	Opti/SN	TPS	1.65	1.69	2.5
PVC-U	3 Chamber	62	Air	16	Opti/SN	Swiss	1.65	1.69	2.6
PVC-U	3 Chamber	62	Air	16	Opti/SN	Super	1.64	1.66	1.0
PVC-U	3 Chamber	62	Air	16	Opti/SN	Super	1.66	1.66	-0.2
PVC-U	5 Chamber	69.5	Air	16	Opti/SN	Super	1.59	1.58	-0.6
Wood	Soft wood	65	Air	16	Opti/SN	Super	1.69	1.59	-5.7
Al.	5 mm thermal brk	50	Air	16	Opti/SN	Super	2.19	2.24 **[1]**	2.3
Al.	23 mm thermal brk	75	Air	16	Opti/SN	Super	1.94	1.94	0.0
PVC-U	3 Chamber	62	Air	16	Pilk K	Super	1.79	1.87	4.5
PVC-U	3 Chamber	62	Argon	16	Opti/SN	Super	1.45	1.49	2.7

Note **[1]** These were specially calculated for the 50 mm deep window that was actually tested
All the other calculated results for the aluminium window with 5 mm thermal break were for a 70 mm deep window.

Figure 1 Positions of the surface thermocouples during the U-value measurements

NPL ID Number: TT301 **Positions of the surface thermocouples on hot and cold side are a mirror image of each other.**

Window description PVC-U / 5 Cham / Optitherm SN / Air / Super Spacer

Hot air 23.332 °C
Cold air 2.197 °C
Air diff 21.136 °C

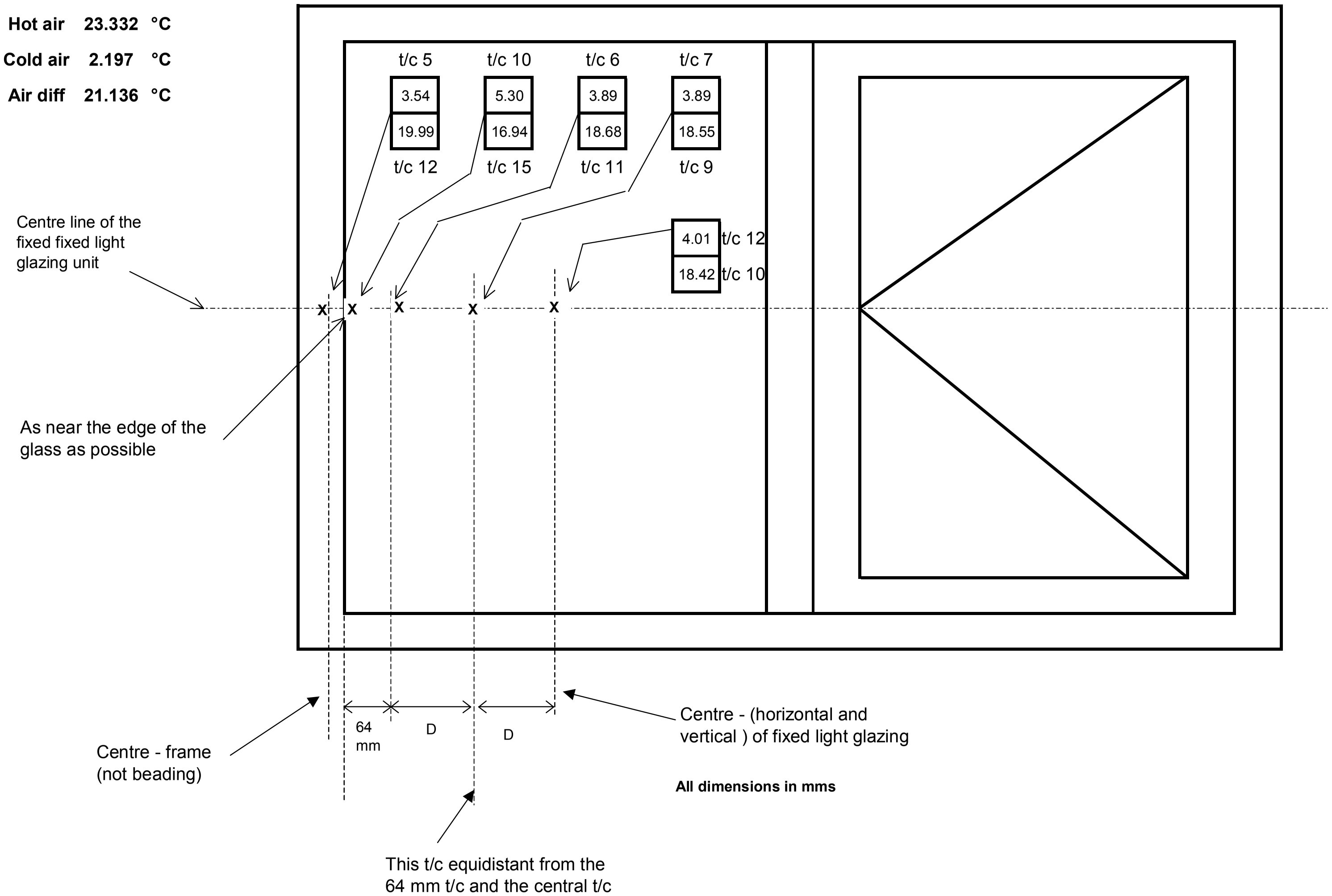


Table 3 Measured surface temperatures

Window system details					Surface temperatures (°C)					Air
Frame	Coating	Gas	Spacer		Frame	Edge	64 mm	Half way	Centre	temp (°C)
Al 5 mm TT300	Opti SN	Air	Super spacer	Cold	6.636	5.277	3.914	3.909	4.008	2.31
				Hot	15.115	15.396	18.262	18.262	18.193	23.08
				Difference	*8.48*	*10.12*	*14.35*	*14.35*	*14.19*	20.77
Al 23 mm TT303	Opti SN	Air	Super spacer	Cold	5.102	5.062	3.911	3.830	3.954	2.12
				Hot	18.200	15.302	18.341	18.246	18.078	23.06
				Difference	*13.10*	*10.24*	*14.43*	*14.42*	*14.12*	20.94
PVC-U 3 TT294 TT302	Opti SN	Air	Super spacer	Cold	4.212	5.992	3.919	3.866	3.988	2.13
				Hot	18.832	15.746	18.374	18.240	18.116	23.20
				Difference	*14.62*	*9.75*	*14.45*	*14.37*	*14.13*	21.07
PVC-U 5 TT301	Opti SN	Air	Super spacer	Cold	3.538	5.305	3.894	3.888	4.007	2.20
				Hot	19.985	16.936	18.680	18.547	18.419	23.33
				Difference	*16.45*	*11.63*	*14.79*	*14.66*	*14.41*	21.14
Wood TT299	Opti SN	Air	Super spacer	Cold	3.990	5.641	3.952	3.989	4.118	2.26
				Hot	20.004	15.028	18.597	18.447	18.334	23.26
				Difference	*16.01*	*9.39*	*14.65*	*14.46*	*14.22*	21.01
PVC-U 3 TT309	Opti SN	Air	Aluminium	Cold	4.21	6.68	3.89	3.89	4.03	2.25
				Hot	18.61	14.83	18.32	18.12	17.87	23.12
				Difference	*14.40*	*8.15*	*14.42*	*14.23*	*13.84*	*20.87*
PVC-U 3 TT304	Opti SN	Air	Azon	Cold	5.110	5.063	3.909	3.827	3.949	2.36
				Hot	18.201	15.307	18.362	18.259	18.103	23.28
				Difference	*13.09*	*10.24*	*14.45*	*14.43*	*14.15*	20.92
PVC-U 3 TT298	Opti SN	Air	Swiggle	Cold	4.283	6.423	3.999	3.987	4.125	2.32
				Hot	18.487	15.152	18.297	18.128	18.062	23.20
				Difference	14.20	8.73	14.30	14.14	13.94	20.88
PVC-U 3 TT307	Opti SN	Air	TPS	Cold	4.421	6.781	4.129	3.962	4.042	2.41
				Hot	18.687	14.480	18.549	18.578	18.464	23.25
				Difference	14.27	7.70	14.42	14.62	14.42	20.84
PVC-U 3 TT306	Opti SN	Air	Swiss	Cold	4.280	6.537	3.973	3.906	4.010	2.28
				Hot	18.537	15.129	18.643	18.598	18.456	23.28
				Difference	14.26	8.59	14.67	14.69	14.45	21.00
PVC-U 3 TT294 TT302	Opti SN	Air	Super spacer	Cold	4.212	5.992	3.919	3.866	3.988	2.13
				Hot	18.832	15.746	18.374	18.240	18.116	23.20
				Difference	*14.62*	*9.75*	*14.45*	*14.37*	*14.13*	21.07
PVC-U 3 TT294 TT302	Opti SN	Air	Super spacer	Cold	4.212	5.992	3.919	3.866	3.988	2.13
				Hot	18.832	15.746	18.374	18.240	18.116	23.20
				Difference	*14.62*	*9.75*	*14.45*	*14.37*	*14.13*	21.07
PVC-U 3 TT310	Opti SN	Argon	Super spacer	Cold	4.576	5.972	4.082	3.985	4.064	2.62
				Hot	18.952	16.071	19.220	19.195	19.132	23.29
				Difference	*14.38*	*10.10*	*15.14*	*15.21*	*15.07*	20.67
PVC-U 3 TT308	Pilk K	Air	Super spacer	Cold	4.099	6.144	4.071	4.005	4.115	2.14
				Hot	18.732	15.025	17.737	17.678	17.642	23.21
				Difference	*14.63*	*8.88*	*13.67*	*13.67*	*13.53*	21.07

Table 4 Simulation results for all the window systems

GGF Pii Project on warm edge spacers											
				U-values calculated by CWCT							
				using CEN radiation/convection mode with BISCO							
IGU Details	**Spacer type**										
Spacer manufacturer	Spacer type	**Wood Frame**		**3 Chamber**		**5 Chamber**		**Aluminium**		**Aluminium**	
Pilkington	Al. Standard type			**PVC-U frame**		**PVC-U frame**		**5 mm thrm. brk**		**23 mm thrm. brk**	
Azon	Azon - Warmlight	**Calculations**		**Calculations**		**Calculations**		**Calculations**		**Calculations**	
Tremco	Swiggle							**NB 70 mm frame**			
Speedframe	TPS										
St Gobain	Swiss spacer	U-value	Change	U-value	Change	U-value	Change	U-value	Change	U-value	Change
Edge-Tech	Super spacer	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$
U-value = 1.7 $W/m^2.K$	Al. Standard type	1.98		2.01		1.98		2.84		2.33	
Gap = 16 mm	Azon - Warmlight	1.89	-0.09	1.94	-0.07	1.91	-0.07	2.75	-0.08	2.26	-0.08
Fill = Air	Swiggle	1.87	-0.11	1.92	-0.09	1.88	-0.10	2.73	-0.11	2.25	-0.08
Coating = Pilk K	TPS	1.83	-0.15	1.90	-0.11	1.83	-0.15	2.71	-0.13	2.21	-0.13
	Swiss spacer	not calc.	-	1.90	-0.11	1.83	-0.15	not calc.	-	not calc.	-
(ε_n =0.15)	Super spacer	1.83	-0.16	1.87	-0.14	1.79	-0.19	2.67	-0.16	2.17	-0.17
U-value = 1.4 $W/m^2.K$	Al. Standard type	1.79		1.82		1.78		2.63		2.14	
Gap = 16 mm gap	Azon - Warmlight	1.69	-0.10	1.73	-0.08	1.71	-0.07	2.54	-0.09	2.04	-0.10
Fill = Air	Swiggle	1.66	-0.12	1.71	-0.10	1.67	-0.11	2.52	-0.11	2.03	-0.11
Coating = Optitherm +	TPS	1.63	-0.16	1.69	-0.12	1.62	-0.16	2.50	-0.13	1.98	-0.16
	Swiss spacer	not calc.	-	1.69	-0.12	1.62	-0.16	not calc.	-	not calc.	-
(ε_n =0.04)	Super spacer	1.59	-0.19	1.66	-0.16	1.58	-0.20	2.46	-0.17	1.94	-0.20
U-value = 1.16 $W/m^2.K$	Al. Standard type	1.63		1.66		1.63		2.47		1.97	
Gap =16 mm gap	Azon - Warmlight	1.53	-0.10	1.57	-0.09	1.55	-0.08	2.38	-0.08	1.86	-0.11
Fill = 90% Argon	Swiggle	1.50	-0.13	1.55	-0.11	1.51	-0.12	2.35	-0.11	1.85	-0.12
Coating = Optitherm+	TPS	1.47	-0.17	1.54	-0.12	1.46	-0.17	2.33	-0.13	1.80	-0.16
	Swiss spacer	not calc.	-	1.53	-0.13	1.46	-0.17	not calc.	-	not calc.	-
(ε_n =0.04)	Super spacer	1.43	-0.20	1.49	-0.17	1.41	-0.22	2.29	-0.18	1.76	-0.21

Table 5 Summary of the average Ψ, U_f and U_w values for the PVC-U windows

3 Chamber PVCu frame CEN				**5 Chamber PVCu frame CEN**			
U_f Outer	1.96	[W/m^2.K]		U_f Outer	1.41	[W/m^2.K]	
U_f Outer&Sash	1.95	[W/m^2.K]		U_f Outer&Sash	1.61	[W/m^2.K]	
U_f Mullion	1.79	[W/m^2.K]		U_f Mullion	1.76	[W/m^2.K]	
IGU 16 mm gap	**Spacer**	Ψ Average (W/m.K)	U_w Window (W/m2.K)	**IGU** 16 mm gap	**Spacer**	Ψ Average (W/m.K)	U_w Window (W/m2.K)
K glass, Air	ALU	0.0610	2.01	**K glass, Air**	ALU	0.0757	1.98
	WARMLIGHT	0.0431	1.94		WARMLIGHT	0.0571	1.91
	Swiggle	0.0387	1.92		Swiggle	0.0486	1.88
	TPS	0.0340	1.90		TPS	0.0381	1.83
	Swiss Spacer	0.0325	1.90		Swiss Spacer	0.0369	1.83
	SUPER	0.0261	1.87		SUPER	0.0273	1.79
Optitherm SN, Air	ALU	0.0684	1.82	**Optitherm SN, Air**	ALU	0.0817	1.78
	WARMLIGHT	0.0477	1.73		WARMLIGHT	0.0623	1.71
	Swiggle	0.0425	1.71		Swiggle	0.0527	1.67
	Swiss Spacer	0.0378	1.69		TPS	0.0418	1.62
	TPS	0.0376	1.69		Swiss Spacer	0.0408	1.62
	SUPER	0.0289	1.66		SUPER	0.0299	1.58
Optitherm SN, Argon	ALU	0.0733	1.66	**Optitherm SN, Argon**	ALU	0.0867	1.63
	WARMLIGHT	0.0515	1.57		WARMLIGHT	0.0667	1.55
	Swiggle	0.0468	1.55		Swiggle	0.0561	1.51
	TPS	0.0408	1.54		TPS	0.0449	1.46
	Swiss Spacer	0.0408	1.53		Swiss Spacer	0.0438	1.46
	SUPER	0.0313	1.49		SUPER	0.0322	1.41

Table 6 Summary of the average Ψ, U_f and U_w values for the aluminium windows

Aluminium frame with 5mm debridged thermal break				**Aluminium frame with 23mm thermal break**			
U_f Outer	4.28	[W/m^2.K]		U_f Outer	2.85	[W/m^2.K]	
U_f Outer&Sash	5.15	[W/m^2.K]		U_f Outer&Sash	3.35	[W/m^2.K]	
U_f Mullion	5.20	[W/m^2.K]		U_f Mullion	3.14	[W/m^2.K]	
IGU 16 mm gap	**Spacer**	Ψ Average (W/m.K)	U_w Window (W/m^2.K)	**IGU** 16 mm gap	**Spacer**	Ψ Average (W/m.K)	U_w Window (W/m^2.K)
K glass Air	Aluminium	0.0647	2.84	**K glass Air**	Aluminium	0.0696	2.33
	WARMLIGHT	0.0440	2.75		WARMLIGHT	0.0462	2.26
	Swiggle	0.0388	2.73		Swiggle	0.0447	2.25
	TPS	0.0330	2.71		TPS	0.0343	2.21
	SUPER	0.0236	2.67		SUPER	0.0241	2.16
Optitherm SN Air	Aluminium	0.0696	2.63	**Optitherm SN Air**	Aluminium	0.0750	2.14
	WARMLIGHT	0.0483	2.54		WARMLIGHT	0.0505	2.04
	Swiggle	0.0414	2.52		Swiggle	0.0482	2.03
	TPS	0.0366	2.50		TPS	0.0372	1.98
	SUPER	0.0265	2.46		SUPER	0.0274	1.94
Optitherm SN Argon	Aluminium	0.0731	2.47	**Optitherm SN Argon**	Aluminium	0.0796	1.97
	WARMLIGHT	0.0519	2.38		WARMLIGHT	0.0537	1.86
	Swiggle	0.0445	2.35		Swiggle	0.0511	1.85
	TPS	0.0397	2.33		TPS	0.0399	1.80
	SUPER	0.0290	2.29		SUPER	0.0281	1.76

Table 7 Summary of the average Ψ, U_f and U_w values for the softwood window

Softwood frame			
U_f Outer		1.45	[W/m^2.K]
U_f Outer&Sash		1.67	[W/m^2.K]
U_f Mullion		1.63	[W/m^2.K]
U_f Cill		1.49	[W/m^2.K]
U_f Head		1.42	[W/m^2.K]
IGU 16 mm gap	**Spacer**	**Ψ** Average (W/m.K)	**U_w** Window (W/m^2.K)
K glass, Air	ALU	0.0767	1.98
	WARMLIGHT	0.0530	1.89
	Swiggle	0.0483	1.87
	TPS	0.0390	1.83
	SUPER	0.0345	1.83
Optitherm SN, Air	ALU	0.0825	1.79
	WARMLIGHT	0.0576	1.69
	Swiggle	0.0521	1.66
	TPS	0.0425	1.63
	SUPER	0.0340	1.59
Optitherm SN, Argon	ALU	0.0872	1.63
	WARMLIGHT	0.0615	1.53
	Swiggle	0.0556	1.50
	TPS	0.0456	1.47
	SUPER	0.0368	1.43

Table 8 Comparison of calculated and measured surface temperatures

Frame	Coating	Gas fill	Spacer	Surface temperature at frame / glazing interface Measured °C	Calculated °C	Difference in surface temperatures (Calc -Meas) °C	Difference between Calculated & measured U-values (Calc - Meas) (%)
PVC-U 3	Optitherm SN	Air	Aluminium	14.83	11.75	-3.1	5.6
PVC-U 3	Optitherm SN	Air	Azon	15.31	13.62	-1.7	5.0
PVC-U 3	Optitherm SN	Air	Swiggle	15.15	14.12	"-1.0[1]	0.1
PVC-U 3	Optitherm SN	Air	TPS	14.48	14.49	0.0	2.5
PVC-U 3	Optitherm SN	Air	Swiss	15.13	14.48	-0.6	2.6
PVC-U 3	Optitherm SN	Air	Super spacer	15.75	15.09	-0.7	-0.2
PVC-U 3	Optitherm SN	Air	Super spacer	15.75	15.09	-0.7	1.0
PVC-U 5	Optitherm SN	Air	Super spacer	16.94	16.99	0.1	-0.6
Wood	Optitherm SN	Air	Super spacer	15.03	15.60	0.6	-5.7
Al 5 mm	Optitherm SN	Air	Super spacer	15.40	13.66	-1.7	2.3
Al 23 mm	Optitherm SN	Air	Super spacer	15.30	15.10	-0.2	0.0
PVC-U 3	Pilkington K	Air	Super spacer	15.03	14.68	-0.3	4.5
PVC-U 3	Optitherm SN	Argon	Super spacer	16.07	15.64	-0.4	2.7

Note[1] This is an anomolous result (See section 6.1.1)

6 DISCUSSION

6.1.1 Problems

The aluminium frame with the 5 mm fill and debridge thermal break that was supplied for hot-box testing was different from the drawings supplied to CWCT. The drawings were of a frame 70 mm thick and the window tested was 50 mm thick. When this was discovered the results had to be recalculated – just for the window system that was tested to facilitate comparison. All the other calculated values for the 5 mm fill and debridge aluminium window are for the 70 mm deep window.

The measured U-value for the 3 chamber PVC-U frame with the Optitherm SN, air filled IGU, with Tremco Swiggle Strip spacer bar system showed no improvement from the measured U-value obtained with the same frame and IGU with the standard aluminium spacer bar system. Measurements of the IGU thickness (see Table 10) indicated that it was actually too thin and that poor manufacturing procedures had possibly resulted in the glass surfaces touching the aluminium strip in the "Swiggle Strip" – thus completely nullifying the benefit of this type of spacer bar. Consequently the results with this system have not been discussed further. It must be remembered that all these IGUs had to be made "by hand" from the same batch of glass supplied by Pilkington and so assembly errors are more likely than usual.

6.1.2 Relationships between the calculated and measured U-values

To assist in seeing the relationships between the measurements and the calculated, especially to see if the trends identified by the calculated results are supported by the measurement results, a number of tables have been produced to highlight those relationships. Those tables are shown in Table 9.

Table 9(a) shows the relationship between the U-values of the windows incorporating the 3 chamber PVC-U frame with the air filled Optitherm SN units with the six different spacer bar systems. This table shows the percentage change in U-value, relative to the unit with the standard desiccant-filled aluminium spacer bar system, for the other 5 spacer bar systems. This relationship is shown both for the calculated and measured values. The calculated values show that the high performance spacer bar systems produce a definite reduction in U-value and also show clear differentiation between the different systems. The measured U-values show the same level of reduction in U-value for the poorer performing spacer bar systems but do not clearly differentiate between the systems. Remember that the NPL hot box should be able to resolve differences between these systems of about 1% or 0.02 W/m^2.K, so not seeing those differences needs an explanation.

Table 9(b) shows the relationship between the U-values of the windows incorporating the air-filled Optitherm SN units with Super Spacer for all five frame types. This table shows the percentage change in U-value, relative to the 3 chamber PVC-U frame window, for the other 4 frame types. This relationship is shown both for the calculated and measured values. This table shows excellent agreement between the trends shown by the calculated values and those shown by the measurements and so reinforces the confidence in the calculated values.

Table 9(c) shows the relationship between the U-values of the windows incorporating the air filled Optitherm SN units with Super Spacer for all 5 frame types. This table shows the percentage change in U-value, relative to the 3 chamber PVC-U frame window, for the other 4 frame types. This relationship is shown both for the calculated and measured values. This table shows excellent agreement between the trends shown by the calculated values and those shown by the measurements and so reinforces the confidence in the calculated values.

Table 9 Relationships between the measured and calculated U-values

Effect of different spacer bars in the air filled Optitherm SN IGU installed in the 3 chamber PVC-U frame						
Frame - constant **Gas - constant** **Coating - constant** **Spacer - CHANGES** **CEN rules only**	***PVC-U*** ***3 Chamber*** ***16 mm Air*** ***Optitherm SN*** ***Aluminium***	PVC-U 3 Chamber 16 mm Air Optitherm SN Azon Warmlight	PVC-U 3 Chamber 16 mm Air Optitherm SN Swiggle Strip	PVC-U 3 Chamber 16 mm Air Optitherm SN TPS	PVC-U 3 Chamber 16 mm Air Optitherm SN Swiss Spacer	PVC-U 3 Chamber 16 mm Air Optitherm SN Super Spacer
Measured U-value % Change	1.720 →	1.65 -4.1	1.71(*) -0.6	1.65 -4.1	1.65 -4.1	1.64(*) -4.7
Calculated U-value % Change	1.82 →	1.73 -4.6	1.71 -5.8	1.69 -6.8	1.69 -6.8	1.66 -8.8

Different frame types with the air filled Optitherm SN IGU with super spacer **NB** For comparison with measurements a 50 mm deep Aluminium window with 5 mm thermal break was calculated					
Frame - CHANGES **Gas - constant** **Coating - constant** **Spacer - constant** **CEN rules only**	***PVC-U*** ***3 Chamber*** ***16 mm Air*** ***Optitherm SN*** ***Super Spacer***	PVC-U 5 Chamber 16 mm Air Optitherm SN Super Spacer	Wood Soft wood 16 mm Air Optitherm SN Super Spacer	Aluminium 5 mm thermal break 16 mm Air Optitherm SN Super Spacer	Aluminium 23 mm thermal break 16 mm Air Optitherm SN Super Spacer
Measured U-value % Change	1.64 →	1.59 -3.0	1.69 3.0	2.19 33.5	1.94 18.3
Calculated U-value % Change	1.66 →	1.58 -4.6	1.59 -3.8	2.24 35.3	1.94 17.2

Different IGUs all with Superspacer installed in the 3 Chamber PVC-U frame			
Frame - constant **Gas - CHANGES** **Coating - CHANGES** **Spacer - constant** **CEN rules only**	***PVC-U*** ***3 Chamber*** ***16 mm Air*** ***Pilkington K*** ***Super Spacer***	PVC-U 3 Chamber 16 mm Air Optitherm SN Super Spacer	PVC-U 3 Chamber 16 mm Argon Optitherm SN Super Spacer
Measured U-value % Change	1.79 →	1.64 -8.4	1.45 -19.0
Calculated U-value % Change	1.87 →	1.66 -11.4	1.49 -20.4

6.1.3 Relationships between the calculated and measured surface temperatures.

The measured and calculated surface temperatures at the frame/glazing interface are shown in Table 8. Ten of the thirteen sets of surface temperatures in that table are within ± 1 °C of each other. The largest discrepancy between the measured and calculated temperatures is for the 3 Chamber PVC-U Optitherm SN standard aluminium spacer.

6.1.4 Main observations

1 Calculations show a small but significant improvement in overall U-value when high performance spacers are used.

2 There is good broad agreement between the measured and calculated U-values.

3 The calculation results (Table 4) show that the numerical improvement in U-value for each of the high performance spacer bar systems was approximately the same for all frame and glazing types (Table 10).

Table 10 Effect on window U-value of the different spacer bars

Spacer bar type	Simulated values-Average improvement in U-value ($W/m^2.K$)	Measured values-Average improvement in U-value ($W/m^2.K$)
Azon - Warmlight	-0.09	-0.07
Swiggle	-0.11	-0.01
TPS	-0.14	-0.07
Swiss spacer	-0.14	-0.07
Super spacer	-0.18	-0.08

4 The results of the calculations show that the percentage improvement for each spacer bar system goes up as the U-value of the window system goes down.

5 The U-value trends between the different frames using the same glazing and spacer bar that were identified by the calculations, were broadly supported by the measured U-values (Table 9b).

5 The U-value trends between the different IGUs in the same frame and with the same spacer bar that were identified by the calculations, were broadly supported by the measured U-values (Table 9c)

6 The U-value trends between the same IGUs with different spacer bars in the same frame, that were identified by the calculations, were not clearly supported by the measured U-values. (See Table 9a). Possible reasons why the measured U-values did not “see” the 5% difference between the high performance spacer bars that was indicated by the simulation results could be due to one or more of the following factors:

6.1.4.1 Variation in real IGU thickness.

Although the air gaps of all the IGUs were nominally 16 mm, simple thickness measurements with the units held at 10 °C show fairly large variations (Table 11). This would have had a significant effect on their actual U-value – thus altering the relationships observed for windows with ideal configurations.

Table 11 IGU thickness at 10 °C mean temperature

Table of Centre of Glazing U-values calculated with BS EN 673	NPL identity number Spacer bar type	**3 Chamber PVC-U / AIR / OPTITHERM SN**					
		TT309 Al.	TT298 Swiggle	TT302 Super Spacer	TT304 Warmlite	TT306 Swiss	TT307 TPS
Measured window U-value	$W/m^2.K$	1.72	1.71	1.66	1.65	1.65	1.65
IGU air gap thickness @ edge (assume glass = 4 mm)	mm	15.75	14.73	14.90	16.37	16.30	15.30
IGU air gap thickness @ centre @ 10 °C (assume glass = 4 mm)	mm	12.91	13.12	13.10	-	14.49	-
Mean air gap thickness @ 10 °C (assumes glass = 4 mm)	mm	14.61	14.08	14.18	-	15.57	-
U-value for actual mean air gap thickness (EN 673)	$W/m^2.K$	1.452	1.488	1.481	-	1.396	-
U-value for an assumed 16 mm thick air gap	$W/m^2.K$	1.399	1.399	1.399	1.399	1.399	1.399
Diff % in U-value of "actual thickness" relative to the 16 mm value	%	-3.8	-6.4	-5.9	-	0.2	-
Diff % in U-value at "actual thickness" relative to IGU with Al spacer	%		-2.5	-2.0	-	3.9	-
Atmospheric pressure during hot-box test	mbar	1026	1022	1020	1009	997	998

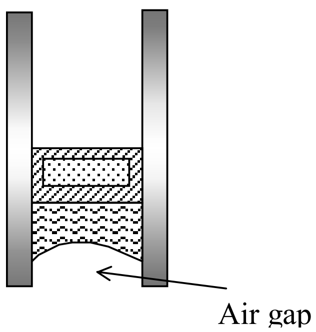
6.1.4.2 Depth of secondary sealant in the IGU

This could have been different from the ideal configuration, especially as the units were hand made.

6.1.4.3 Air gaps between secondary sealant and glass edge

Because these units were hand made, some of the IGUs had fairly large air gaps – as shown in Figure 2.

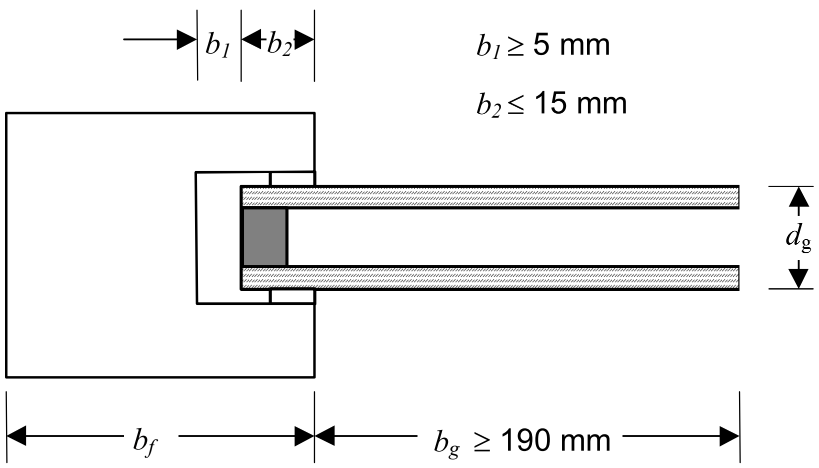
Figure 2 Air gap at IGU edge



6.1.4.4 Depth of penetration of the IGU in the frame.

In BS EN ISO 10077-2 the specification for the position of the insulation panel in the frame (required to calculate the linear thermal transmittance) is as shown in Figure 3.

Figure 3 Position of insulation panel in frame



These criteria are used when simulating the window U-value – but they may not be the dimensions found in practice. This is another source of uncertainty.

7 CONCLUSIONS

High performance spacer bars produced a small but significant improvement in overall window U-values of between 0.09 and 0.18 W/m^2.K. (See Table 4).

The improvement that each spacer bar type produced was approximately the same for all window configurations (See Table 10). The percentage improvement that resulted from using "warm edge spacer bars" was therefore larger for the lower U-value window systems.

The measurements mainly supported the trends in U-value change that were identified by the calculations, but there were some differences. The most obvious difference was with the complete set of measured U-values for the 3 chamber PVC-U frame/ Optitherm SN/ Air filled IGUs and all the different spacer bar systems. (See Table 9a). The calculated U-values showed a clear differentiation between spacer bar types; the measured U-values did not.

There was also a pronounced difference between the surface temperatures measured at the frame/glazing interface and the equivalent calculated temperature (Table 8) for some of the windows. Again the calculations showed a clear improvement (increase) in internal surface temperature near the glazing / frame interface when high performance spacer bar systems were used and clearly differentiated between the different spacer bar types. The measured values did not.

The possible causes of these discrepancies were discussed in Section 6. They were:

- The insulated glazing units had been “hand made” and the air gap thickness of the different units varied (See Table 11).

- The depth of the secondary sealant varied from unit to unit.

- There were air gaps between the surface of the secondary sealant and the glass edge (See Figure 2).

- The depth of penetration of the insulated glass unit into the frame may not always been the same as in the calculation (See Figure 3).

ANNEX 1 – LIST OF PROJECT PARTNERS

- Glass & Glazing Federation
- National Physical Laboratory
- Centre for Window and Cladding Technology
- British Woodworking Federation
- Council for Aluminium in Building
- British Plastics Federation (Window group)
- Pilkington Glass plc
- Interpane (UK) Ltd
- Azon Ltd
- Solaglas (UK) Ltd
- Edgetech (UK) Ltd.
- Tremco Ltd
- Bostik Findley Ltd.
- Speed Frame Ltd
- Abbott Group Ltd
- Beaufort Ltd

ANNEX 2 WINDOW FRAME DRAWINGS

Figure 4 Section drawings of the softwood window

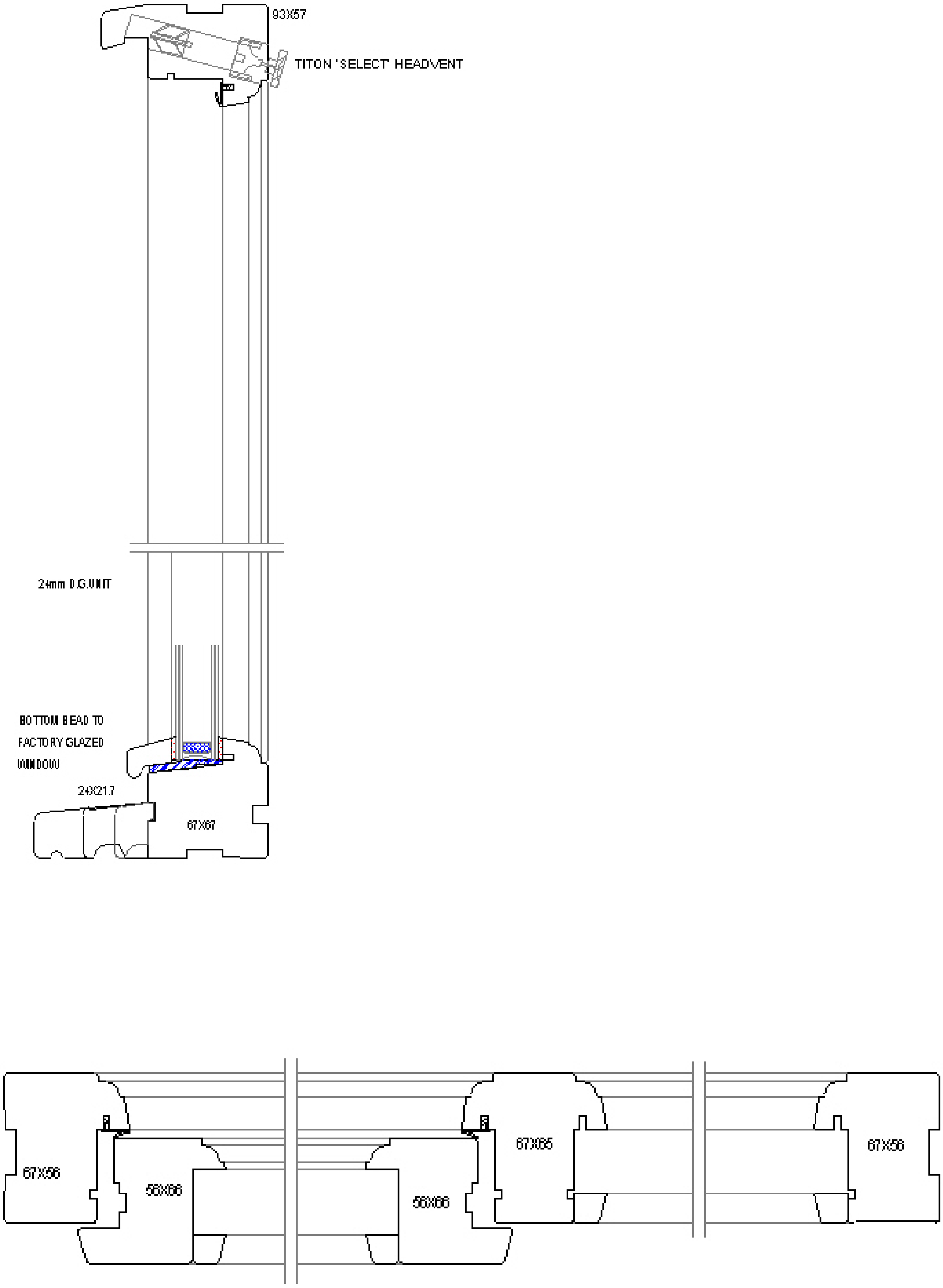


Figure 5 Section drawings of the 3 Chamber PVC-U window

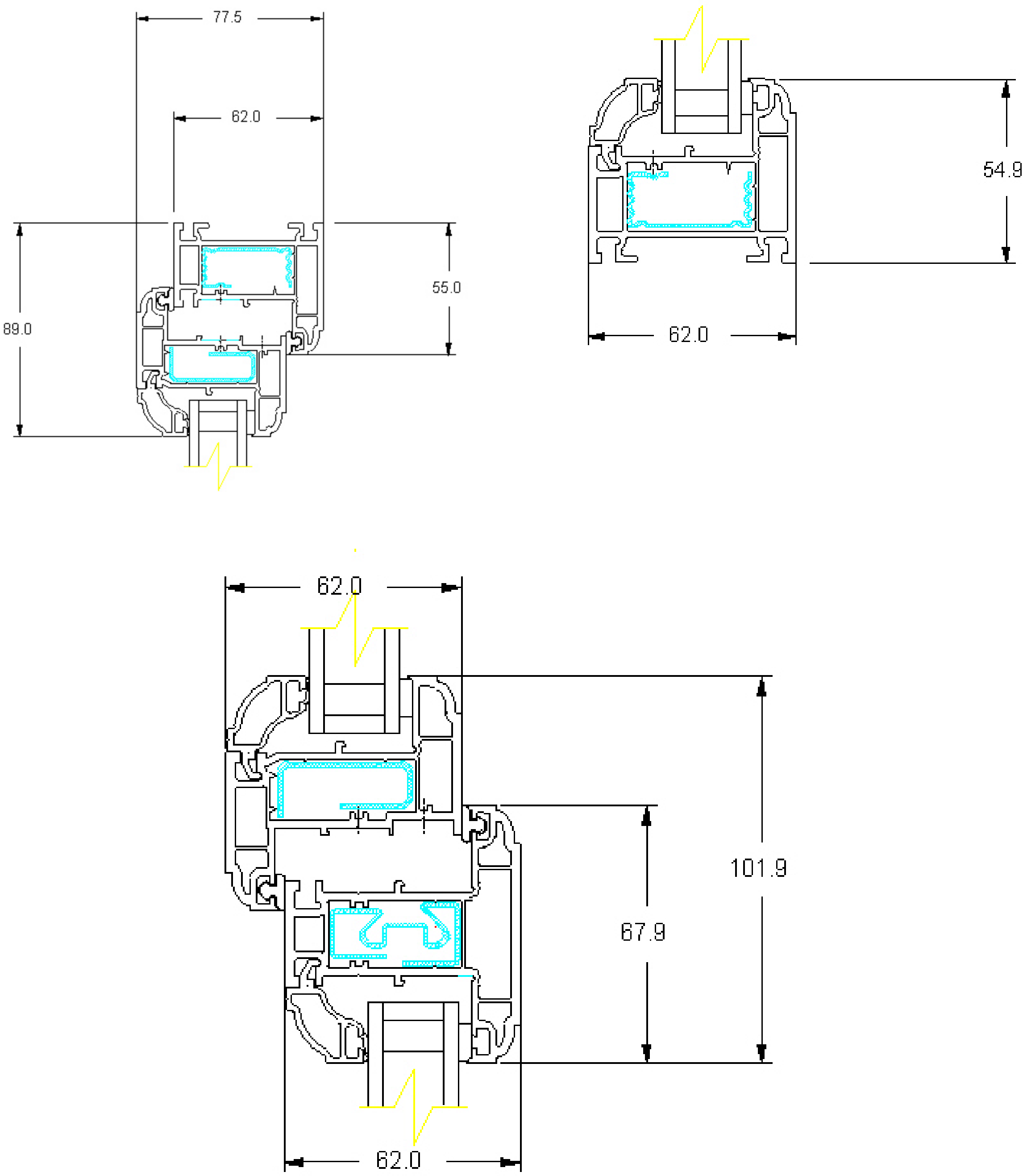


Figure 6 Section drawings of the 5 Chamber PVC-U Frame

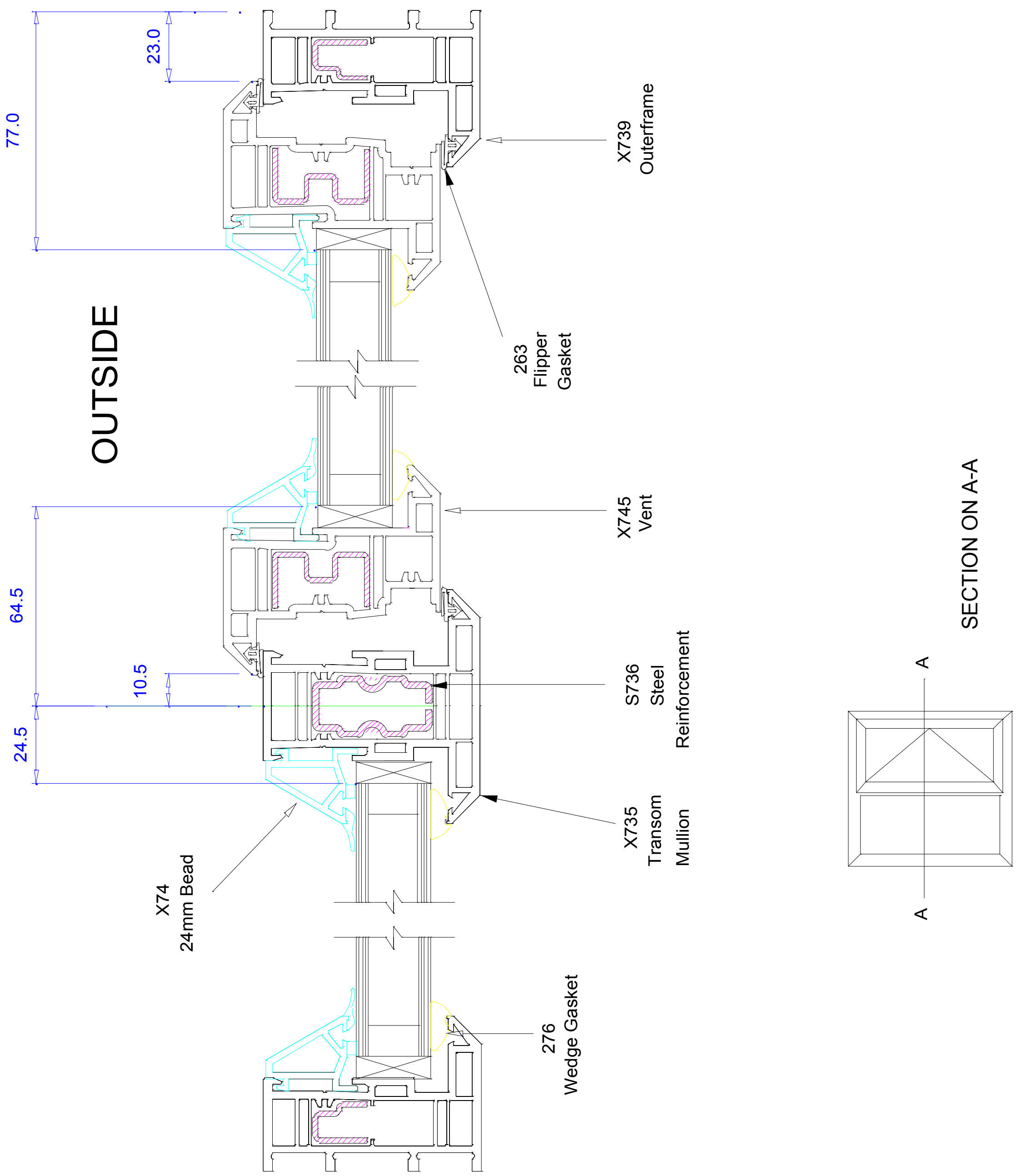


Figure 7 Section drawings of the aluminium frame - 5 mm fill and debridge

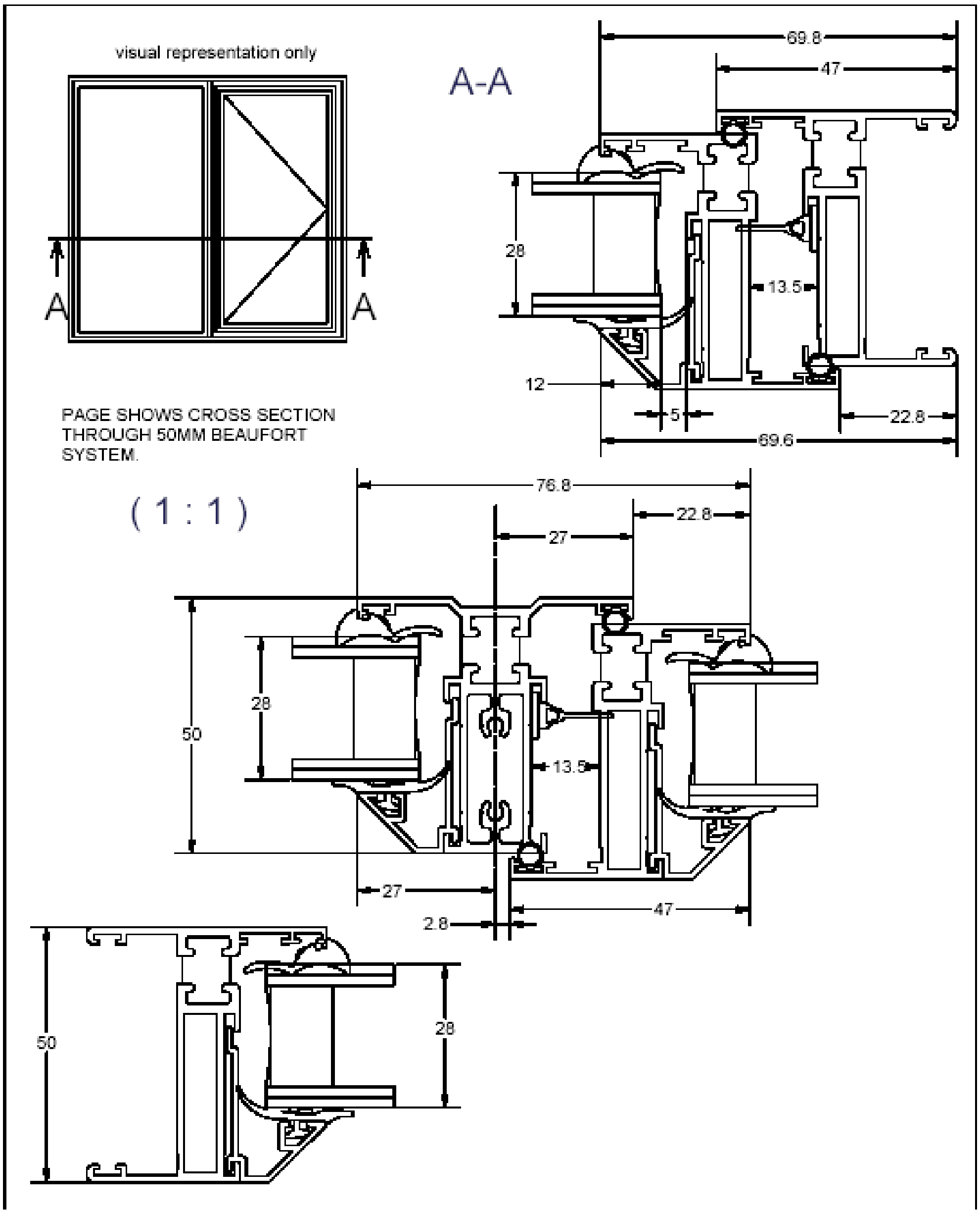
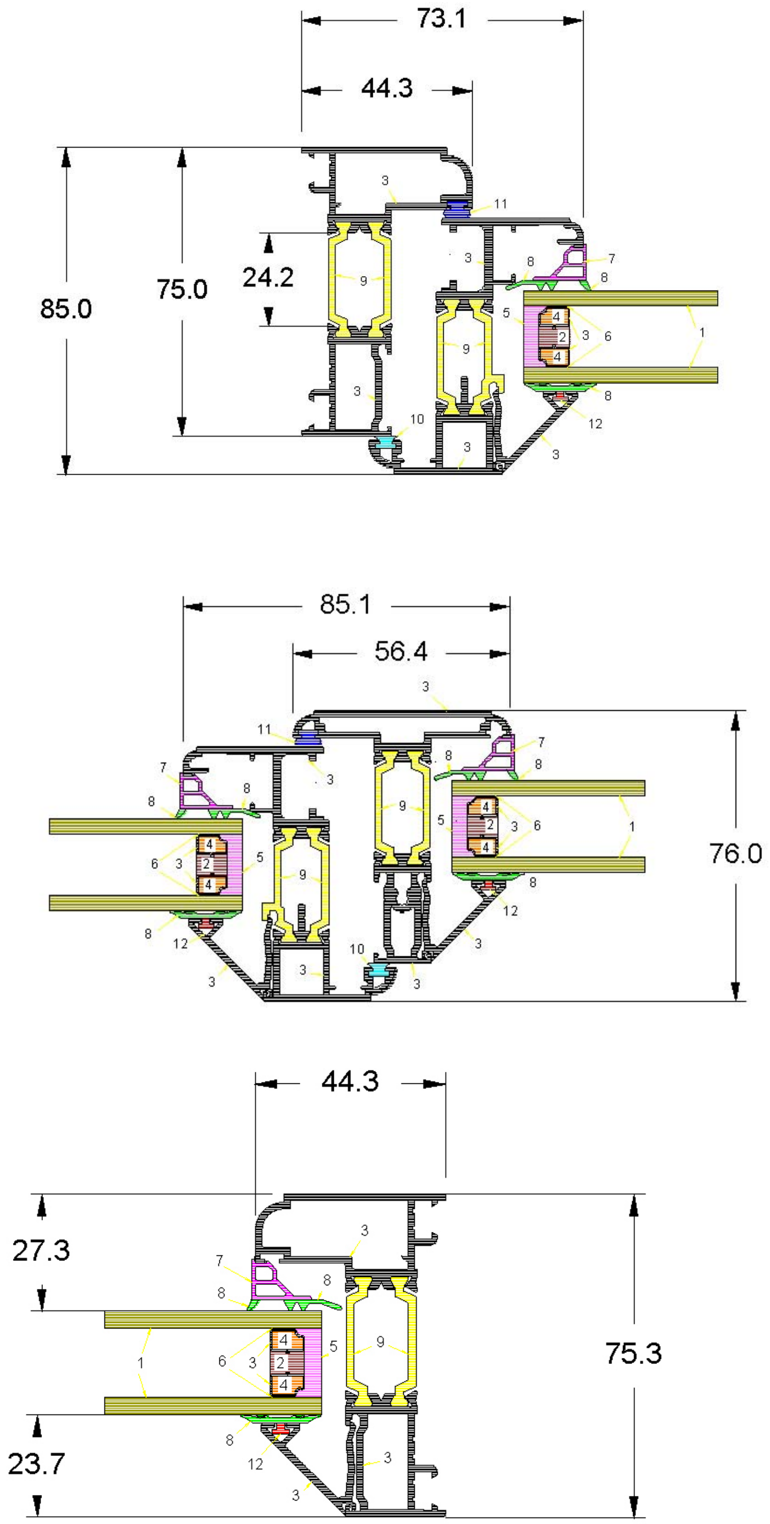
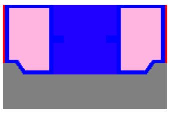


Figure 8 Section drawings of the aluminium window 23 mm polyamide thermal break



ANNEX 3 GLAZING UNIT SPACER BAR DETAILS

Figure 9 Spacer bar details

Spacer		Aluminium Spacer	Warmlight Spacer	Swiggle Strip Spacer	Data source
Dimension	mm	16 x 12	16 x 12	16 x 8.75	
					
		Aluminium 160	Aluminium 160	Aluminium 160	* : Azon
Material and thermal conductivity,	W/m².K	Butyl Hot Melt 0.24	PU Resin * 0.17	Swiggle Bulk Compound** 0.265	** : NPL
		Silica Gel 0.13	Silica Gel 0.13		
		Polysulphide 0.40	Polysulphide 0.40		
			PIB 0.20		

Spacer		Thermal Plastic Spacer	Super Spacer	Swiss Spacer	
Dimension	mm	16 x 12	16 x 9.52	16 x 9.5	
					
		Polyisobutylene 0.20	EDM Foam *** 0.181	SAN (Styrol Acryl Nitril Copolymer),	*** : Speed Frame
		Polysulphide 0.40	Butyl Hot Melt 0.240	with 35% glass fibre, UV stabilized****	**** : Solaglass
Material and thermal conductivity				0.19	
	W/m².K			Silicon (desiccant) 0.13	
				Aluminium***** 14.3	
				Butyle hot melt**** 0.25	
				Ploysulfide 0.40	

ANNEX 4 THERMAL CONDUCTIVITY DATA

Material	Thermal conductivity (W/m.K)	Data source
Aluminium	160	BS EN ISO 10077-2
Steel	50	BS EN ISO 10077-2
Rigid PVC	0.17	BS EN ISO 10077-2
Softwood (typical construction timber, density 630 kg/m^3)	0.13	CIBSE Guide A, table 3.44
Glass (soda lime)	1	BS EN ISO 10077-2
Polyamide (23 mm thermal break)	0.3	BS EN ISO 10077-2
(50:50) Polyol Resin/Isocyanate Hardener (MDI) (5 mm thermal break)	0.168	Beaufort
Mohair sweep	0.14	BS EN ISO 10077-2
Foam Rubber	0.06	BS EN ISO 10077-2
Q-LON (PU Foam)	0.06	Abbott
ALFAS DSX (PVC Foam)	0.045	Abbott
Flexi PVC gasket	0.14	BS EN ISO 10077-2
Semi Flexi PVC	0.16	Sapa
TPE (Thermoplastic Elastomer)	0.21	Beaufort Secure Design
PU Resin	0.17	BS EN ISO 10077-2
Silica Gel	0.13	BS EN ISO 10077-2
Molecular sieve	0.1	BS EN ISO 10077-2
Polysulphide	0.4	BS EN ISO 10077-2
PIB	0.2	Sapa
Butyl Hot Melt	0.24	BS EN ISO 10077-2
Swiggle Bulk Compound	0.265	BS EN ISO 10077-2
Polyisobutylene	0.2	BS EN ISO 10077-2
EDM Foam	0.181	BS EN ISO 10077-2
SAN (Stlrol Acryl Nitril Copolymer) with 35% glass fibre, UV stablized	0.19	BS EN ISO 10077-2
Aluminium Foil	14.3	Saint Gobain

ANNEX 5 DETAILED MEASUREMENT DATA

Table 12 Measurement details TT294

TT294 3 Chamber PVC-U frame with steel reinforcement 4/16/4 Air filled units with Optitherm SN with EdgeTech Superspacer		
Window dimensions		
Height	1.479	m
Width	1.230	m
Thickness	62.3	mm
Percentage of the window area that is frame	27.73	%
Measured values		
Mean warm air temperature	23.31	°C
Mean warm baffle temperature	22.00	°C
Mean cold air temperature	2.30	°C
Mean cold baffle temperature	2.35	°C
Mean cold reveal temperature	2.76	°C
Power to hot box	70.738	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	32.807	W/m²·K
Warm side convective fraction*	0.435	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.57	°C
Cold side environmental temperature*	2.32	°C
Environmental temperature difference	20.24	°C
Environmental temperature mean	12.44	°C
Measured thermal transmittance (U)	1.62	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.64**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 13 Measurement details TT298

TT298 3 Chamber PVC-U frame with steel reinforcement 4/16/4 Air filled units with Optitherm SN with Tremco Swiggle Strip		
Window dimensions		
Height	1.479	m
Width	1.227	m
Thickness	62.0	mm
Percentage of the window area that is frame	27.8	%
Measured values		
Mean warm air temperature	23.20	°C
Mean warm baffle temperature	21.86	°C
Mean cold air temperature	2.33	°C
Mean cold baffle temperature	2.36	°C
Mean cold reveal temperature	2.85	°C
Power to hot box	72.685	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	33.911	W/m²·K
Warm side convective fraction*	0.437	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.44	°C
Cold side environmental temperature*	2.35	°C
Environmental temperature difference	20.10	°C
Environmental temperature mean	12.40	°C
Measured thermal transmittance (U)	1.69	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.71**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 14 Measurement details TT299

TT299		
Wood frame		
4/16/4 Air filled units with Optitherm SN with EdgeTech Superspacer		
Window dimensions		
Height	1.474	m
Width	1.226	m
Thickness	65.0	mm
Percentage of the window area that is frame	29.4	%
Measured values		
Mean warm air temperature	23.35	°C
Mean warm baffle temperature	22.04	°C
Mean cold air temperature	2.28	°C
Mean cold baffle temperature	2.32	°C
Mean cold reveal temperature	2.84	°C
Power to hot box	72.525	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	33.909	W/m²·K
Warm side convective fraction*	0.437	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.61	°C
Cold side environmental temperature*	2.30	°C
Environmental temperature difference	20.31	°C
Environmental temperature mean	12.46	°C
Measured thermal transmittance (U)	1.67	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.69**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 15 Measurement details TT300

TT300 Aluminium frame 5mm thermal break 4/16/4 Air filled units with Optitherm SN and EdgeTech Superspacer		
Window dimensions		
Height	1.481	m
Width	1.231	m
Thickness	50.0	mm
Percentage of the window area that is frame	22.6	%
Measured values		
Mean warm air temperature	23.23	°C
Mean warm baffle temperature	21.55	°C
Mean cold air temperature	2.37	°C
Mean cold baffle temperature	2.43	°C
Mean cold reveal temperature	3.10	°C
Power to hot box	89.662	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	43.074	W/m²·K
Warm side convective fraction*	0.457	
Cold side convective fraction*	0.761	
Warm side environmental temperature*	22.32	°C
Cold side environmental temperature*	2.41	°C
Environmental temperature difference	19.91	°C
Environmental temperature mean	12.36	°C
Measured thermal transmittance (U)	2.16	W/m²·K
Total surface resistance *	0.176	m²·K/W
Thermal transmittance (U) standardised [2]	**2.19**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 16 Measurement details TT301

TT301 5 Chamber PVC-U frame 4/16/4 Air filled units with Optitherm SN with EdgeTech Superspacer		
Window dimensions		
Height	1.480	m
Width	1.230	m
Thickness	69.5	mm
Percentage of the window area that is frame	27.9	%
Measured values		
Mean warm air temperature	23.41	°C
Mean warm baffle temperature	22.10	°C
Mean cold air temperature	2.24	°C
Mean cold baffle temperature	2.29	°C
Mean cold reveal temperature	2.74	°C
Power to hot box	68.999	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	31.986	W/m²·K
Warm side convective fraction*	0.433	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.67	°C
Cold side environmental temperature*	2.26	°C
Environmental temperature difference	20.40	°C
Environmental temperature mean	12.47	°C
Measured thermal transmittance (U)	1.57	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.59**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 17 Measurement details TT302

TT302 3 Chamber PVC-U frame 4/16/4 Air filled units with Optitherm SN with EdgeTech Superspacer		
Window dimensions		
Height	1.479	m
Width	1.229	m
Thickness	62.0	mm
Percentage of the window area that is frame	28	%
Measured values		
Mean warm air temperature	23.26	°C
Mean warm baffle temperature	21.94	°C
Mean cold air temperature	2.17	°C
Mean cold baffle temperature	2.21	°C
Mean cold reveal temperature	2.69	°C
Power to hot box	71.538	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	33.259	W/m²·K
Warm side convective fraction*	0.436	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.52	°C
Cold side environmental temperature*	2.19	°C
Environmental temperature difference	20.33	°C
Environmental temperature mean	12.35	°C
Measured thermal transmittance (U)	1.64	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.66**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 18 Measurement details TT303

TT303 SAPA A1 Frame 4/16/4 Air filled units with Optitherm SN with EdgeTech Superspacer		
Window dimensions		
Height	1.479	m
Width	1.229	m
Thickness	75.0	mm
Percentage of the window area that is frame	23.7	%
Measured values		
Mean warm air temperature	23.17	°C
Mean warm baffle temperature	21.72	°C
Mean cold air temperature	2.14	°C
Mean cold baffle temperature	2.19	°C
Mean cold reveal temperature	2.77	°C
Power to hot box	80.977	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	38.665	W/m²·K
Warm side convective fraction*	0.448	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.37	°C
Cold side environmental temperature*	2.16	°C
Environmental temperature difference	20.21	°C
Environmental temperature mean	12.27	°C
Measured thermal transmittance (U)	1.91	W/m²·K
Total surface resistance *	0.177	m²·K/W
Thermal transmittance (U) standardised [2]	**1.94**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 19 Measurement details TT304

TT304 3 Chamber PVCu frame with steel reinforcement 4/16/4 Air filled units with Optitherm SN with Azon Warmlight		
Window dimensions		
Height	1.479	m
Width	1.227	m
Thickness	62.0	mm
Percentage of the window area that is frame	28.5	%
Measured values		
Mean warm air temperature	23.28	°C
Mean warm baffle temperature	21.96	°C
Mean cold air temperature	2.29	°C
Mean cold baffle temperature	2.34	°C
Mean cold reveal temperature	2.81	°C
Power to hot box	70.773	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	32.838	W/m²·K
Warm side convective fraction*	0.435	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.53	°C
Cold side environmental temperature*	2.31	°C
Environmental temperature difference	20.22	°C
Environmental temperature mean	12.42	°C
Measured thermal transmittance (U)	1.62	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.65**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 20 Measurement details TT306

TT306		
3 Chamber PVCu frame with steel reinforcement		
4/16/4 Air filled units with Optitherm SN with Swiss Spacer		
Window dimensions		
Height	1.479	m
Width	1.227	m
Thickness	62.0	mm
Percentage of the window area that is frame	27.8	%
Measured values		
Mean warm air temperature	23.29	°C
Mean warm baffle temperature	21.96	°C
Mean cold air temperature	2.27	°C
Mean cold baffle temperature	2.32	°C
Mean cold reveal temperature	2.82	°C
Power to hot box	70.854	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	32.880	W/m²·K
Warm side convective fraction*	0.435	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.54	°C
Cold side environmental temperature*	2.30	°C
Environmental temperature difference	20.24	°C
Environmental temperature mean	12.42	°C
Measured thermal transmittance (U)	1.62	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.65**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 21 Measurement details TT307

TT307 3 Chamber PVCu frame with steel reinforcement 4/16/4 Air filled units with Optitherm SN with TPS		
Window dimensions		
Height	1.479	m
Width	1.228	m
Thickness	62.0	mm
Percentage of the window area that is frame	28.2	%
Measured values		
Mean warm air temperature	23.26	°C
Mean warm baffle temperature	21.94	°C
Mean cold air temperature	2.40	°C
Mean cold baffle temperature	2.45	°C
Mean cold reveal temperature	2.92	°C
Power to hot box	70.416	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	32.696	W/m²·K
Warm side convective fraction*	0.435	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.51	°C
Cold side environmental temperature*	2.43	°C
Environmental temperature difference	20.08	°C
Environmental temperature mean	12.47	°C
Measured thermal transmittance (U)	1.63	W/m²·K
Total surface resistance *	0.178	m²·K/W
Thermal transmittance (U) standardised [2]	**1.65**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 22 Measurement details TT309

TT309 3 Chamber PVCu frame with steel reinforcement 4/16/4 Air filled units with Optitherm SN and standard desiccant filled aluminium		
Window dimensions		
Height	1.480	m
Width	1.230	m
Thickness	62.0	mm
Percentage of the window area that is frame	29.5	%
Measured values		
Mean warm air temperature	23.12	°C
Mean warm baffle temperature	21.77	°C
Mean cold air temperature	2.24	°C
Mean cold baffle temperature	2.28	°C
Mean cold reveal temperature	2.76	°C
Power to hot box	72.881	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	34.012	$W/m^2{\cdot}K$
Warm side convective fraction*	0.437	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.36	°C
Cold side environmental temperature*	2.26	°C
Environmental temperature difference	20.10	°C
Environmental temperature mean	12.31	°C
Measured thermal transmittance (U)	1.69	$W/m^2{\cdot}K$
Total surface resistance *	0.178	$m^2{\cdot}K/W$
Thermal transmittance (U) standardised [2]	**1.72**	**$W/m^2{\cdot}K$**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 23 Measurement details TT308

TT308 3 Chamber PVCu frame with steel reinforcement 4/16/4 Air filled units with Pilkington K		
Window dimensions		
Height	1.480	m
Width	1.230	m
Thickness	62.0	mm
Percentage of the window area that is frame	29.5	%
Measured values		
Mean warm air temperature	23.21	°C
Mean warm baffle temperature	21.82	°C
Mean cold air temperature	2.10	°C
Mean cold baffle temperature	2.16	°C
Mean cold reveal temperature	2.66	°C
Power to hot box	76.545	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	35.944	W/m²·K
Warm side convective fraction*	0.442	
Cold side convective fraction*	0.760	
Warm side environmental temperature*	22.43	°C
Cold side environmental temperature*	2.13	°C
Environmental temperature difference	20.31	°C
Environmental temperature mean	12.28	°C
Measured thermal transmittance (U)	1.77	W/m²·K
Total surface resistance *	0.177	m²·K/W
Thermal transmittance (U) standardised [2]	**1.79**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.

Table 24 Measurement details TT310

TT310 3 Chamber PVCu frame with steel reinforcement 4/16/4 Argon filled units with Optitherm SN and EdgeTech Superspacer		
Window dimensions		
Height	1.479	m
Width	1.227	m
Thickness	62.0	mm
Percentage of the window area that is frame	27.8	%
Measured values		
Mean warm air temperature	23.29	°C
Mean warm baffle temperature	22.08	°C
Mean cold air temperature	2.64	°C
Mean cold baffle temperature	2.68	°C
Mean cold reveal temperature	3.14	°C
Power to hot box	62.554	W
Air flow rate in the cold box	1.6	m/s
Air flow rate in the hot box	<0.2	m/s
Calculated values		
Heat flux density through window*	28.465	W/m²·K
Warm side convective fraction*	0.426	
Cold side convective fraction*	0.759	
Warm side environmental temperature*	22.60	°C
Cold side environmental temperature*	2.66	°C
Environmental temperature difference	19.93	°C
Environmental temperature mean	12.63	°C
Measured thermal transmittance (U)	1.43	W/m²·K
Total surface resistance *	0.179	m²·K/W
Thermal transmittance (U) standardised [2]	**1.45**	**W/m²·K**

{*} Values obtained using graphs produced from measurements on the calibration panels.