RESEARCH INTO THE THERMAL PERFORMANCE OF TRADITIONAL WINDOWS: TIMBER SASH WINDOWS

ENGLISH HERITAGE

RESEARCH REPORT

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RESEARCH INTO THE THERMAL PERFORMANCE OF TRADITIONAL WINDOWS: TIMBER SASH WINDOWS

EXECUTIVE SUMMARY

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RESEARCHING THE THERMAL PERFORMANCE OF TRADITIONAL BUILDINGS

The national and global imperative to improve energy security and reduce carbon emissions is turning the spotlight on the existing building stock. Traditional and historic buildings can often adopt modern technologies, such as more efficient boilers, lamps, control and management techniques, and low-carbon energy supplies. However, changing the building fabric is more difficult, particularly for walls, windows and doors, which give the building so much of its character. This is not just an aesthetic concern: changing balances between heat, air and moisture movement may also affect the integrity of the building and the health of its occupants.

There is often a presumption that old is bad and new is good. This is not necessarily so: historic and traditional buildings have stood the test of time, demonstrating their sustainability in an ever-changing world. With hindsight, many well-meaning interventions in the 20th Century have turned out to have been mistaken. For example, harder and less permeable paints, coatings, mortars and renders often accelerated the deterioration of the fabric they were expected to protect, while new windows and pointing have taken the character out of many well-loved buildings and streetscapes.

To better understand the performance of traditional and historic buildings and elements, and the scope for upgrading, English Heritage is commissioning a number of research projects, and will be reporting on these as soon as results come available. Each report will include a technical summary of the research, and an executive summary that puts the work into a broader context.

This is the first of the series, showing the results of laboratory tests of heat loss though a traditional double-hung sliding sash timber window. At the time of writing (October 2009), tests of a metal window are in progress, and *in-situ* measurements of the U-values of solid brick walls have begun.

This Executive Summary should be read in conjunction with the research report prepared for English Heritage by Dr Paul Baker, at Glasgow Caledonian University. It summarises the report's conclusions, and sets the timber sash window research into a broader context.

1. BACKGROUND

English Heritage supports national and global efforts to reduce energy consumption and greenhouse gas emissions, in which existing buildings are being asked to play an ever-increasing role. A few years ago large-scale reconstruction was widely advocated, but this is now seen to be impractical and the emphasis has moved towards refurbishment, with a presumption of window replacement. English Heritage is questioning the extent to which this is necessary or desirable, because:

- traditional windows can be very durable: many original Georgian and Victorian windows are still in place, whereas modern windows tend to be designed to have very much shorter lives (typically 20 years);
- current calculation methods may be pessimistic about the performance of traditional windows and the opportunities for improvement; and
- window replacement can easily destroy the character of a traditional building, as has been widely demonstrated over the past 30 to 40 years in nearly every part of the UK.

Consequently, English Heritage has funded research at Glasgow Caledonian University [GCU], carried out in conjunction with Historic Scotland, who commissioned similar work on a different timber window. The English Heritage work also included tests on condensation.

The results presented here are part of an onging programme of research into the thermal performance of traditional building materials and components. Testing of a steel and cast-iron windows with leaded lights is currently underway.

2. THE RESEARCH UNDERTAKEN

English Heritage provided GCU with a traditional 2 x 2 traditional double-hung vertical sliding sash window in poor condition. The window, which measured 1.77 x 1.16 m overall, was installed between two environmental chambers, one of which ("the cold room") was maintained at 2°C to simulate outdoor winter conditions, whilst the other ("the hot room") was held at 22°C to represent room conditions. Heat-flow tests were undertaken with the window as-found, after repair, and again after draughtproofing. The effects of adding curtains, blinds, shutters and secondary glazing were also evaluated. Formation of condensation was also monitored with and without secondary glazing, and with the window both open and shut.

3. HEAT TRANSFER THROUGH WINDOWS

Heat loss[1] from a room through a window during the heating season is complex, with three main mechanisms:

- By convection and conduction, from the warm room air to the colder surfaces of the glass and the frame.
- By the colder surface of the window absorbing infra-red radiation from the room.
- By uncontrolled air leakage, which can either bring in cold air from the exterior or take warm air out from the interior; often called *air infiltration*, this can occur even when the window is closed.

During the day, windows are also a source of heat gain through direct and diffuse solar radiation, but this study was concerned with heat losses only.

4. HEAT LOSS THROUGH THE GLASS AND FRAMES

Whether it leaves the room by convection, conduction or radiation, the lost heat all passes through the glass and the frame as conduction. GCU measured the flow through the glass by averaging the results from two heat flux meters attached to the centres of the top right and bottom left panes. These results are summarised in Table 1, with the measured heat transfer rates[2] converted into U-values[3] for the glass.

The glass is the most conductive part of the window, but heat is also lost through the frame, albeit at a lower rate. The complex frame geometry makes it impossible to measure these losses accurately using heat flux sensors. The contribution of the frame to overall heat loss was therefore estimated by comparison with tests at the National Physical Laboratory, as discussed below.

TABLE 1: CONDUCTION HEAT LOSSES THROUGH THE GLASS AND WINDOW

	For glass only: Directly measured			For glass & frame: Using FRAME model		
DETAILS OF THE TEST ASSEMBLY	U-value of glass (W/m^2K)	Reduction in heat loss through glazing only	Temperature of innermost surface (°C)	U-value of whole window, (W/m^2K)	Reduction in heat loss through whole window	COMMENTS
Window as found	5.3	—	12 (glass)	4.3	—	
Joinery repaired	5.3	—	12 (glass)	4.3	—	This also reduced air infiltration by 34%
Heavy curtains	3.3	39%	21 (curtain)	2.5	41%	
Well-fitting shutters	2.0	64%	17 (shutter)	1.7	58%	
Plain roller blind	3.4	37%	18 (blind)	2.7	38%	When the blind was tightly fitted, the U-values fell by about 0.3
Reflective roller blind	1.8	66%	19 (blind)	1.9	57%	Reflective side facing towards the outside
Honeycomb blind	2.1	60%	20 (blind)	2.1	51%	Insulating blind
Low-emissivity secondary glazing	2.0	63%	19 (glass)	1.8	58%	Aluminium frame secondary system with spring balances
Low-emissivity secondary glazing and shutters	1.4	73%	20 (shutter)	1.6	62%	With both the glazing and the shutters closed

NB: the experimental error in the tests is equivalent to an uncertainty of ± 0.3 in the U-values above[4]

From the first two columns of Table 1, it can be seen that relatively simple methods of insulation can substantially reduce heat loss through the glass of single-glazed windows. In addition, the increased internal surface temperature of curtains, blinds, shutters and secondary glazing (shown in the third column) will limit downdraughts and reduce radiation losses, which may make the room feel more comfortable at a given temperature.

The effects of the frame were estimated by relating the measured U-values for the glass of the single glazed window to those from sophisticated hot-box tests of a similar traditional window at the National Physical Laboratory. This then allowed the two-dimensional heat conduction model FRAME to be calibrated and used with the empirical values to estimate the overall conduction heat loss of the window assembly. The results are summarised in the fourth and fifth columns of Table 1, which show that estimated heat losses by conduction and radiation through the window as a whole can be reduced by:

- 40 to 50%, simply by closing curtains or lowering plain blinds;
- 50 to 60%, by using shutters or insulating blinds with reflective surfaces facing outdoors;
- over 60%, by using secondary glazing with a low-emissivity coating; and
- even more where curtains, blinds or shutters are used alongside secondary glazing.

The results show that a traditional window with low emissivity ("low-e") secondary glazing is perfectly capable of meeting the regulatory requirements for new buildings during the day, and can do still better at night, when the blinds and shutters are closed. Further savings could be made, for example, if the secondary glazing used insulating frames (made for example of timber), or if it were to incorporate double glazing, as is widespread practice in northern Europe.

5. HEAT LOSS BY AIR LEAKAGE

Heat loss by air infiltration was inferred by setting up air-pressure differences across the window assembly and determining the relationship between air flow and pressure. At a 50 Pa pressure, the leakage rate through the window as-received was 183 m^3/hour. Repairs cut leakage to 120 m^3/h, and *in-situ* draughtproofing (which still left the window operable) to 26 m^3/h with the window closed. With secondary glazing installed as well, leakage fell to 8 m^3/h.

6. THE COMBINED EFFECTS OF CONDUCTION AND AIR LEAKAGE

None of the results for conduction heat loss shown in Table 1 are significantly affected by the measures to reduce air leakage discussed in Section 5. To get the best performance it is important to tackle both aspects. Indeed, we estimate that if the window tested had been installed in a typical house, air leakage would have been responsible for:

- over 60% of the overall heat loss through the window in its as-received state;
- about half its overall heat loss after the joinery was repaired but the window was not draughtproofed; and
- less than 20% of the heat loss if the window were fully draughtproofed but not insulated.

By combining repair with draughtproofed secondary glazing, total heat loss could be reduced to one-quarter of that of the window in its original state; and by even more at night with shutters, curtains or blinds in place. Thus it is certainly not essential to replace existing windows to obtain levels of improvement in thermal performance that make traditional timber sash windows comparable with standard modern windows[5].

7. PROVIDING VENTILATION AND AVOIDING CONDENSATION

The original window was so leaky that air infiltration would have met most wintertime ventilation requirements for occupied rooms, even when it was closed. The refurbished window would likewise have allowed sufficient ventilation, but draughtproofing reduced the measured air infiltration rate to about 60% of that achieved by a standard trickle ventilator (such as those often fitted to modern windows).

At this stage, one needs to reconcile heat retention with ventilation[6] and moisture removal. In some rooms, it may be possible to leave some windows tightly closed, because sufficient air can be provided elsewhere (e.g. via other windows, ventilators, or mechanical systems). In other cases – especially where there is only one window per room – the window will need to provide ventilation as well. With secondary glazing, the simplest approach is to open the inner window by a small amount, and rely on infiltration through the original window; if necessary this original window can be opened slightly too. The risk is that this might cause condensation problems, so to study the possible outcomes GCU undertook some tests of condensation with secondary glazing.

8. THE CONDENSATION TESTS

While occasional condensation is acceptable, persistent condensation is unslightly and can lead to decay of materials and mould growth. The condensation tests involved collecting and weighing the amount of water deposited on the inside of the original window over a 5-hour period, with the warm room at 22°C with a relative humidity of 60%[7], and the cold room at 2°C as usual.

The results for condensation on the inside of the original window were as below. No condensation was found on the secondary glazing itself.

When the secondary glazing was closed and reasonably well sealed (as in the tests), it protected the primary window from condensation. With the secondary glazing slightly opened, the presence and amount of condensation on the original window depended on the direction of air movement:

TABLE 2: CONDENSATION TEST RESULTS AT 60% RH	
Single glazed window, closed, no secondary glazing	33 g
Added secondary glazing, both windows closed or with primary window open	0 g
Added secondary glazing, slightly open; primary window closed	36 g
Added secondary glazing, slightly open; primary window slightly open	48 g
As above, but with hot room at small positive pressure to cold room	69 g
As above, but with hot room at small negative pressure to cold room	0 g

- if the outside air flowed inwards to the room, there was no problem; however
- if there was little or no flow, condensation on the original window increased; and
- if the flow was outwards and the main window was also open, condensation increased further.

The results demonstrate that there will be a risk of condensation in cold weather if the indoor air is humid and the secondary glazing is left open for ventilation, unless the flow of air can be controlled to be always, or at least nearly always, inwards from the exterior to the interior. These risks will be highest in rooms where there are high rates of moisture generation, or low rates of ventilation.

9. CONCLUSIONS

The timber sash window tests at Glasgow Caledonian University suggest that:

- There are major opportunities for improving the thermal performance of existing windows by relatively simple methods, including traditional curtains, blinds and shutters.
- There is a good potential for improvement from draughtproofing, with air infiltration through the repaired and draughtproofed window being somewhat less than through a standard trickle ventilator.
- There is potential for further improvement where secondary glazing with a low-emissivity coating is used as well. This gives good performance in the daytime, and better still at night when curtains, blinds and shutters can be closed.

However, when designing secondary glazing to avoid heat losses, it is important to ensure that ventilation is sufficient, and that the risk of condensation is minimised. The box below provides some simple guidelines for this.

SOME COMMENTS ON CONDENSATION AND SECONDARY GLAZING

As discussed above, draughtproof secondary glazing[8] with a clean low-emissivity hard coating facing the outside offers major reductions in heat loss through existing windows by controlling conduction, radiation and air leakage. There are potentially further opportunities to reduce conduction losses if double or vacuum glazed secondary units can be accommodated, and by improving the thermal insulation of the frames.

However, secondary glazing can be relatively airtight, so other means of ventilation may need to be considered. Condensation on the primary system may arise if the secondary system is opened for ventilation in cold weather and/or where rooms are relatively humid, (typically owing to high rates of indoor moisture production and/or low ventilation rates), and the air leakage is outwards[9].

These condensation risks will be minimised where the secondary glazing is either:

- able to be kept closed in cold weather, because there are alternative means of ventilation[10];
- located where the normal direction of air flow is from outside to inside, e.g. on the windward side of a building, on the lower floors, or where a designed natural or mechanical extraction system helps to ensure inward airflow[11];
- fitted with devices which avoid reverse airflow in adverse circumstances, e.g. a one-way trickle ventilator or a small fan incorporated in the window[12]; or
- where the primary and secondary window assemblies incorporate some alternative means of ventilating between the exterior and the room interior, but bypassing the cavity between the primary and secondary glazing (e.g. a bypass trickle ventilator on the secondary glazed unit).

NOTES:

1. During the day, windows also gain heat from outside by direct and diffuse radiation, but these effects are not dealt with here.

2. The climate chamber air conditioning initially created high air velocities over the window surfaces, leading to high rates of convection heat transfer between the rooms and the glazing, and anomalously high initial U-values. Baffles were fitted to avoid this.

3. A U-value is the heat loss through a square metre of a building element – here the window glass – for each degree of temperature difference between inside and outside. It is normally expressed as W/m^2K (watts per metre squared kelvin). Typical values in buildings range from as low as 0.1 W/m^2K for a very highly insulated wall, to 7 W/m^2K for a single-glazed roof light; the smaller the U-value the less the heat loss.

4. The 2006 CIBSE Guide A quotes U-values for vertical single glazing of 5.75 W/m^2K for windows under normal exposure, and 5.16 W/m^2K for windows in sheltered conditions (Table 3.23).

5. Sometimes even approaching those of more advanced designs.

6. The saying "build tight, ventilate right" is widely used in new construction.

7. These interior conditions are relatively humid, representing a dew-point temperature of 14°C, an absolute moisture content of 10.0 g/kg of dry air, and a water-vapour pressure of 1.68 kPa. At 2°C, air will have a moisture content of no more than 4.4 g/kg of dry air and a water vapour pressure of 0.71 kPa, even when conditions are very wet. In a traditional building with leaky windows (such as the test window as-found or as-repaired), and an exterior temperature of 2°C, the room test conditions could occur only transiently (for example during cooking, bathing, washing and drying clothes, or during a party, when there were many people present). On the other hand, if the window were closely draughtproofed and the sole source of ventilation, one sedentary occupant could produce enough moisture for the room to reach the test humidities.

8. Where draughtproof secondary glazing is fitted, it is neither necessary nor desirable to draughtproof the primary windows, because a small amount of ventilation of the gap by the outside air will actually help prevent condensation.

9. Particular care is needed when reviewing the condensation risk in the upper floors of naturally-ventilated buildings, where air leakage will tend to be outwards especially on the lee side.

10. For example, through a segregated trickle ventilator leading directly to the outside, through other windows or ventilators, via a mechanical system, or perhaps through existing chimneys.

11. Normally this would use extractor fans, but natural 'passive stack' extraction systems are also available.

12. These also offer opportunities for recovering some of the heat which would otherwise be lost to the outside through the space between the primary and secondary windows.

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GLASGOW CALEDONIAN UNIVERSITY

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SOME USEFUL DEFINITIONS

U-value A measurement of the heat transferred through a material: the lower the U-value, the slower the rate of heat flow and the better the insulating quality. Expressed as watts per square metre per degree of temperature Calcius or Kelvin (W/m^2K) .

Emissivity [**e**] The amount of heat lost from a surface by radiation is expressed by the emissivity, which varies from 0 (no radiation loss) to 1 (maximum loss). Emissivities of non-metallic building materials, paints and standard clear glass tend to be between 0.8 and 1.0; polished metals and low-emissivity coated glasses radiate heat much less readily, and have emissivities in the range 0.03 to 0.10.

SAP An acronym for the Standard Assessment Procedure, at time of press the UK Government's preferred method for calculating the energy performance of domestic buildings.

Heat flux The flow of energy through a surface, per unit of area. Expressed as W/m^2.

Relative humidity [**RH**] A measurement of the moisture level of the air. It is the ratio between the amount of water in the air at a given temperature and the maximum amount of water it could potentially hold at that temperature, and is expressed as a percentage.

This report summarises the results of research on the thermal performance of traditional windows and methods of reducing heat loss carried out by the Centre for Research on Indoor Climate & Health, Glasgow Caledonian University [GCU] on behalf of English Heritage.

1. INTRODUCTION

In 2004, the UK's carbon dioxide emissions stood at 559 million tonnes per year, with 27% of this attributed to the energy used in people's homes. It has been estimated that approximately a third of the CO_2 emissions from the average home could be saved by adopting simple energy saving measures, but achieving further reductions in carbon emissions from UK households to meet the UK Government's 80% target is a major challenge. Some hold the opinion that traditionally-constructed buildings are energy inefficient and should be replaced with new build rather than refurbished. However, whilst the operational carbon emissions of new buildings are often lower than traditional buildings, the latter already embody carbon and energy is required to demolish them and dispose of the resulting waste, and produce and transport new building materials. Existing buildings also have cultural and societal value. The question is how can we maintain our architectural heritage whilst improving the existing housing stock in response to climate change and the urgent need to reduce CO_2 emissions?

The options for upgrading the thermal performance are particularly limited for pre-1919 dwellings with solid wall constructions. Traditional single-glazed windows are considered as perhaps the easiest option for replacement with modern double glazing. Traditional windows are often considered to be draughty, prone to condensation and hard to maintain. On the other hand, with good care and maintenance traditional windows may outlast modern replacements and may be considered as a sustainable resource. The heat lost through a single glazed window is about twice that through a double glazed window meeting the current UK building regulations and standards (for example, a reference U-value of 2.0 W/m^2K is given for SAP calculations [1]). Whilst secondary glazing may be effective as an option to preserve existing traditional windows, there is little information on the performance of more traditional (and cheaper) methods of reducing heat loss, such as shutters, blinds and curtains.

The work presented here quantifies the effectiveness of relatively simple measures to improve the thermal performance of traditional windows by draught-proofing, and using blinds, curtains, shutters and secondary glazing.

A traditional Victorian sash window with single glazing was provided for testing. The window was mounted in an insulated panel between the two independently controlled rooms of an environmental chamber at GCU. Under a 20°C temperature gradient, the conductive heat flow through the glazing was measured using heat-flux sensors for the glazing only and with the various improvement options. The reduction in conductive heat loss and U-values were estimated. The improvements in the air-tightness were assessed after refurbishing the joinery, and again after draught-proofing. Condensation tests were also carried out on the window before and after installation of secondary glazing, since the assessment of condensation risk should be considered as part of the overall evaluation of the improvements made to the window.

2. THE TEST WINDOW AND OPTIONS

English Heritage provided an old two-by-two panel sash window for testing. The condition of the window was poor, with a decayed sill and the frame out of true, which resulted in a particularly bad gap between the top of the upper sash and the case. The paintwork and putty had also deteriorated, and one pane was cracked.

The outer frame dimensions were approximately 1770 mm high by 1160 mm wide, and 130 mm deep. The exposed sash dimensions were 1557 mm high by 923 mm wide. Each of the four panes was approximately 71.5 mm high by 42.5 mm wide, giving a glazed area of 1.22 m², compared to the total window area of 2.05 m² (i.e. 59% glazing).

Top: Exterior view of test window as received; *left* detail showing the decayed sill; *right* detail showing the gap between the upper sash and the frame

After the first series of tests on the window in the as-received condition, the basic joinery was refurbished by skilled joiners from Historic Scotland [HS], and additional improvements were carried out by GCU as follows:

- Frame squared up (HS)
- Part of sill and outer section of frame replaced (HS)
- Broken pane & putty replaced (HS)
- Gaps filled with plastic wood (GCU)
- Sash boxes and top of window sealed off with plywood and sealant (GCU)
- Coat of white primer applied (GCU)

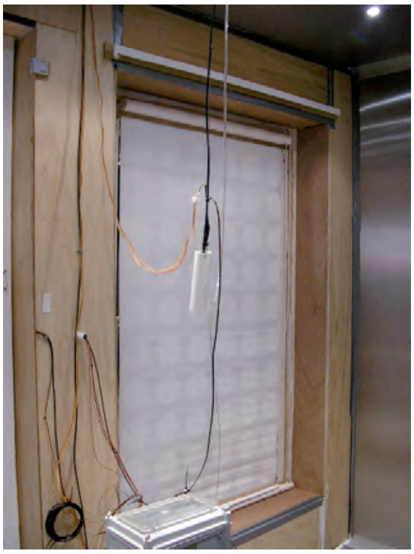
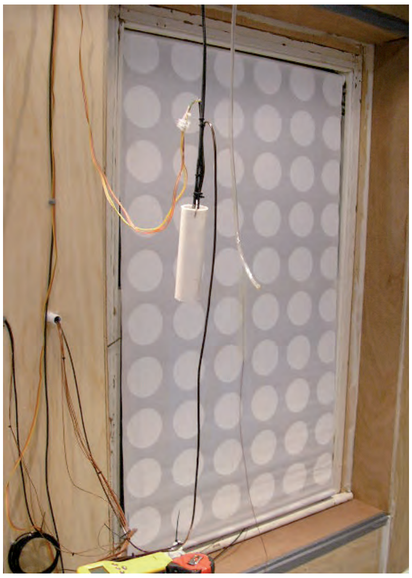
Above left: Window after joinery repairs; *right* after gap filling and coating with white primer

The window was subsequently draught-proofed using a proprietary system, which comprises a flexible sealant applied to the frame after careful preparation. One surface is coated with a detergent solution to prevent the sealant from sticking; the sealant is then applied to the adjacent untreated surface. The sealant is allowed to cure and the detergent removed, and the sashes can then be opened as usual.

Draughtproofing with proprietary system: *top* applying detergent to lower sash; *bottom* applying the sealant to the staff bead

TABLE 1: TEST OPTIONS EXAMINED IN GCU ENVIRONMENTAL CHAMBER

DESCRIPTION			
1	Heavy curtains fitted to rail on inside of insulated panel above window		
2	Three panel shutters constructed from 18mm plywood		
3	As per Option 2, but with foam strip draught-proofing applied around perimeter of shutters to give a tight fit against window frame		

4	Modern roller blind fitted on frame above sashes		
5	Modern roller blind fitted at the top of the window case inner lining to give a tighter fit to window		
6	Modern roller blind as per Option 4, but with low-emissivity film fixed to the window-facing side of the blind		

7	Modern roller blind as per Option 4, with low-e film fixed to the room-facing side of the blind		
8	Low-e roller blind as per Option 6, together with shutters as per Option 2		
9	Manufactured "thermal" honeycomb blind (NB: this option was not tested on the window in the as-received condition)		

10	A low-e secondary glazing system (fitted after refurbishment of the window)		
11	Secondary glazing as per Option 10, together with shutters as per Option 2		

3. THERMAL PERFORMANCE TESTS

The test window was installed in a 300 mm-thick insulated panel mounted between the two rooms of the GCU Environmental Chamber, with the window frame set flush with the cold face of the panel as recommended by BS EN ISO 12567-1:2000 [2]. Sealant was used around the joints between the window and the insulated panel in order to seal all gaps and hold the window firmly in position.

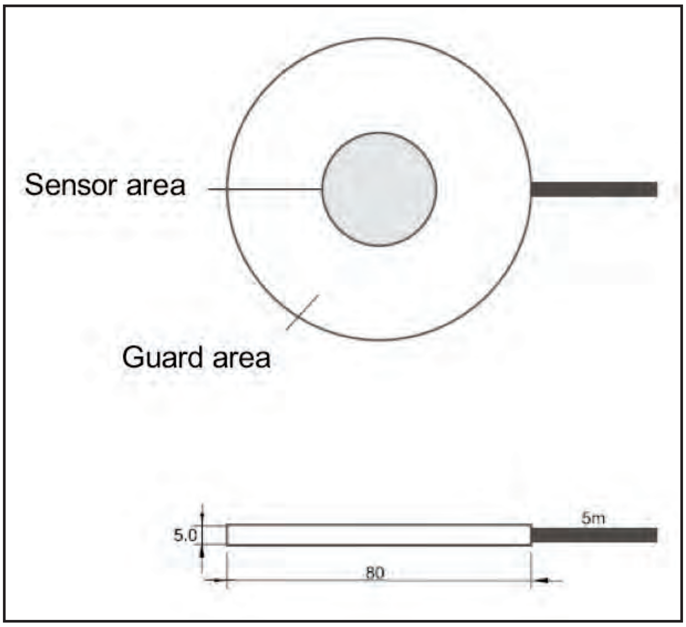
The Environmental Chamber is designed to test the performance of building materials & components under the range of climate conditions experienced in the UK. The chamber consists of two walk-in rooms: an “exterior” room which can be used to simulate outdoor weather, and an “interior” room to simulate typical indoor environmental conditions. The exterior room also has the facilities to simulate driving rain and solar radiation (using infra-red lamps) on a wall surface. Both rooms can be pressurised. The aperture formed between the rooms can accommodate a wall up to 3 m wide by 2.4 m high. By moving the interior room different wall thicknesses can be constructed. The two rooms can be controlled within the temperature and humidity ranges shown below. The temperature and humidity in both rooms, and the driving rainfall and infra-red lamps, are fully controllable from either built-in controllers or a PC.

The GCU environmental chamber, and its operating range

TABLE 2: TEMPERATURE AND HUMIDITY RANGES FOR GCU ENVIRONMENTAL CHAMBER		
	TEMPERATURE RANGE	RELATIVE HUMIDITY RANGE
EXTERIOR ROOM	-20 to 30°C	20% to 90%
INTERIOR ROOM	10 to 40°C	20% to 90%
NB: The relative humidity is not controlled if the set-point temperature is below 10°C		

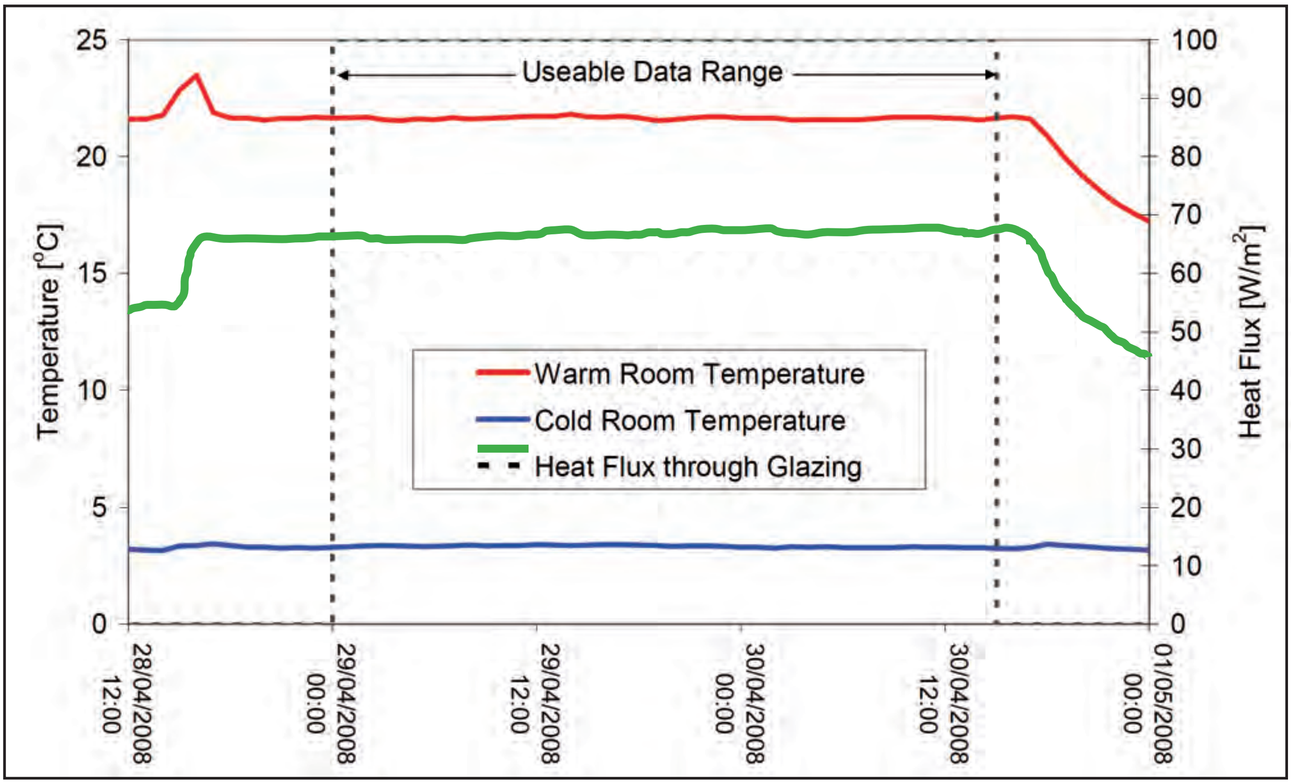
The whole-window U-value cannot be measured in the test facility (an accurate hot-box facility is required, such as the National Physical Laboratory guarded hot box). However, since the main conductive heat loss is through the glazing, heat-flux meters mounted on the glazing can be used to determine this directly, and with surface temperature measurements, the centre of pane U-value can be estimated for the glazing alone and with the addition of the various options. Hukseflux Type HFP01 heat flux sensors were used, affixed to the glass with double-sided adhesive tape.

Air temperatures in both the interior (warm) and exterior (cold) rooms, the surface temperatures of the glazing and the surface of curtains, shutters and blinds were measured with type-T thermocouples. Glazing surface thermocouples were affixed to the glass with transparent tape. All sensors were logged at 1-minute intervals and stored as 10-minute averages using a Delta-T Devices Ltd. Deltalogger.



Left: Heat flux sensor positions on glazing; *above* sensor dimensions

The test conditions generally used were 2°C in the exterior room and 22°C in the interior room. To avoid condensation during the heat-flux tests, the relative humidity in the interior room was set at 30%. Generally, tests were run for a sufficient duration to allow the environmental conditions in the test rooms and the heat flow through the window to stabilise after the installation of each option, and then collect at least two to three days data for analysis; for example the graph below shows data for a test with a heavy curtain.



Above: Example of test, showing warm and cold room temperatures and heat flux through glazing.

3.1 ANALYSIS

The effect of the various options on the conductive heat loss through the glazing was estimated as follows:

A U-value was calculated from the average heat flux meter reading and surface temperature difference between the outer glazing surface and the room facing surface of each option with a correction for the standardised internal and external surface resistances and the thermal resistance of the heat flux meter, using the following equation:

$$U = \frac{1}{\left(\frac{T_{si} - T_{se}}{Q}\right) + 0.17 - 6.25 \times 10^{-3}} \ \mathrm{W/m^2K}$$

where T_{si} and T_{se} are respectively the internal and the external surface temperatures, and Q is the heat flux. The term 0.17 is the sum of the standard internal and external surface resistances. The term 6.25×10^{-3} is the correction for the heat-flux meter.

This approach is justified because the boundary conditions in both rooms of the chamber are unknown and would require extensive calibration outside the scope of this investigation. However, steps were taken to reduce excessive air movement in both rooms by baffling of the air conditioning system. Without baffling, it was observed that the heat flux increased, and calculating the glazing U-value from the heat flux divided by the air temperature difference gave unreasonably high results.

The reduction in conductive heat loss was calculated from the improvement in U-value due to the option compared to the value for single glazing only.

The temperature of the surface of the curtain, shutter or blind facing the interior (warm) room is also reported, for comparison with the glazing temperature of the window without the option. This gives an indication of the improved comfort that should be experienced by lower radiative losses to a better-insulated window.

3.2 RESULTS

The test results are shown in Table 3, and compared in the figures on the next page.

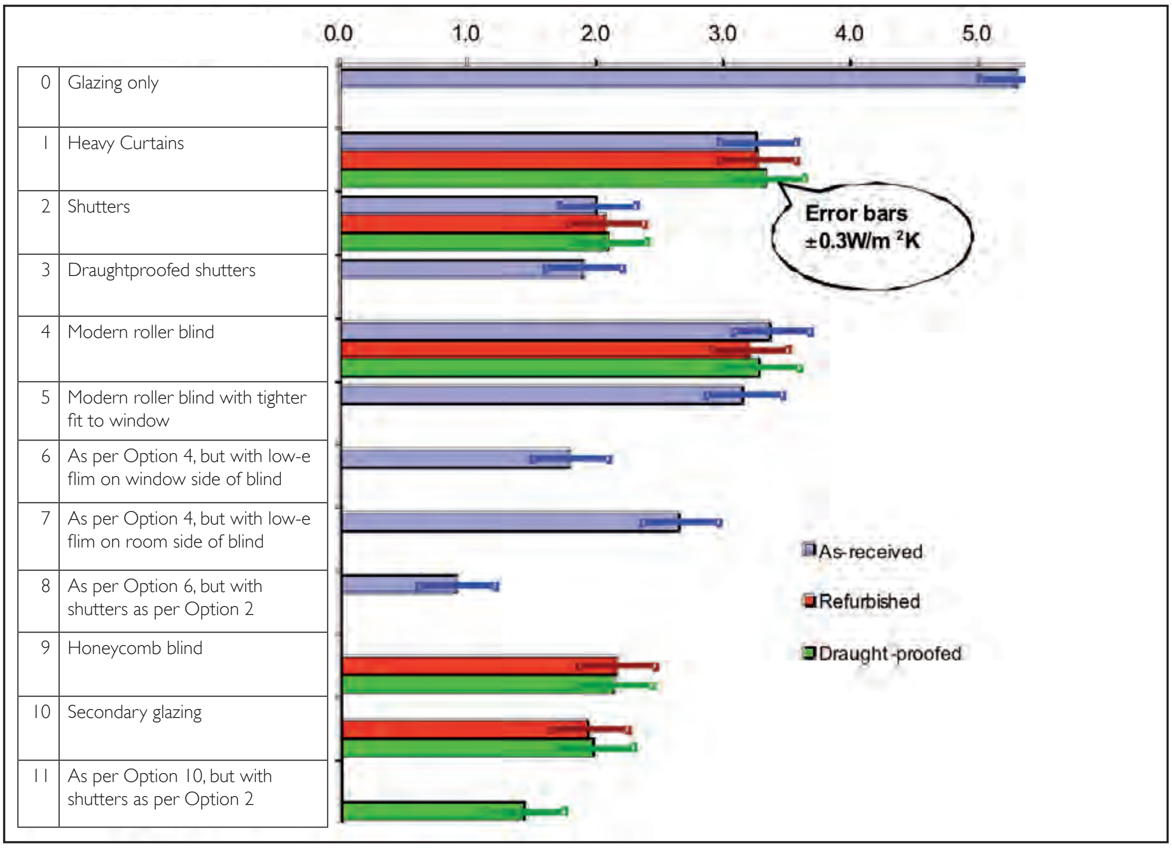
The estimated uncertainty in the U-value measurements is 0.3 W/m^{2}K. In the conductive heat loss measurements it is about 6%, due largely to temperature stratification down the window. For example, during the testing of the modern roller blind the average temperature of the inside surface of the top pane was 11.4°C, compared with 9.5°C for the bottom pane (near to the heat-flux meter locations). This stratification was confirmed by a thermographic survey of some of the options.

TABLE 3: TEST RESULTS

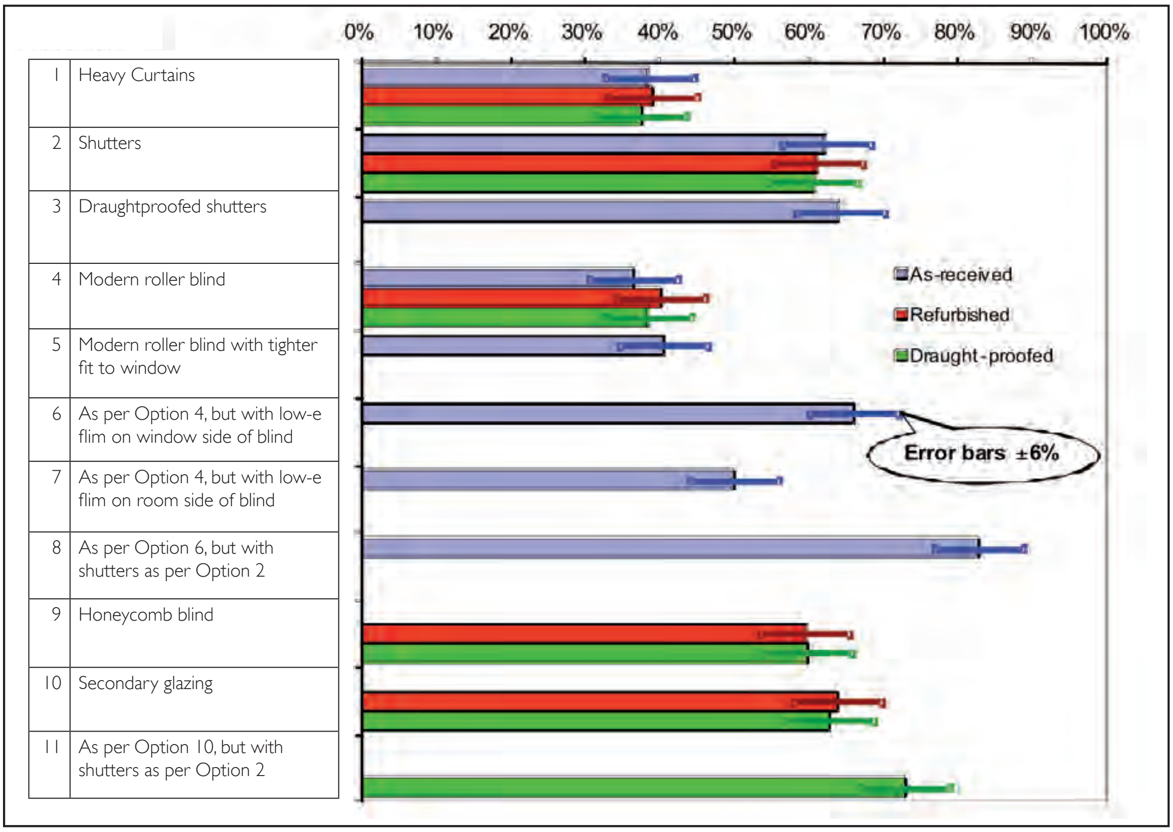
The effect of the various options on reduction in heat loss through the glass of the single glazing, the estimated U-values and measured average surface temperatures

		U-VALUE (W/M^{2}K)	REDUCTION IN HEAT LOSS	TEMPERATURE OF SURFACE FACING INTO ROOM (°C)
WINDOW AS-RECEIVED				
0	Centre of glazing	5.3	—	12
1	Heavy curtains fitted to rail on inside of insulated panel above window	3.3	39%	20
2	Shutters	2.0	62%	17
3	Draught-proofed shutters	1.9	64%	17
4	Modern roller blind	3.4	37%	18
5	Modern roller with tighter fit to window	3.2	41%	17
6	As Option 4, with low emissivity plastic film fixed to the window facing side of the blind	1.8	66%	19
7	As Option 4, with low-e plastic film fixed to the room facing side of the blind	2.7	50%	18
8	Low-e roller blind as per Option 6 and Shutters as per Option 2	0.9	83%	20
AFTER IMPROVING JOINERY				
1	Curtains	3.3	39%	21
2	Shutters	2.1	61%	17
4	Roller blind	3.2	40%	18
9	Honeycomb blind	2.2	60%	20
10	Secondary glazing	1.9	64%	18
AFTER DRAUGHT-PROOFING				
1	Curtains	3.3	38%	20
2	Shutters	2.1	61%	17
4	Roller blind	3.3	38%	18
9	Honeycomb blind	2.1	60%	20
10	Secondary glazing	2.0	63%	19
11	Secondary glazing + shutters	1.4	73%	20

THE EFFECT OF THE OPTIONS ON U-VALUE



THE EFFECT OF THE OPTIONS ON REDUCTION IN HEAT LOSS THROUGH THE GLAZING



The differences between the U-value and conductive heat loss results on the window before and after repair and following draught-proofing are not significant given the measurement uncertainty. It should be noted that these conductivity tests do not measure the effects of any air infiltration, which are reviewed separately in Section 4.

All the measures have some impact on reducing the heat flow through the glazing. The shutters are the most effective traditional solution, showing a 61-64% reduction in conductive heat loss. Draught-proofing the shutters has no significant effect on the conductive heat loss. The modern roller blind with the low emissivity foil facing the window is also an effective option. Secondary glazing produces a similar result to the shutters and the foiled blind, but would have the advantage of being effective throughout the day rather than only at night as may be expected with the typical use of blinds, etc. The combinations of blind with shutters and secondary glazing with shutters further improve effectiveness.

The results also show that all options give higher surface temperatures than single glazing alone, providing added improvements to thermal comfort.

3.3 WHOLE WINDOW CONDUCTIVE HEAT LOSSES

The results above show the effect of the various options on reducing the conductive heat loss through the glazing of the sash window. The impact of the measures on the whole window (frame and glazing) was estimated using calculations derived with a 2-D finite element model, FRAME [3] – specifically designed for windows – to give a U-value of 4.3 W/m²K for the complete window (i.e. both the frame and the single glazing). Measurements on a similar window carried out by the National Physical Laboratory [4] gave a U-value of 4.4 W/m²K.

The Table below gives estimates of the whole window U-value given the improvements due to the various options, including the estimate using the FRAME program of the effect each option has on reducing heat flow through the timber frame of the window.

Modelling using FRAME gave the following estimates of the window frame U-values:

- Window with single glazing only: 2.5 W/m²K
- Window with blinds that only cover sashes: 1.7-1.8 W/m²K (about 30% reduction in heat loss through frame)
- Window with options that completely cover the window: 1.3-1.4 W/m²K (about 45% reduction in heat loss through frame)

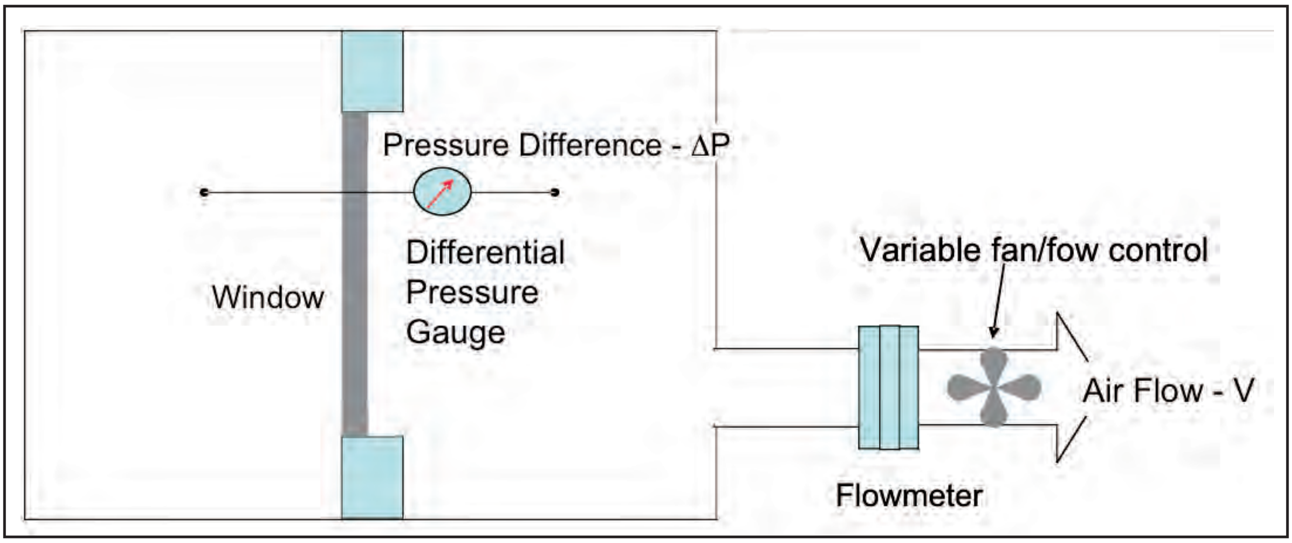
TABLE 4: ESTIMATES OF THE WHOLE WINDOW U-VALUES AND REDUCTION IN TOTAL HEAT LOSS THROUGH THE WINDOW WITH THE VARIOUS OPTIONS

		WHOLE WINDOW U-VALUE (W/M²K)	REDUCTION IN TOTAL HEAT LOSS THROUGH WINDOW
0	Window with single glazing only	4.3	
1	Heavy curtains fitted to rail on inside of insulated panel above window	2.5	41%
2	Shutters	1.8	58%
3	Draught-proofed shutters	1.7	59%
4	Modern roller blind	2.7	38%
5	Modern roller with tighter fit to window	2.6	39%
6	As per Option 4, with low-e plastic film fixed to the window-facing side of the blind	1.9	57%
7	As per Option 4, with low emissivity plastic film fixed to the room-facing side of the blind	2.3	46%
8	Low-e roller blind as per Option 6, and shutters as per Option 2	1.4	67%
9	Honeycomb blind	2.1	51%
10	Secondary glazing	1.8	58%
11	Secondary glazing and shutters	1.6	62%

4. AIRTIGHTNESS TESTS

Complaints regarding draughty old windows are common; as well as causing discomfort, leaky windows result in higher heat demand and CO_2 emissions. On the other hand, it is also important to maintain sufficient ventilation for good indoor air quality. The tests described below were carried out to quantify the effectiveness of refurbishing and draught-proofing the window and measuring the airtightness of the secondary glazing system.

The airtightness characteristics of the window as-received, after repair, following draught-proofing and installation of secondary glazing were measured by a pressurisation method with both test rooms at 22°C. The diagram below shows the basic principle of the test.



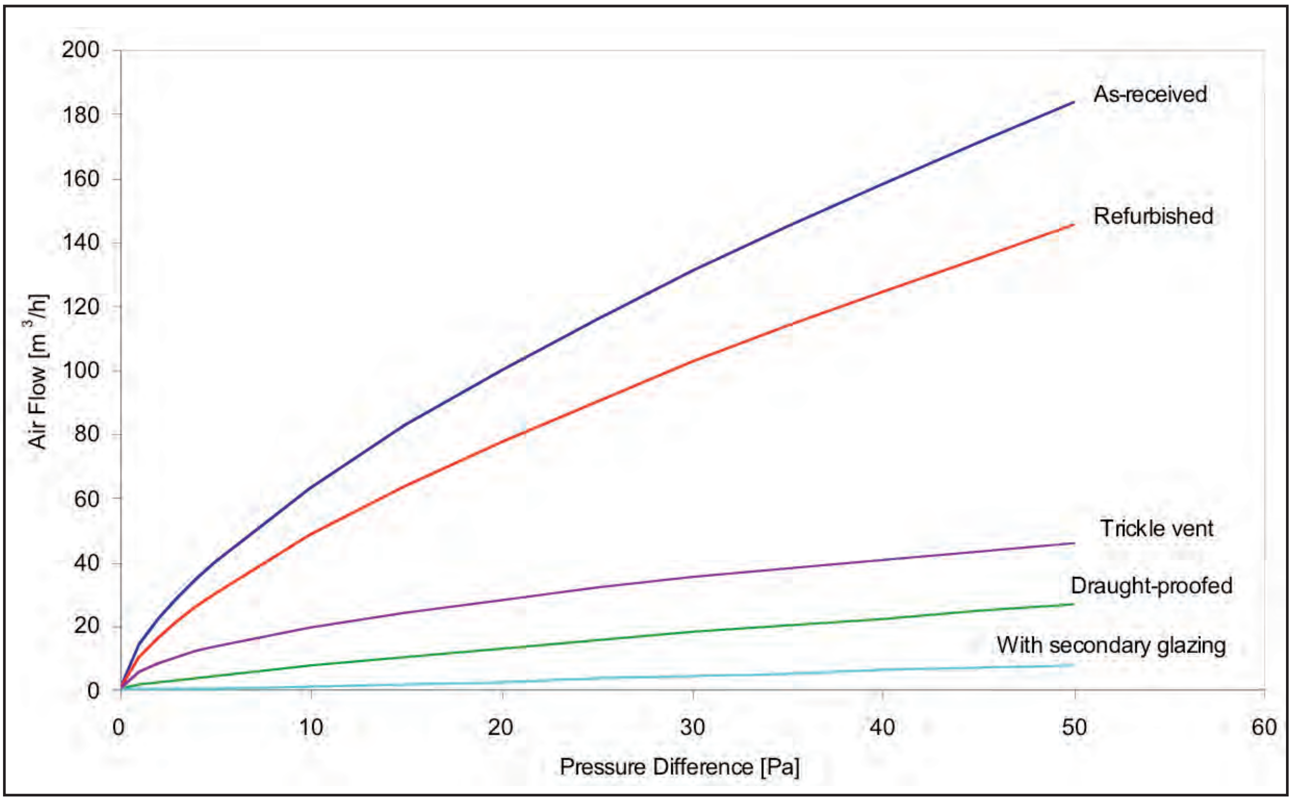
Above: Diagram explaining the pressurisation test – the air flow (V) is adjusted to produce a pressure difference (ΔP). This procedure is repeated to produce a range of values, usually up to and including 50 Pa pressure difference.

The tests were carried out in two parts, (i) with the window covered by an air impermeable polythene sheet, which is taped to surrounding panel, to determine the background air leakage of the test room; and (ii) without the window covered to determine the total air leakage of the room and window at each pressure difference.

The background leakage at each pressure difference was subtracted from the total leakage to estimate the window leakage.

Left: The window was covered with air-impermeable polythene sheet to determine background air leakage of room

The results are plotted and a power law relationship is usually fitted to the data. The results for the window in the as-received condition and after repair, draught-proofing and installation of secondary glazing are shown in below. The air leakage characteristics of a trickle vent with an area of 4000 mm² measured in a Canadian study [5] are included for comparison.

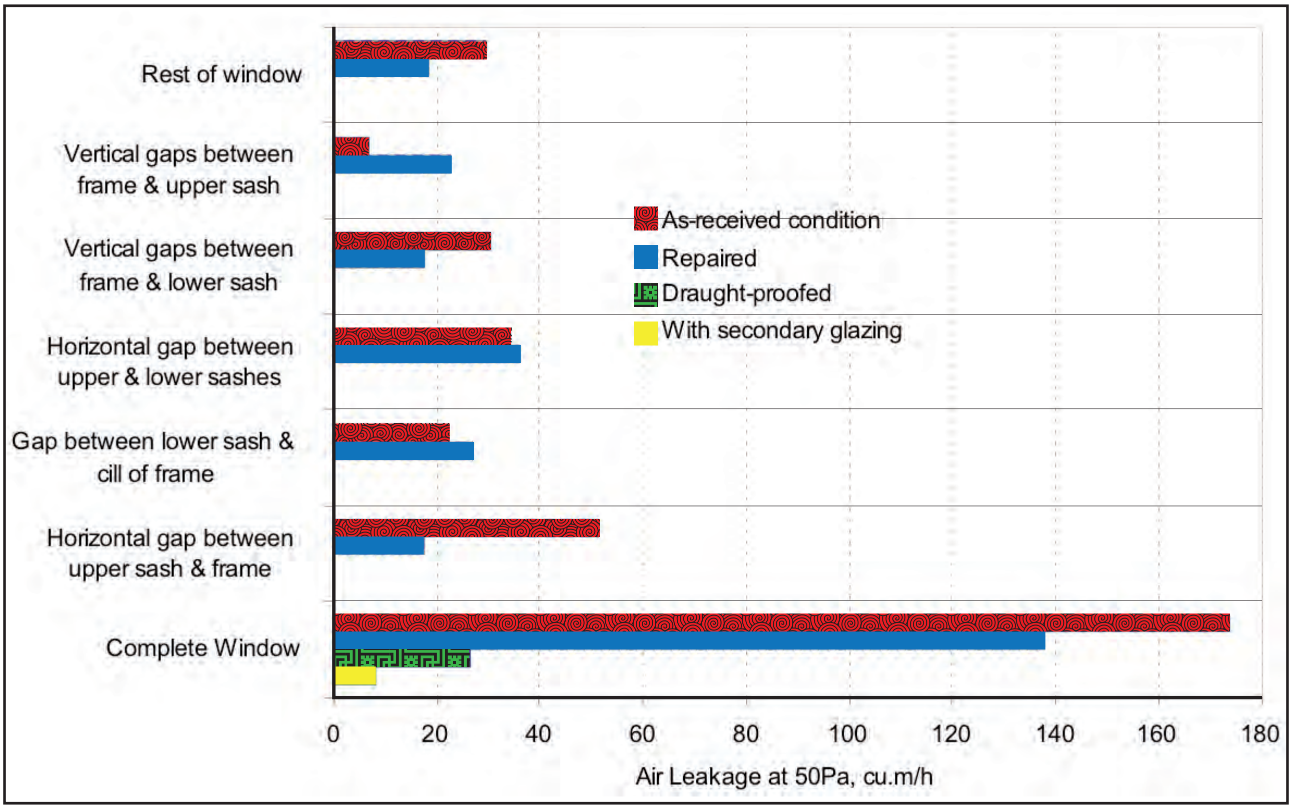


Above: Air leakage characteristics of the window in as-received condition, after repair, after draught-proofing and following installation of secondary glazing. The air leakage characteristic of a trickle vent is included for comparison.

The reductions in air leakage compared to the as-received condition are given in Table 5:

TABLE 5: REDUCTION IN AIR LEAKAGE COMPARED TO AS-RECEIVED WINDOW	
	REDUCTION IN AIR LEAKAGE
Repair to joinery, etc.	34%
Draught-proofing	86%
Secondary glazing	96%

During testing of the window in the as-received condition and after repair, the magnitude of the air leakage through the various gaps in the window was determined by progressively sealing each gap with tape and re-testing, until all obvious gaps were sealed. The air leakage paths are compared using the air leakage values at 50 Pa pressure difference before and after repair in the chart below. The air leakage results for the draught-proofed window and following installation of the secondary glazing are included for comparison.



Above: Comparison of the main air leakage paths before and after repair of window

The main benefits of the repair have been to reduce the air leakage through (1) the horizontal gap between the upper sash and frame, by re-aligning the window and (2) the leakage through the smaller gaps constituting the "rest of the window" by sealing with plastic wood compound and painting. However, whilst overall there is a significant improvement due to the repair, there is a slight increase in the leakage through the other main gaps. More substantial improvements follow draught-proofing and installation of well sealed secondary glazing. The air leakage of the draught-proofed window is less than that of the trickle vent.

5. THE COMBINED EFFECT OF CONDUCTION AND VENTILATION

The combined effect on the heat loss through the window of improvement measures designed to reduce conductive heat loss and draught-proofing are estimated below for selected examples: the shutters and secondary glazing.

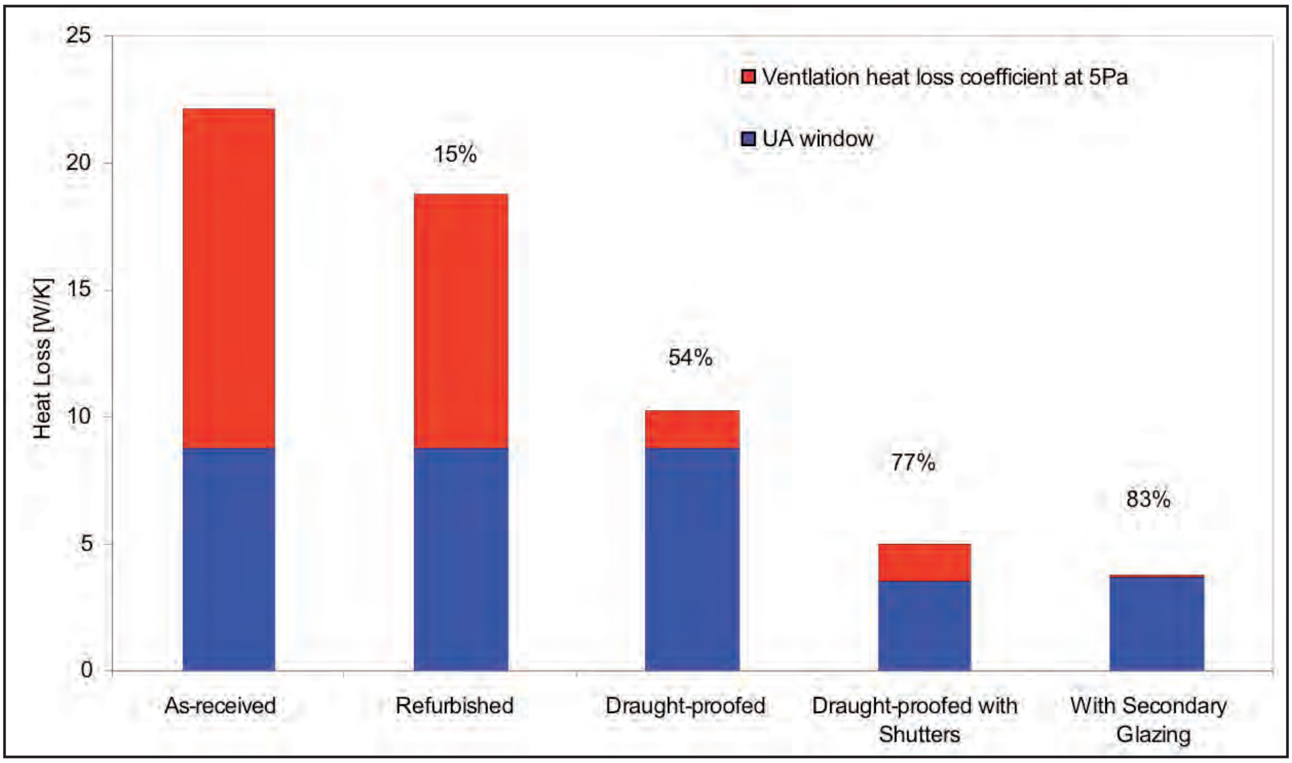
The heating load due to ventilation through the window is calculated as follows:

$$0.34 \times fn(\Delta P) \times \Delta T \ \ [\mathrm{W}]$$

where 0.34 is the specific capacity heat × density of air ($\mathrm{Wh/m^3K}$), $fn(\Delta P)$ is the airflow ($\mathrm{m^3/h}$) as a function of the pressure difference across the window, and ΔT is the temperature difference between room and outdoor air (K).

The value $0.34 \times fn(\Delta P)$ may be termed the ventilation heat-loss coefficient (W/K). Combining the window U-value (heat loss by conduction) with the ventilation heat loss coefficient gives an overall performance metric. For example, the chart below combines the window UA-value – i.e. U-value × total window area – with the heat loss due to ventilation at a 5 Pa pressure difference, which approximates to an average pressure difference that may be expected in winter. Examples are given for the as-received and refurbished window, the window after draught-proofing with and without shutters, and with secondary glazing; the shutters and secondary glazing being the most effective options for reducing conductive losses.

The chart illustrates how the combined effects of reduced conduction and ventilation contribute to improving the thermal performance of the window. For the original window, air leakage at 5 Pa accounts for 60% of the overall heat loss, and conduction through the glass and frames only 40%. After refurbishing and draught-proofing, overall heat loss is reduced to 46% of the original value, and air leakage accounts for only 14% of this much smaller total. Secondary glazing reduces the air leakage to almost zero, and heat losses to 17% of the original value, but ventilation air would have to be provided by other means.



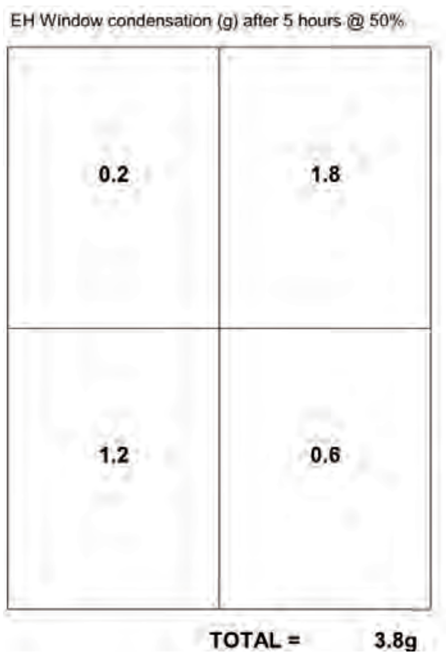
Above: Examples of the total heat loss coefficients for the window for ventilation rates at 5Pa pressure difference. The percentage labels represent the total reduction in heat loss compared with the as-received case.

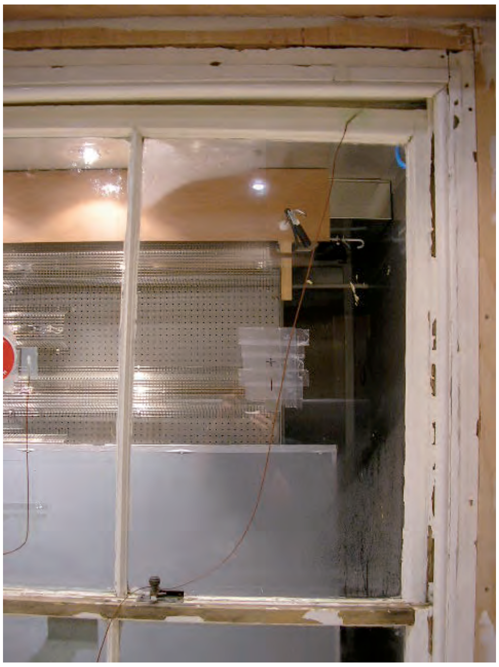
6. CONDENSATION TESTS

Two tests were carried out on the as-received window with the relative humidity raised to (i) 50% and (ii) 60% for five hours, with a warm room temperature of 22°C and the cold room at 2°C. At the end of this period any condensation on the glazing was mopped up using absorbent paper and weighed.

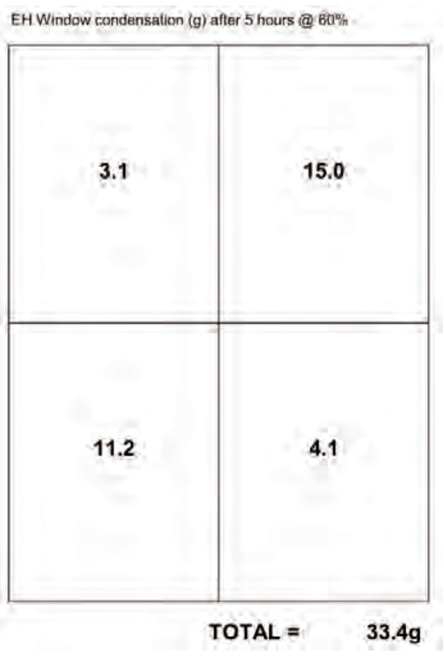
The figures below show the condition of the window after five hours exposure to the higher relative humidity, and the amount of condensation collected on each of the four panes.

CONDENSATION AFTER 5 HOURS AT 50% RELATIVE HUMIDITY





CONDENSATION AFTER 5 HOURS AT 60% RELATIVE HUMIDITY



After five hours at 50% RH, condensation occurred mainly as misting on the lower part of each pane. Whilst the condensation was noticeable, the overall quantity collected was small: just over a teaspoonful for the whole window. By contrast, after 5 hours at 60% RH, condensation covered the panes and was running down them. About nine times more water was collected, compared with the test carried out at 50% RH.

Following the installation of the secondary glazing, the test at 60% relative humidity was repeated. Four options were examined:

1. Both the secondary glazing and the window firmly closed.
2. The bottom sash of the secondary glazing opened to form a 5-mm gap, but the sash window closed.
3. The bottom sash of the secondary glazing opened to form a 5-mm gap, and the top sash of the window opened to form a 5-mm gap.
4. The secondary glazing firmly closed, and the top sash of the window opened to form a 5-mm gap.

With the secondary glazing open to simulating "leaky" secondary glazing, condensation formed on the panes of the sash window, but there was no evidence of condensation when the secondary glazing was firmly closed. All the condensation test results after 5 hours at 60% relative humidity are summarised in Table 6.

TABLE 6: CONDENSATION COLLECTED ON PANES OF SASH AND CASE WINDOW AFTER 5 HOURS WITH ROOM CONDITIONS AT 60% RELATIVE HUMIDITY AND EXTERNAL TEMPERATURE 2°C

		CONDENSATION COLLECTED (GRAMS)
0	Window without secondary glazing	33
1	Window and secondary glazing closed	0
2	Window closed & secondary glazing open	36
3	Window and secondary glazing open	48
4	Window open & secondary glazing closed	0

If warm moist air is allowed into the gap between the secondary glazing and the sash window, the temperature of the air will fall below its dew point as it cools, resulting in condensation on the colder surface of the window. Table 6 shows that the risk of condensation is at least as high for the open secondary glazing as for the window alone. The situation is exacerbated if both the window and the secondary glazing are open: this may allow a continuous flow of warm air to the outside resulting in a higher condensation rate. On the other hand, if the secondary glazing is firmly closed the risk of condensation appears to be negligible, whether the original sash window is open or closed.

A preliminary investigation into the effects of deliberately ventilating through the window with the secondary glazing slightly open, indicate that if there is a small positive pressure difference (about 2 Pa) between the cold and the warm test chambers (i.e. cold air drawn through the window into the room), there appears to be no risk of condensation, since the cold air has a lower dew point. Conversely, there is a high risk of condensation when the situation is reversed and warm air is exhausted via the gap between the secondary glazing and the window to the cold chamber, with 69 g of condensation collected after five hours. In a room where the window may be the only source of ventilation, the results suggest that the secondary glazing system should be suitably designed with, for example, a pressure controlled trickle vent to prevent exfiltration of warm air and also avoid excessive infiltration [6, 7].

7. CONCLUSIONS

The conduction and ventilation heat losses through a traditional sash window have been measured independently with various measures and improvements.

All the options tested in the GCU Environmental Chamber reduce the conductive heat loss through the glazing. Shutters are the most effective option of the traditional methods. The low emissivity secondary glazing system, the honeycomb blind and modern roller blind coated with a low emissivity film facing the glazing gave similar performances to the shutters, however the secondary glazing system has the advantage that its benefits can be realised throughout the day. Combinations of options offer further improvements in thermal performance.

As a guide to U-value improvements, assuming that a typical sash window with single glazing only has a U-value of 4.3 W/m^2K, then heavy curtains and ordinary roller blinds reduce the U-value to around 2.6 W/m^2K and shutters, improved blinds and low emissivity secondary glazing to around 1.9 W/m^2K.

All the options offer improved thermal comfort due to higher surface temperatures resulting in lower radiative losses to a better insulated window compared with single glazing alone.

As anticipated, refurbishing the window and draught-proofing it, whilst reducing air leakage, gave no significant improvement in conduction loss through the glass as measured by the heat flux method. On the other hand, improving the air tightness of traditional windows by reducing unwanted air leakage will decrease the ventilation heat load of a building. Draught-proofing reduces the air leakage of the window by about 85% compared with that of the original window. The airtightness of the draught-proofed window is comparable with that of a standard 4000 mm^2 trickle vent.

Combining draught-proofing with measures such as shutters or secondary glazing produce significant improvements with reductions in heat loss of 70% or more under typical conditions.

The tests at the upper end of the range of domestic humidity conditions (22°C, 60% RH) showed that the risk of condensation on the original window was high. Once the well-sealed secondary glazing system was added, there was never any condensation on the secondary glazing itself, and:

- When closed, the secondary glazing protected the original window from condensation, whether the original window was open or shut.
- When the secondary glazing was open a little, the amount of condensation on the original window was slightly more than when the secondary glazing was not fitted.
- With both the secondary glazing and the original window open a little, the amount of condensation on the original window increased. This condensation could be stopped if the room was at a small negative pressure (2 Pa) in relation to the outside, when the drier outside air was drawn into the room via the window.

Care must therefore be taken with specification, installation and maintenance, to ensure that any secondary glazing seals well when closed. If this is done, it will not be necessary or desirable to draught-proof the original window.

The tests have shown that major improvements to traditional windows are possible. However, when deciding what to do, it is important to adopt a holistic approach that takes account of the dynamic conditions which may be expected in real buildings and balances the potential for reducing heat loss with the need for sufficient ventilation to remove moisture and pollutants. For example, unless an inward flow of air can be guaranteed, secondary glazing should be closed tight in cold weather to minimise the risk of condensation on the original window, as otherwise if any condensation occurs and is not mopped up it could lead to mould growth and decay. However, if there is not enough alternative ventilation when the window is closed, there will be a risk of poor indoor air quality, mould growth on colder surfaces (with possible health implications for the occupants), and damage to the building fabric.

8. REFERENCES

1. SAP 2005, *The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2005 Edition, Revision 2*, Building Research Establishment, June 2008
2. BS EN ISO 12567-1:2000, *Thermal performance of windows and doors. Determination of thermal transmittance by hot box method. Complete windows and doors*, BSI, ISBN 0 580 36028 8
3. FRAME 3.1, Enermodal Engineering Ltd., Canada 1993
4. Baker P. H., *Thermal Performance of Traditional Windows, Technical Paper 1*, Technical Conservation Group, Historic Scotland, November 2008 (http://www.historic-scotland.gov.uk/gcu-technical-_thermal-efficiency-traditional-windows.pdf)
5. Karava P., Athienitis A., Stathopoulos T., "Experimental investigation of the performance of trickle ventilators", in *Proceedings of 4th Annual Hybvent Conference*, Concordia University, Montreal, Canada, May 2002
6. McEvoy M. E., Southall R. G., Martin C. J., "Outdoor Measurements of the Influence of Aspect Ratio Performance on the Performance of Supply Air Windows", in *Architectural Science Review*, Vol. 46, 2003
7. Baker P. H., McEvoy M. E., Southall R. G., *Improving Air Quality in Homes with Supply Air Windows, Information Paper IP6/03*, BRE 2003, ISBN 1 86081 628 2