CENTRE FOR WINDOW AND CLADDING TECHNOLOGY

Guide to the Design of Thermally Improved Glazing Frames

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Centre for Window and Cladding Technology 1995

This research report was written by the Centre for Window and Cladding Technology to provide technical guidance to designers of glazing frames. The report is based on a number of comparative computer predictions of heat transfer through glazing frames. The results described in this report must not be used as proof of performance of any glazing frame of a similar design, material or construction.

The research work was funded by the Department of the Environment under contract number 39/13/182.

The author gratefully acknowledges the support of ANSYS, Inc. ANSYS® is a registered trademark of SAS IP. ANSYS® is published by

ANSYS, Inc.
201 Johnson Road
Houston, PA 15342-1300
USA

Centre for Window and Cladding Technology
November 1995

ISBN 1 874003 16 5

Published by
Centre for Window and Cladding Technology University of Bath, Claverton Down, Bath BA2 7AY

CONTENTS **Page**

1 Introduction

The need to understand and predict heat transfer through the various component parts of the building envelope is growing in importance with the introduction of ever-tighter regulations designed to reduce energy usage and CO_2 emissions. In response to the need for better energy efficiency designers are required to prove and improve the thermal performance of many of the components used in the building envelope.

The building envelope, particularly in domestic buildings, for the most part comprises layered structures for which the bulk thermal properties are readily determined. This is true of walls, glazing and, to a lesser degree, roofs. However, the edges of many of these constructions, and the components which are adjacent to these edges, are often of uncertain performance.

The major issues of heat loss through the building envelope are now focused on the edges of wall constructions, particularly around openings, and the various types of glazing frame. The Building Regulations Approved Document L (1995) advises on ways of reducing thermal bridging around openings, and includes a table of typical window U-values which allow for heat loss through the window frame. However, this table of U-values is of little use to the glazing frame designer, as it is simply a list of safe estimates of window heat loss grouped according to frame material and glazing type.

There is clearly a need for a more detailed map of the heat transfer processes through different glazing frames, particularly if glazing frame designers are to develop products that are better matched to the more advanced glazing types now being developed. This study is intended to both illustrate in more detail the range of glazing frames currently available (some of which are not represented in Approved Document L), and to provide the glazing frame designer with a starting point for modifications to reduce frame heat loss.

1.1 The performance of glazing frames

Glazing frames have a range of functions, most important of which is the requirement to support and retain the glazing. Consequently the frames must be designed to meet certain criteria of strength and stability. However, in most cases it is possible to include in the frame design some element or elements which are intended specifically to reduce heat transfer through the frame, if the frame material itself does not meet this objective.

Whether or not frame heat transfer is actually reduced by a particular design modification that is carried out, and by how much, is not easy to determine. In particular there is little guidance or information that the designer can make use of to decide how best (in terms of economy of material use and economy of manufacture) to improve the thermal performance of a particular frame.

It must also be realised that for many export markets the window manufacturer may be called upon to design frames with a level of performance far superior to any currently specified in the UK. In order to generate new markets overseas the designer must become aware of the effect of various design changes on the thermal performance of frames. With the current international emphasis on reducing energy usage and CO_2 emissions the designer must learn how to improve thermal performance. A widely used window and door heat transfer rating scheme in use in the USA (NFRC 1991, NFRC 1995) perhaps indicates the direction of future developments in the UK - interest in this type of rating scheme has already been shown in other countries, and the rating scheme is based on the use of low cost computer software which can also be used as a design tool. Clearly designers in those countries which use such a rating scheme have a significant advantage if the rating tools can be used in the design process.

1.2 Assessing heat transfer

In part the availability of design guidance is driven by the requirement to assess performance, in order to meet some performance specification. As walls form the major part of the building envelope, traditional wall constructions were the first components for which a U-value had to be determined. Accordingly there are basic calculation methods suitable for simple layered components, and these methods can be used to predict the performance of both walls and glazing. However, these methods cannot be used to take account of complex elements which bridge (and interact with) the glazing or the wall construction, such as glazing frames, because the simple calculation methods assume one-dimensional heat transfer; glazing frames always experience two- and three-dimensional heat transfer.

The purpose of this study is to generate a set of data relating to heat transfer through various types of glazing frame. Such a collection of data can be used to indicate the effect of differences in design, and so becomes a useful guide for the designer. However, in order to investigate the effect of single design changes it is preferable to use a method of assessment which does not require prototype frames to be produced and measured. The majority of heat transfer measurement techniques require careful calibration, and a single frame, with one type of glazing, may require several days to obtain a single measurement. Clearly this study, which examines the performance of 72 different glazing frames, each with two glazing types, would require several years to obtain a full set of results, many of which would be of little value because the effects of a localised design change on overall performance may be masked by experimental uncertainties.

To get around this problem a computer-based method of analysis is used, which simulates heat transfer through a glazing frame and allows the effect of design changes to be examined one at a time, without altering the performance of the remainder of the frame. A range of frame types has been chosen as representative of those currently found in practice, comprising 56 window frames and 16 curtain walling frames. It is anticipated that future studies will expand on the basic frames considered here, to cover the whole range of frames, current and future, that are likely to be of interest to the glazing frame designer, specifier or architect. Research is also being undertaken to relate simulated performance values to data obtained by measurement - simulation methods like those used here have already been found to give overall window U-values consistently within 10% of those obtained by measurement (NFRC 1995).

1.3 Heat transfer and simulation methods

This study used finite element analysis, using the commercially available software ANSYS®, to assess the heat transfer through the glazing frames. The exact methods used are described in Appendix A of this report, and Appendix B lists the values of material thermal conductivity used for the analyses. However, key assumptions and the general layout of each set of results is described here.

1.4 The simulated frames

The frames considered in this study comprise 56 window frames and 16 curtain walling frames. However, to simplify the analyses only a cross-section of each frame is considered - effects at the corners of the glazing, where frames meet, are difficult to simulate. As the frames are linear in geometry the major part of each glazing frame is expected to perform as shown in the results presented here.

1.4.1 Curtain walling

In curtain walling systems the framing elements are based on aluminium extrusions, with the principle difference between systems being in the method of creating a 'thermal break' between the warm-side and cold-side aluminium sections. Significant variations in curtain walling systems are also found in the insulated spandrel panels that are often used to reduce heat transfer through the facade (the equivalent of an insulated wall in a domestic building). Insulated panel design will be the subject of a future study however, and so the curtain wall frames included in this document are used only to show the effect of various methods of establishing a thermal break.

1.4.2 Windows

In the case of windows the problem is more complex, as there are four common framing materials - timber, PVC-U, aluminium and steel - and there are also a number of composite frames making use of two or more of these materials (new materials such as pultruded grp have not been considered in this initial study). Furthermore in a typical window there may be a number of different frame cross-sections, comprising fixed frames, frames with vents and mullion or transom frames with glazing or vents on both sides. The following sections describe assumptions that have been made to reduce the number of analyses.

1.5 Simplifying assumptions

A number of assumptions have been made in order to reduce the total number of simulations required:

1.5.1 Frame type

The primary objective of this initial study is to identify basic principles of heat transfer in glazing frames, whilst also providing a guide to the performance of typical frame designs. To simplify the study only fixed frames have been examined, and the effect of any adjacent wall construction on the frame has not been considered.

If opening frames had been included in the study then the number of alternatives to consider would have increased several-fold. Similarly, there are a large number of wall constructions into which a window may be installed, and the position of the window within the opening may also vary, precluding a sensible study of this interaction until the range of frame performance has been established.

1.5.2 Frame size

To assist in the comparison of the various frame types the projected width of the frames has been standardised at 55 mm, for window frames, and 60 mm, for curtain walling.

A standard frame width allows direct comparison of different frames. The standard sizes are based on a survey of frames currently available. Fixed light window frames were found to have projected widths in the range 50-70 mm for PVC-U, timber and thermally-broken metal frames, or 25-45 mm for traditional steel frames, with current architectural preferences moving towards more slender frames. A projected width of 55 mm was taken for all window frames, with the steel frames being fitted with a timber sub-frame to make up the difference (this issue is discussed in more detail in the introduction to Chapter 5). Note that the use of a non-typical 55 mm width is intended to discourage the use of performance values obtained in this report for similar frames currently in the marketplace - there are many factors which influence the heat transfer through a frame and even a small difference in design or material selection can change the performance significantly.

It is important to note that although window frame U-values are often compared directly this is not sensible if the frames have different projected widths. An overall window U-value is calculated for each of the window frame simulations in this study, which is particularly important for the handful of simulations where sills are considered. The window overall size has been taken as 900 mm wide by 1250 mm high (a reasonable size for a fixed light window), and the formulae described in section 1.6 may be used to calculate values for other window types.

For curtain walling a more typical 60 mm projected width is taken, but the performance values given in this study are unlikely to be applied to existing frames because, as indicated in the introduction to Chapter 7, there are good reasons for preferring the use of measurement to assess the heat transfer through curtain walling frames.

A selection of the various window frames considered in this study are shown in Figure 1.1. Note that the projected width, 55 mm, does not include the overlap of the glazing seals with the glazing, which may differ significantly between frames.

1.5.3 Glazing type

The glazing type has been standardised as a 4/16/4 air-filled unit for windows, or a 6/12/6 mm unit for curtain walling (both conventional double glazing and low-e glazing have been studied).

The glazing unit thicknesses have also been based on a study of types currently used. The 4/16/4 mm unit used for the window simulations offers the best centre-glazing U-value combined with the least use of material in the frame itself. However, for two of the steel window frames a thinner 4/8/4 mm glazing unit has been used, consistent with the smaller dimensions of the standard frames currently used for steel windows. The 6/12/6 mm unit used for the curtain walling simulations is typical of these systems.

For the majority of the simulations a standard glazing unit edge detail has been assumed. The glazing rebate depth has been set as 12.5 mm for the window simulations, and 15 mm for the curtain wall simulations. Again these values were determined from a survey of typical values. The glazing spacer has always been arranged to be flush with the edge of the frame, disregarding the overlap of the gaskets or glazing compounds. The dimensions of the standard glazing unit edge details are shown in Figure 1.2.

1.5.4 Glazing size

When assessing the heat transfer through any glazing frame the interaction of the frame with the glazing should be fully determined. The temperature variation in the frame and glazing when considered separately are different to those which are found when the frame and glazing are joined together, and this interaction is termed an 'edge effect'. Simulations can be used to show that the edge effect may be observed up to 150 mm from the edge of a frame. To be certain of including the full edge effect in the simulations a projected width of glazing has been included up to 200 mm from the solid edge of each frame. The 'cut' edge of the glazing, and any edge of the frame that would normally be in contact with a wall are assumed to be perfectly insulated - heat transfer does not occur - such that heat flow is one-dimensional at these boundaries. To confirm that sufficient glazing has been included to fully capture the edge effect point temperatures are determined at the 'cut' edges of the glazing unit and compared to values calculated for the particular centre-pane U-value. In every case the simulated temperatures were found to be within 0.1°C of the expected values.

1.5.5 Window sills

Window sills generally fall into two categories - sills which are produced by the window frame manufacturer and have the same basic features, and sills which comprise nothing more than a piece of pressed steel added to the frame by the architect or engineer.

The first type of sill sits underneath the window frame, and reduces the amount of glazing that can be used in the window. For this study these sills have a standard projected width of 30 mm, and protrude 100 mm from the front surface of the frame. However, the window may be mounted recessed into the wall opening, in which case the underside of the sill is covered and protected from heat transfer, or it may be mounted close to the outer leaf of the wall, with the underside of the sill fully exposed to heat transfer with the cold-side environment. Both of these cases are considered in this study.

The second type of sill simply laps under the frame, and reduces the glazing size only by the thickness of the metal sheet from which the sill is manufactured. In this study these sills are taken as 2 mm thick, but they still protrude 100 mm from the front face of the window frame and have a drop of 30 mm from the base of the frame. It is assumed that these sills will only be used when the intention is to avoid reducing the glazing area, and this implies that the window is mounted flush with the outer surface of the wall, thereby fully exposing the underside of the sill.

The general arrangement of the various sill types is highlighted in Figure 1.3.

1.6 Results format

The result of each simulation is a prediction of the overall heat transfer through the frame (or half-frame in the case of the symmetrical curtain walling frames) and 200 mm projected width of glazing, together with a set of temperatures for various points on the frame. For each glazing frame the results are presented in a two page format, as illustrated in Figure 1.4.

The left-hand page of each set of results describes the basic frame, indicates any key features and discusses the results for the particular frame, highlighting any important issues. Note that Chapter 8 of this report discusses general principles of heat transfer and proposes a simple schematic for understanding heat transfer through glazing frames, and it may be appropriate to read Chapter 8 before examining the results in any detail.

Below the description is a statement of the simulated performance of the frame, listing the following parameters:

Q_{total} — the total simulated heat transfer through the frame and glazing as shown

U_{glass} — the centre-pane U-value of the glazing
P_{glass} — the projected width of the glazing (200 mm)
ΔT_{glass} — the overall temperature difference (20°C)

Q_{glass} — the expected heat transfer through the glazing, ignoring edge effects

$$Q_{glass} = U_{glass} P_{glass} \Delta T_{glass}$$

Q_{frame} — the heat transfer associated with the frame

$$Q_{frame} = Q_{total} - Q_{glass}$$

P_{frame} — the projected width of the frame (55, 57 or 85 mm)
ΔT_{frame} — the overall temperature difference (20°C)

U_{frame} — the U-value of the frame

$$U_{frame} = \frac{Q_{frame}}{P_{frame} \Delta T_{frame}}$$

For the window frames there is also a calculation of the window overall performance. The overall U-value of a window is obtained by determining the overall heat loss through the component parts of the window, and dividing by the overall area and overall temperature difference

$$U_{window} = \frac{U_{glass} A_{glass} \Delta T + \sum U_{frame} A_{frame} \Delta T}{A_{total} \Delta T}$$

Note that the overall temperature difference ΔT appears in each term on the right-hand side of this expression and can be eliminated.

The overall area of the window must also be equal to the sum of the projected areas of each of the frames and the glazing

$$A_{window} = A_{glass} + \sum A_{frames}$$

Interactions between the frame and glazing are allowed for in the frame U-values. The area of each frame is determined on the basis of the mean length of each frame in the window.

Figure 1.5 shows a projection of a typical window. For all of the windows in this study frames 1, 2 and 3 are identical (type A), and frame 4 differs in projected width and U-value only if a sill is included in the simulation (type B). The mean length and projected area of each frame is

$$L_1 = L_4 = W - P_A$$

$$L_2 = L_3 = H - \frac{1}{2}P_A - \frac{1}{2}P_B$$

$$A_1 = L_1 P_A$$

$$A_2 = L_2 P_A$$

$$A_3 = L_3 P_A$$

$$A_4 = L_4 P_B$$

The terms in the overall window U-value calculation are made up from

U_{glass}	the centre-pane U-value of the glazing
A_{glass}	the projected area of the glazing
$U_{sides/top}$	the U-value of the side and top frames
$A_{sides/top}$	the projected area of the side and top frames
U_{frame}	the U-value of the simulated frame
A_{frame}	the projected area of the simulated frame
A_{total}	the overall projected area of the window
U_{window}	the overall U-value of the window

For a frame with a sill the areas are

$$A_{sides/top} = A_1 + A_2 + A_3$$

$$A_{frame} = A_4$$

otherwise the terms for 'sides/top' are neglected and the frame area is the full area

$$A_{frame} = A_1 + A_2 + A_3 + A_4$$

The right-hand page of each set of results shows three figures, one of which indicates key dimensions of the frame, and the remaining two of which indicate temperature contours and point temperatures for the frame with ordinary glazing and low-e glazing respectively.

Only key dimensions are shown for the frames. Where a frame has been dimensioned in a previous example the dimensions are not repeated. Each figure is on a 1:1 scale, and dimensions can be scaled on the basis of a 200 mm projected width for the glazing.

The temperature contours (lines of uniform temperature, isotherms) are always at 4, 8, 12 and 16 °C, and are used to indicate the general path of heat transfer through each frame. Heat transfer always occurs locally in the direction perpendicular to the temperature contour, and so changes in the direction of a contour can be used to identify where heat transfer is strongest within the frame. Note that in the air-space of the low-e glazing unit the temperature contours are more closely spaced, and this is an indication of a higher thermal resistance. Widely-spaced temperature contours indicate a lower thermal resistance.

The point temperatures, in degrees centigrade, are listed along the sides of each frame, and the points to which they refer are indicated by tick marks on the frame. The tick marks and temperature values are in the same sequence - lines are only drawn between the tick mark and the numerical temperature where this avoids possible confusion. Note that the left-hand side of each frame is exposed to the warm environment, which is at a temperature of 20°C, and the right-hand side of each frame is exposed to the cold environment at 0°C.

1.6.1 Relating point temperatures to cold-side and warm-side temperatures

A feature of the analyses reported here is that if either of the environmental temperatures is changed then the temperatures of every point in the frame change in proportion to the overall change. For example, if a 10°C isotherm is drawn for an analysis based on the overall temperatures of 20°C and 0°C then this would become the 15°C isotherm if the analysis were repeated with overall temperatures of 25°C and 5°C. This result is a consequence of the fact that the various thermal resistances used for the analysis are independent of temperature. The temperature at any point, T_{point}, is related to the overall temperatures T_{warm} and T_{cold} by the term

$$\frac{T_{point} - T_{cold}}{T_{warm} - T_{cold}}$$

which is a function only of the thermal resistance of the frame, and therefore constant if the thermal resistance is independent of temperature. This simple relationship may be used to recalculate the point temperatures for different warm-side and cold-side temperatures.

1.7 The future

It is anticipated that this study will be extended in the future to cover items such as different window frame types, advanced 'super window' frames, insulated panels and other, more complex, structures. Suggestions for components to be studied in future reports are welcomed.

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Figure 1.1 Typical window frames included in the simulation study

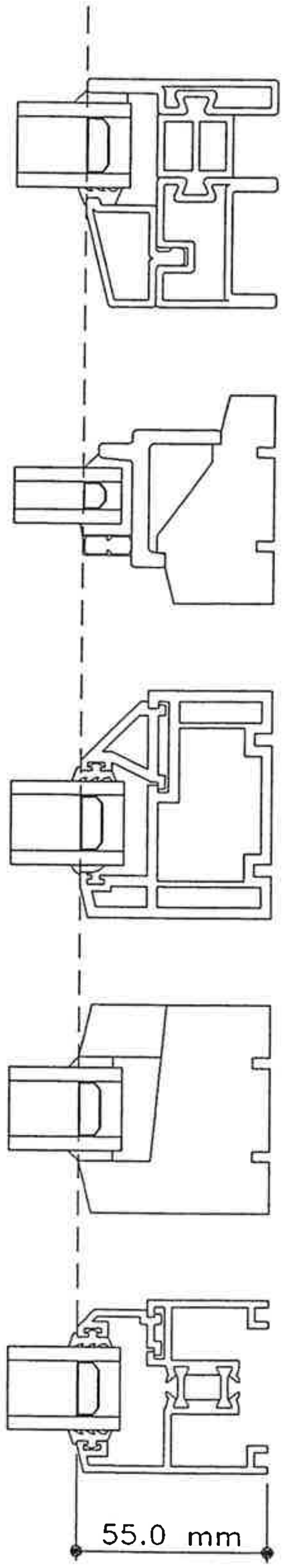
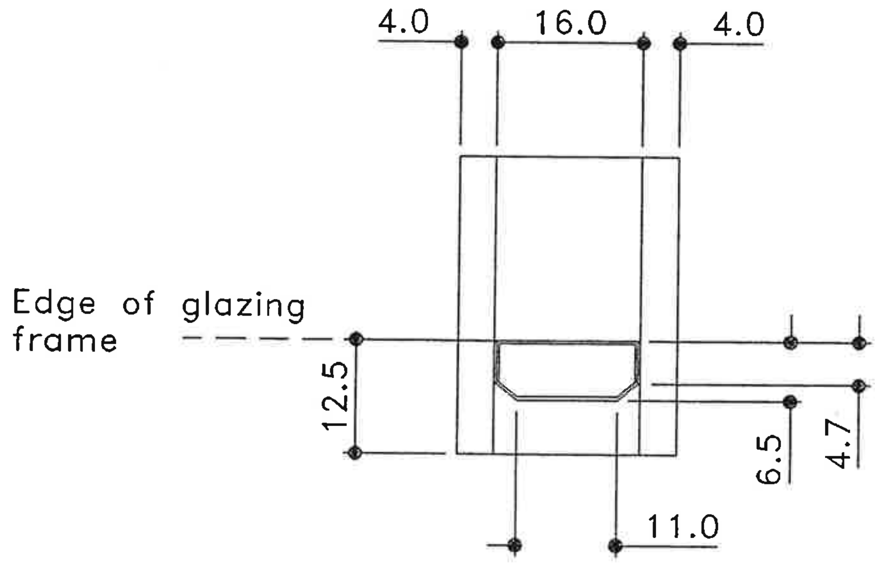
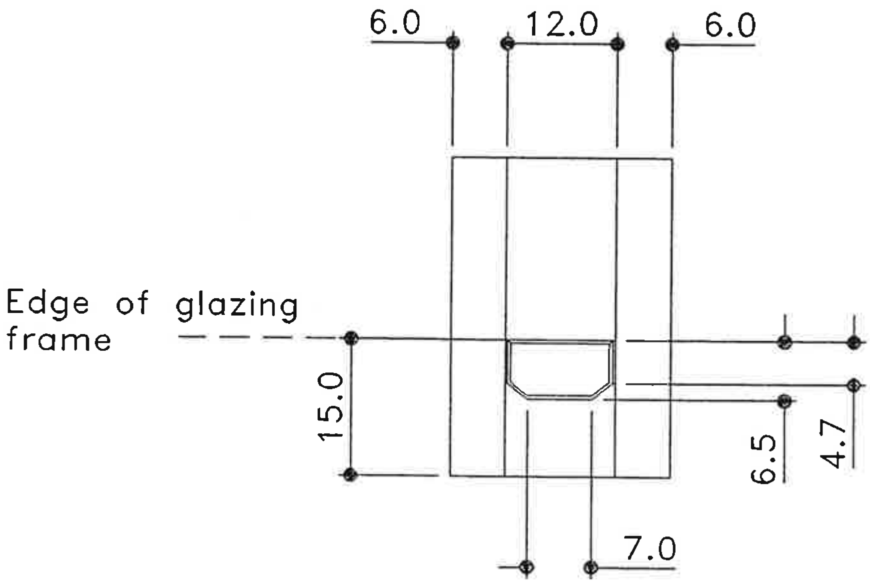


Figure 1.2 **Dimensions of the glazing unit edge details**





Butyl tapes 0.25 mm thick
Aluminum spacer wall thickness 0.33 mm

Figure 1.3 **Dimensions and exposure of various sill types**

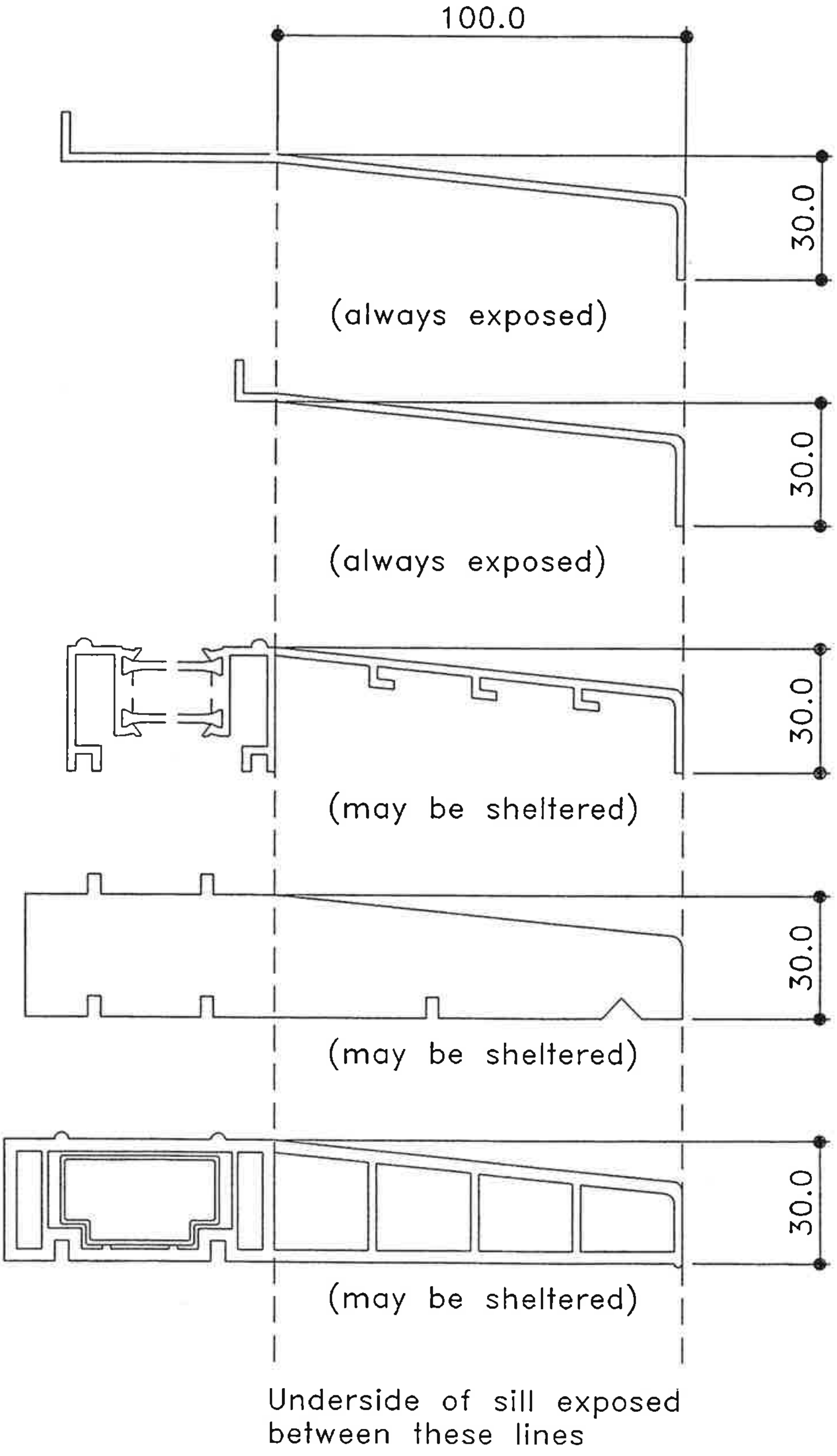


Figure 1.4 General format of results presentation

2.1 Basic aluminium frame without a thermal break

This type of frame has a high U-value. The warm-side surface temperature is very low and this may lead to condensation problems.

This first example shows that the U-value of the frame is higher when low-emissivity glazing is used. As the resistance to heat transfer through the glazing air-space increases so does the temperature of the warm-side pane of glass. This results in a greater temperature difference from the centre of the glass to the edge of the glass (which is controlled by the performance of the frame) and so there is greater heat transfer along the glass and through the glazing edge spacer. The higher frame U-value arises because the glazing has been assumed to have a uniform U-value, and the extra heat transfer at the edge of the glazing unit has been associated with the frame. The overall window U-value clearly shows the improvements brought about by the use of low-emissivity glazing, although a reduction of 37% in the centre-glazing U-value has only resulted in a reduction of 20% in the overall window U-value.

Importantly, on the warm-side of the glazing edge the glass temperature is higher than the frame temperature - the direction of heat transfer is therefore down the warm-side glass, back through the warm-side glazing gasket and out through the frame. The frame cold-side surface is colder than the glass cold-side surface, and so some heat is then transferred into the cold-side glass through the cold-side glazing gasket! This frame is an excellent example of a cold-bridge, and a good demonstration that heat does not have to flow in a straight line from warm to cold!

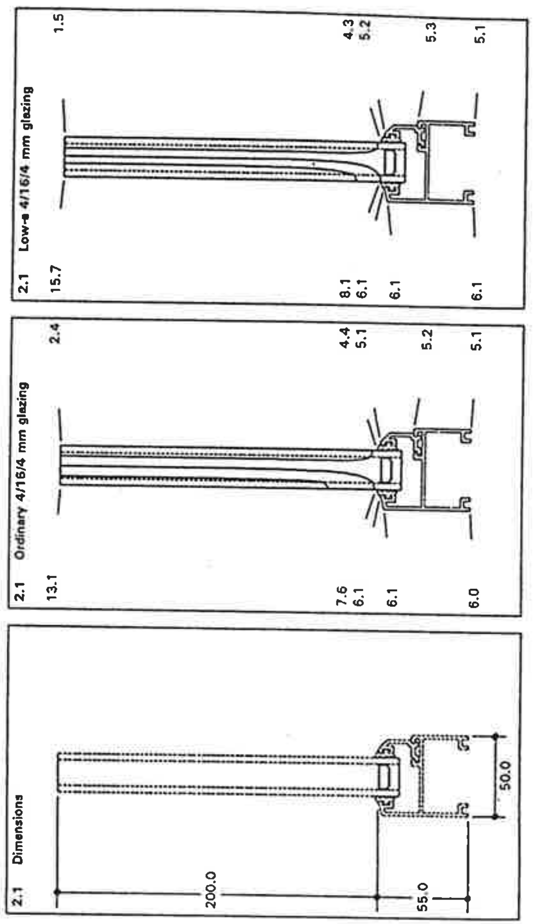
Performance

	Ordinary	Low-e	
Q_{total}	19.06	15.42	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	8.06	8.50	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.33	7.73	W/m²K

Typical window, 900 mm wide × 1250 mm high

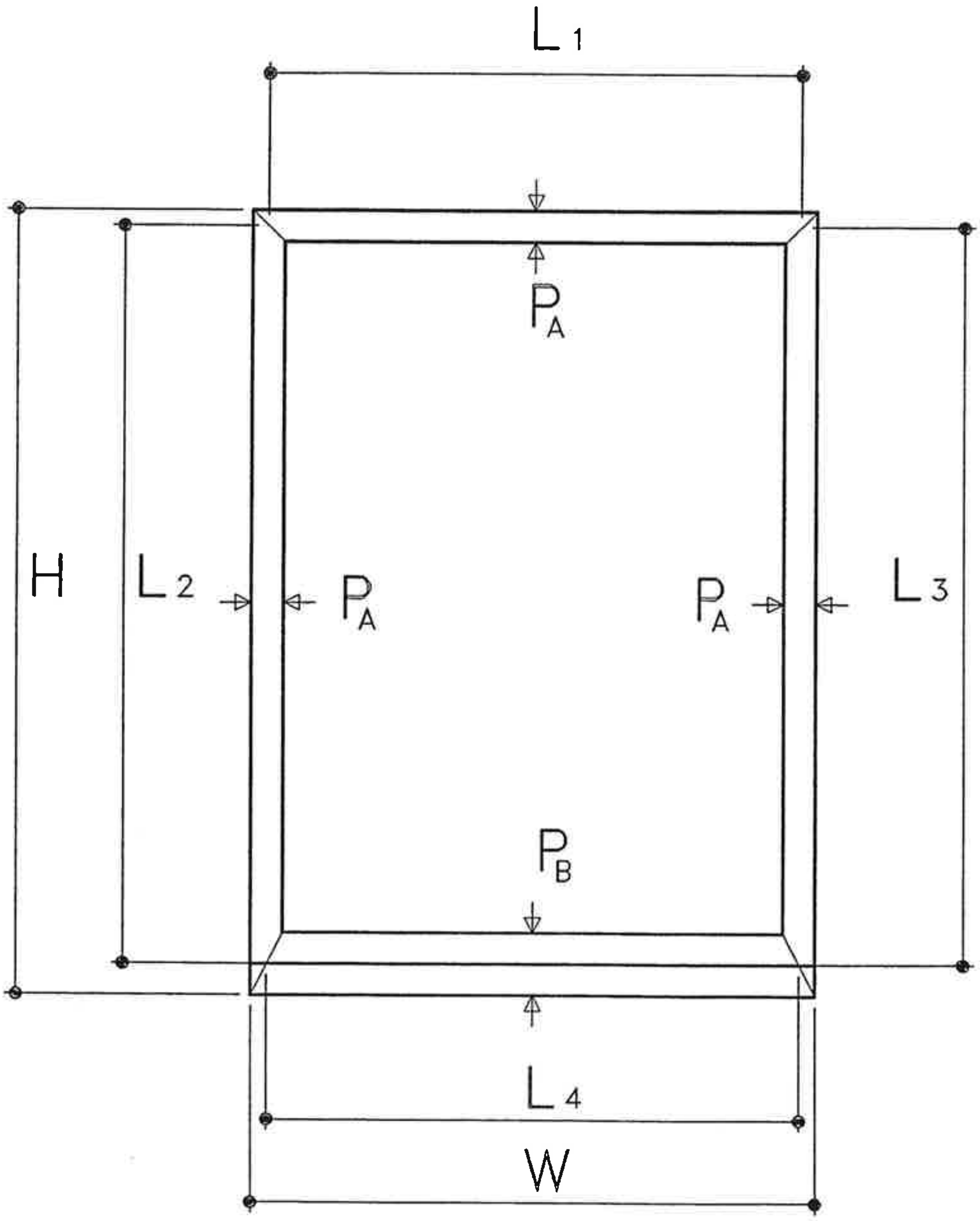
U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	7.33	7.73	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.66	2.93	W/m²K

2-2



2-3

Figure 1.5 **Projected view of a window, showing frame dimensions**



2 Aluminium windows

Aluminium has many advantages as a window frame material. It is durable, may be extruded to form complex sections, accepts a wide range of surface treatments and coatings, and is lightweight. However, aluminium is also an excellent conductor of heat, and window frames formed from aluminium must be carefully designed if excessive heat loss is to be avoided.

A window frame which is formed as a single aluminium profile, with a direct path through the aluminium from the warm-side surface to the cold-side surface, will have a high U-value and a low warm-side surface temperature. Although all aluminium frames were once of this type many have now been developed to give a lower U-value by the introduction of a piece of material with a significantly lower thermal conductivity between the warm-side and cold-side parts of the profile. This 'thermal break' serves to isolate the warm-side and cold-side surfaces of the frame and reduces the U-value significantly, with a corresponding increase in the warm-side surface temperature.

There are two types of thermal break that are currently used in aluminium windows. In the first type the frame is produced as a single extrusion, with a rectangular channel into which a thermosetting resin is poured. When the resin has hardened the aluminium bridge that formed the base of the channel is cut away. The shape of the channel may be defined by a standard, such as the American AAMA TIR-A8-90, although the width of the de-bridging cut may be left to the discretion of the designer. The surface finish of the frame may be applied before or after the resin is added, but care must be taken that the resin is compatible with the surface coating.

The second type of thermal break uses extruded polyamide strips, inserted as a pair of parallel strips for structural rigidity. The frame is produced as two separate aluminium extrusions, with grooves into which the polyamide strips are located; the frames are then crimped to secure the strips. Polyamide extrusions are available on a commercial basis, and the same design of thermal break may be used by a number of window frame manufacturers. However, some manufacturers may choose to design their own thermal break, and this is particularly the case in mainland Europe. An advantage of extruded polyamide thermal breaks is that the two aluminium parts of the frame may readily have different surface treatments or coatings.

This chapter examines different thermal break types, and also looks at the effect of adding a sill to the window - particularly important if the frame is thermally broken but the sill is not! The remainder of the frame is conventional in design, with a glazing bead and EPDM glazing gaskets. The glazing unit has a typical edge detail, with an aluminium spacer, a butyl primary seal and a silicone secondary seal.

2.1 Basic aluminium frame without a thermal break

This type of frame has a high U-value. The warm-side surface temperature is very low and this may lead to condensation problems.

This first example shows that the U-value of the frame is higher when low-emissivity glazing is used. As the resistance to heat transfer through the glazing air-space increases so does the temperature of the warm-side pane of glass. This results in a greater temperature difference from the centre of the glass to the edge of the glass (which is controlled by the performance of the frame) and so there is greater heat transfer along the glass and through the glazing edge spacer. The higher frame U-value arises because the glazing has been assumed to have a uniform U-value, and the extra heat transfer at the edge of the glazing unit has been associated with the frame. The overall window U-value clearly shows the improvements brought about by the use of low-emissivity glazing, although a reduction of 37% in the centre-glazing U-value has only resulted in a reduction of 20% in the overall window U-value.

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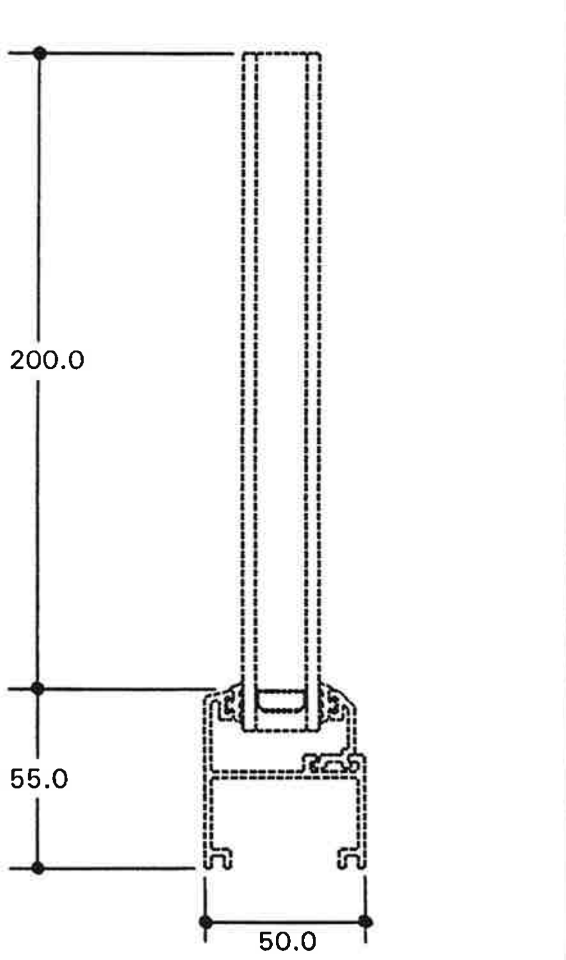
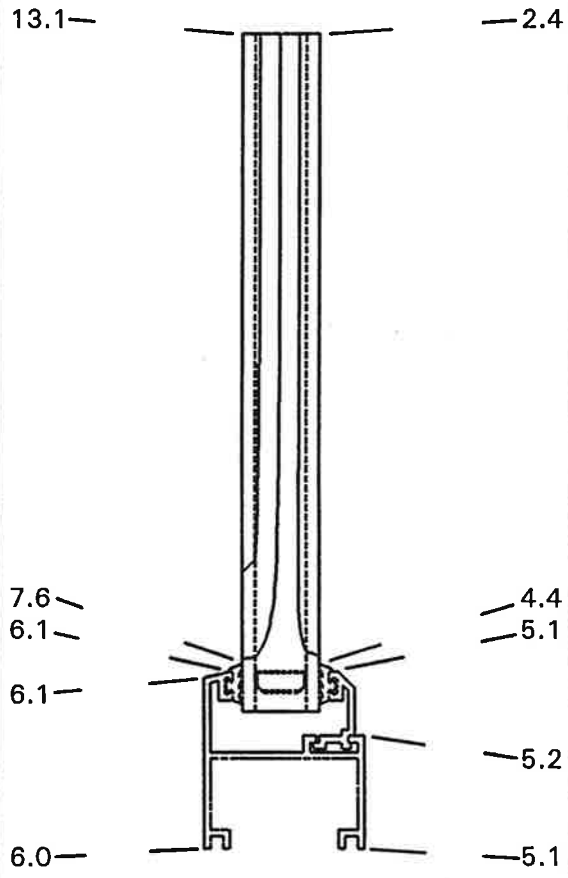
U_{window}	3.66	2.93	W/m²K

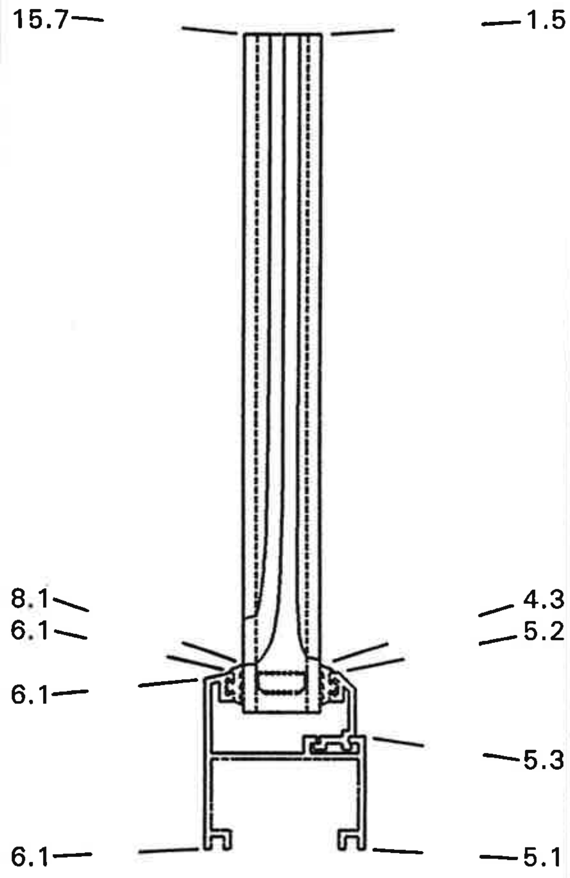
2.1 Dimensions



2.1 Ordinary 4/16/4 mm glazing



2.1 Low-e 4/16/4 mm glazing



2.2 Aluminium frame with resin pour-and-de-bridge thermal break, fully de-bridged

The thermal break cavity in this example is designed to AAMA TIR-A8-90 class BB. The de-bridging cut is a maximum 6.35 mm wide.

The inclusion of this thermal break significantly improves the U-value of the frame compared to the basic frame of example 2.1. The warm-side surface temperature is also significantly increased, thereby reducing the condensation risk.

It is important to note that the aluminium surface temperatures show no variation across the width of each surface - the aluminium effectively averages out the thermal performance of the thermal break and glazing edge. The heat flow through a thermally-broken aluminium frame closely approaches a one-dimensional case, and this allows calculation methods such as that reported in the AWAs "Assessment of thermally improved aluminium extrusions for use in windows and doors" to be developed and used, with some confidence in the result.

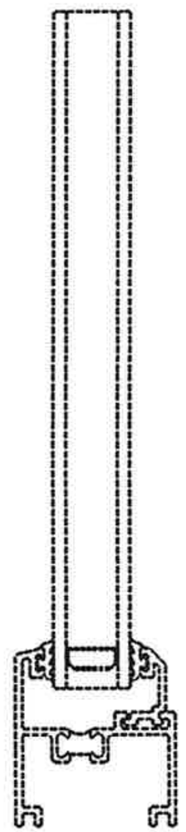
Performance

	Ordinary	Low-e	
Q_{total}	15.98	12.26	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.98	5.34	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.53	4.85	W/m^2K

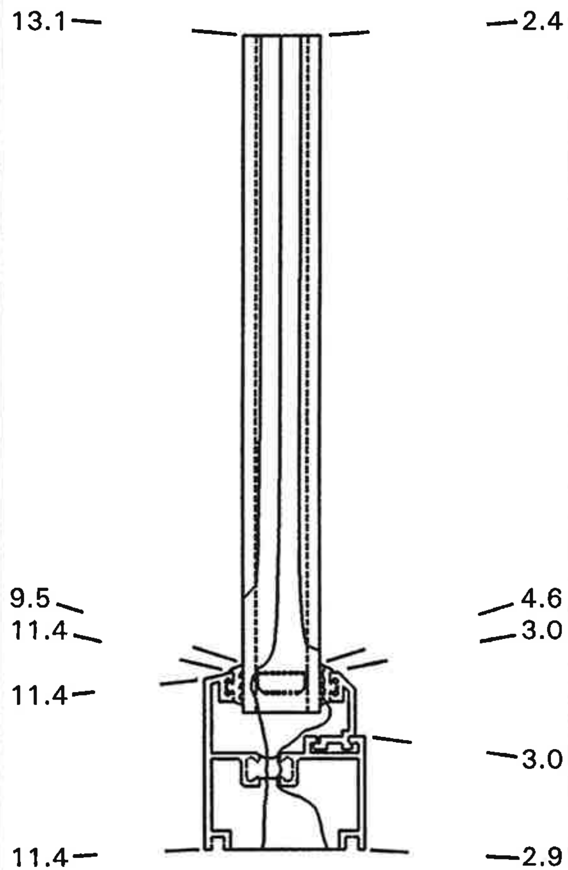
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	4.53	4.85	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.11	2.35	W/m^2K

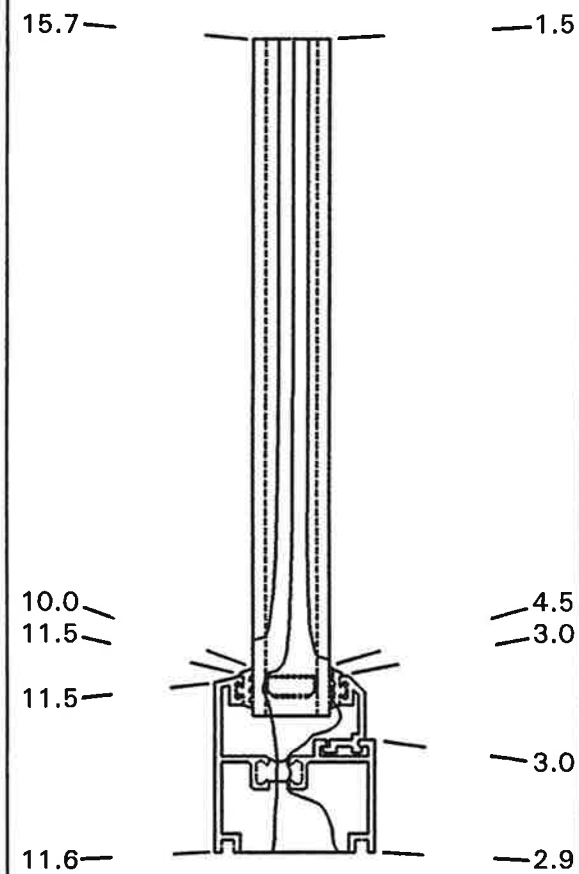
2.2 Dimensions



2.2 Ordinary 4/16/4 mm glazing



2.2 Low-e 4/16/4 mm glazing



2.3 Aluminium frame with resin pour-and-de-bridge thermal break, partly de-bridged

In this frame the thermal break cavity is again designed to AAMA TIR-A8-90 class BB. However, the de-bridging cut is only 4.0 mm wide.

The narrower cut increases the frame U-value very slightly, as the mean length of the thermal break is reduced. However, the change in performance is negligible, because the thermal break is not the only path for heat transfer through the frame.

Halving the thermal resistance of one heat transfer path will not halve the total heat transfer through the frame. In many glazing frames, as will be demonstrated further in later chapters, the least resistive path for heat transfer is through the aluminium spacer at the edge of the glazing unit.

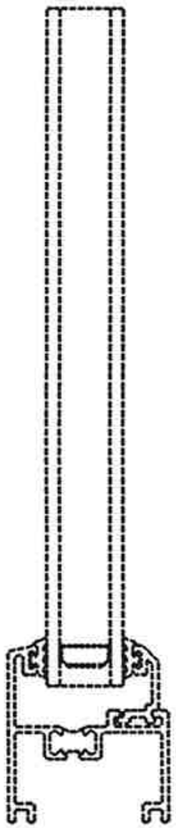
Performance

	Ordinary	Low-e	
Q_{total}	16.02	12.31	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.02	5.39	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.56	4.90	W/m^2K

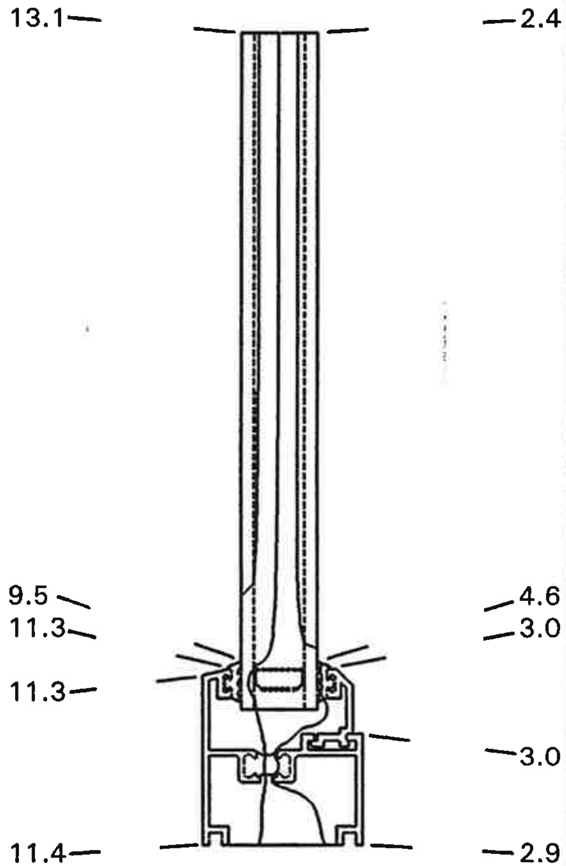
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	4.56	4.90	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.11	2.36	W/m^2K

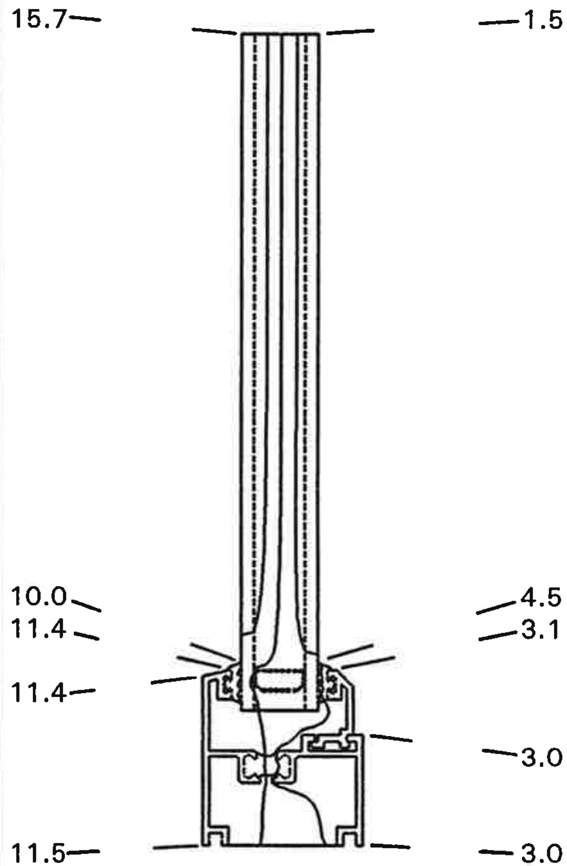
2.3 Dimensions



2.3 Ordinary 4/16/4 mm glazing



2.3 Low-e 4/16/4 mm glazing



2.4 Aluminium frame with short extruded polyamide thermal break

This frame uses a very short polyamide extrusion, typical of those encountered in some aluminium windows. The thermal conductivity of the polyamide is double that of the thermosetting resin used for the previous examples, and so the U-value is higher than for the pour-and-de-bridge thermal breaks of examples 2.2 and 2.3.

The thermal resistance of an object is equal to its length L (in the direction of heat transfer) divided by the product of its width W (perpendicular to the direction of heat transfer) and the material thermal conductivity λ, or

$$\Re = \frac{L}{W \lambda}$$

Overall, this pair of polyamide thermal breaks offers a path for heat transfer that is slightly longer and narrower than the resin thermal break of the previous examples, but this is offset by the much higher thermal conductivity of the material.

Note also that with low-emissivity glazing the cold-side glass edge temperature is lower than with ordinary glazing for the simple reason that the cold-side centre-glass temperature is lower - more heat is drawn out of, and through, the glazing edge spacer. Improving the centre-glazing properties results in an increased warm-side glass temperature and a reduced cold-side glass temperature, thus having a double effect on heat transfer through the glazing edge spacer.

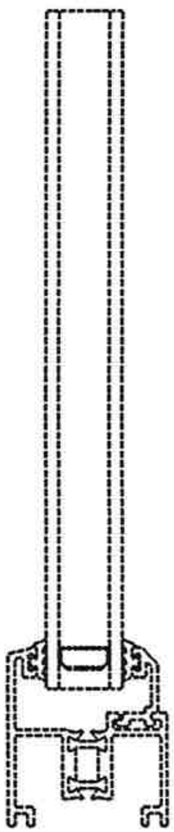
Performance

	Ordinary	Low-e	
Q_{total}	16.29	12.58	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.29	5.66	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.81	5.15	W/m^2K

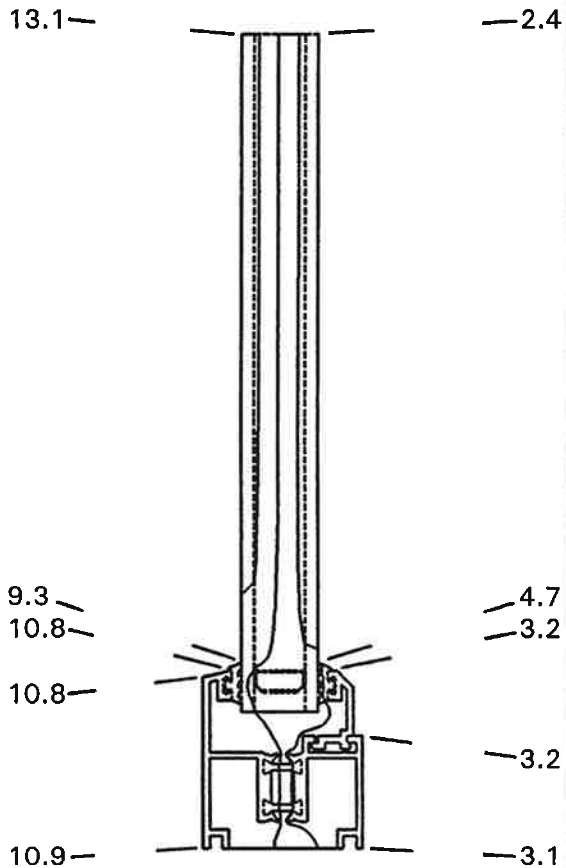
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	4.81	5.15	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.16	2.41	W/m^2K

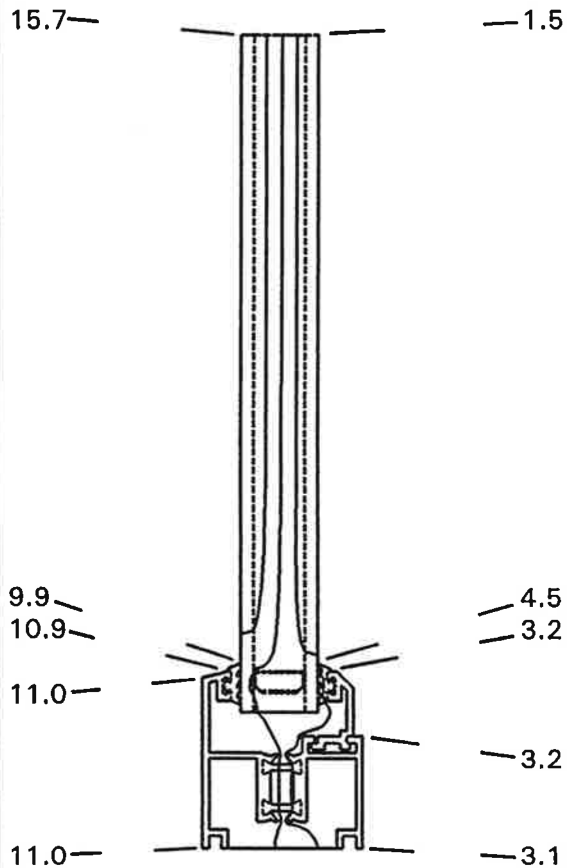
2.4 Dimensions



2.4 Ordinary 4/16/4 mm glazing



2.4 Low-e 4/16/4 mm glazing



2.5 Aluminium frame with long extruded polyamide thermal break

This frame uses much longer polyamide extrusions. The U-value of the frame is now slightly lower than obtained with the pour-and-de-bridge thermal break.

The development of extruded polyamide strip has been more advanced in mainland Europe, where the strips have taken on a range of more complex shapes, many intended to make the heat transfer path longer and narrower.

It is interesting to note that the warm-side frame surface temperature is 1°C higher than with the short polyamide strips, but that the glass warm-side edge temperature has increased by just 0.3°C. The temperature difference across the warm-side glazing gasket has therefore increased by 0.7°C from example 2.4. The edge of the glazing unit is again shown to be the weak link in the overall performance of the window.

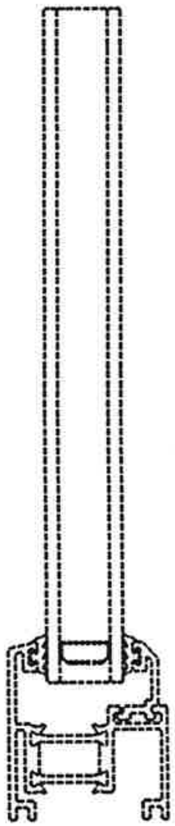
Performance

	Ordinary	Low-e	
Q_{total}	15.71	11.99	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.71	5.07	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.28	4.61	W/m²K

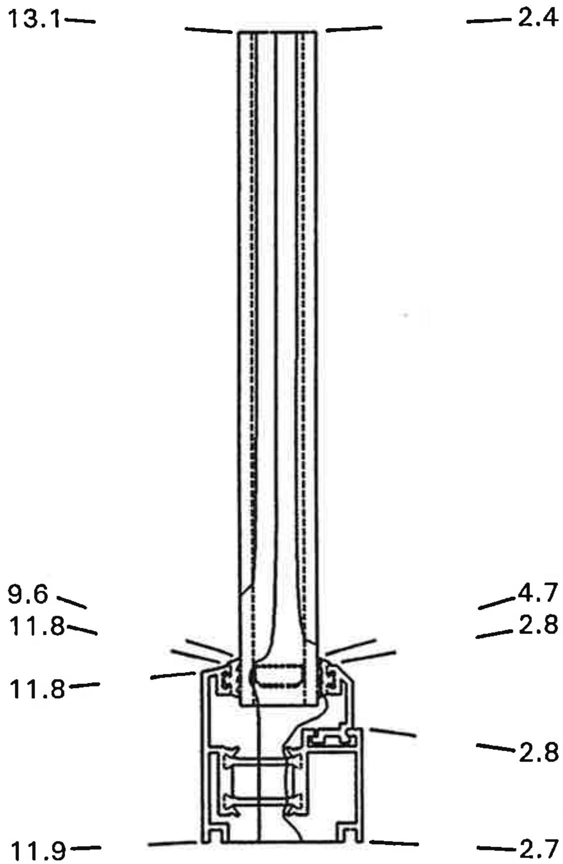
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.28	4.61	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.06	2.30	W/m²K

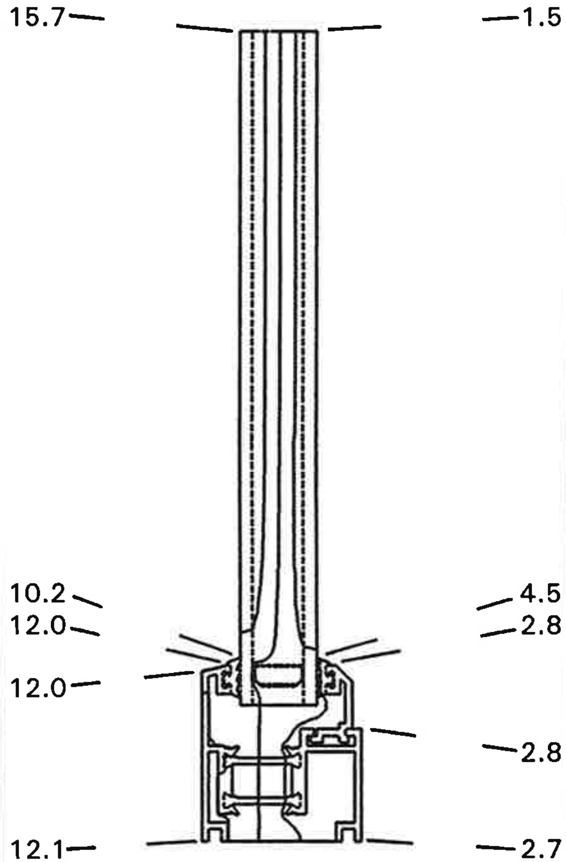
2.5 Dimensions



2.5 Ordinary 4/16/4 mm glazing



2.5 Low-e 4/16/4 mm glazing



2.6 Aluminium frame with long extruded polyamide thermal break and increased warm-side surface area

Long before the introduction of thermal breaks, the trick of increasing the warm-side surface area had been used by curtain walling designers to improve the condensation performance of frames. It is noticeable that the U-value of the frame increases, but not in proportion to the increase in warm-side surface area - as stated in example 2.3 the effect of a change in one heat transfer path is not mirrored by an identical change in the overall performance.

The mean temperature difference between the warm-side environment and the warm-side frame surface is proportional to the ratio of frame heat transfer (Q_{frame}) to warm-side surface area. In this example the increase of 8% in the frame heat transfer is outweighed by the 32% increase in the frame surface area, and as a result the warm-side environment-to-frame temperature difference is reduced. Since the environment temperature is fixed this can only mean an increase in the frame warm-side surface temperature.

Note that the increase in frame U-value is a consequence of the high thermal conductivity of aluminium - the length of the heat transfer path has been increased but for such an excellent conductor of heat this is insignificant when compared to the reduced warm-side surface resistance. However, if the surface area had been increased by increasing the projected width of the frame there might have been a reduction in the U-value, which is proportional to the ratio of frame heat transfer to frame projected width.

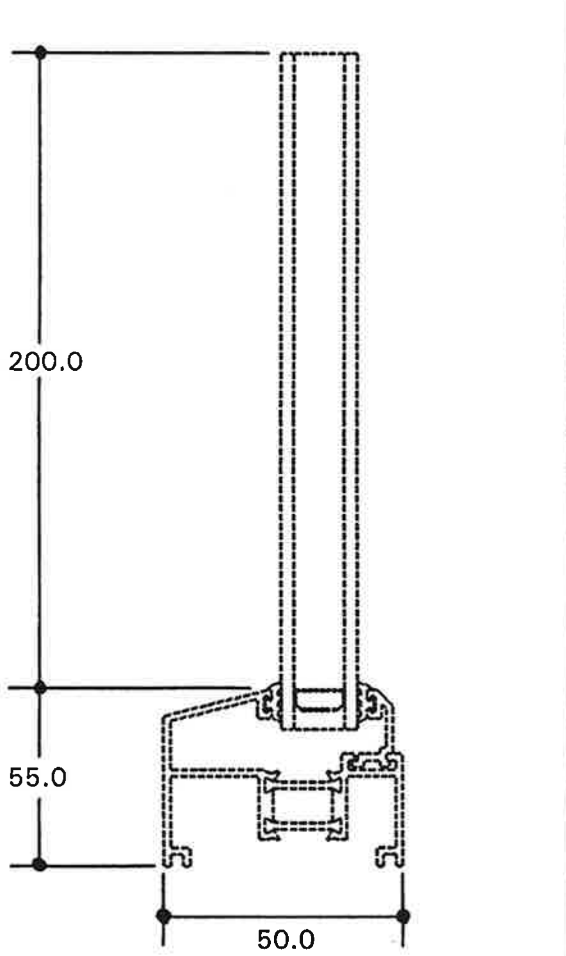
Performance

	Ordinary	Low-e	
Q_{total}	16.14	12.40	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.14	5.48	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.67	4.98	W/m²K

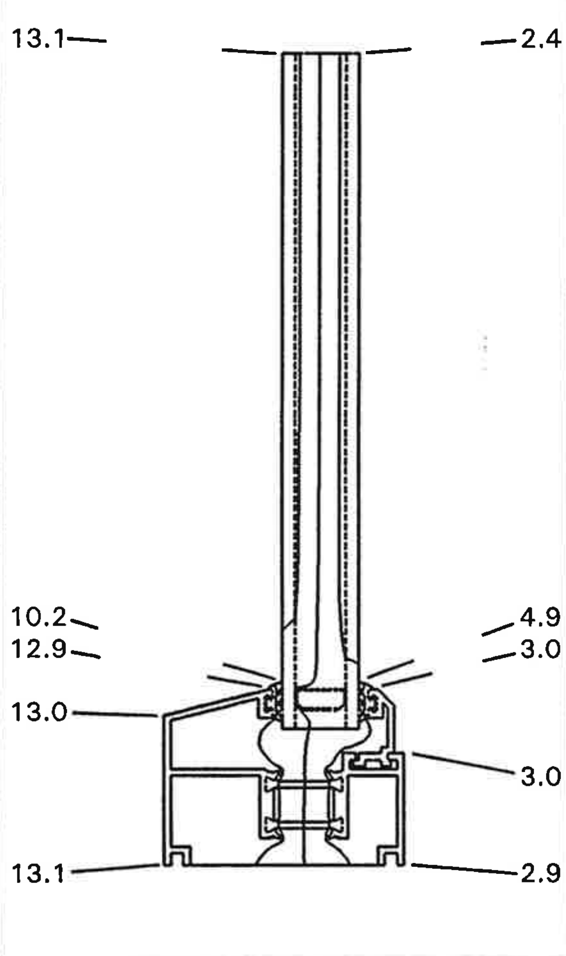
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.67	4.98	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.13	2.38	W/m²K

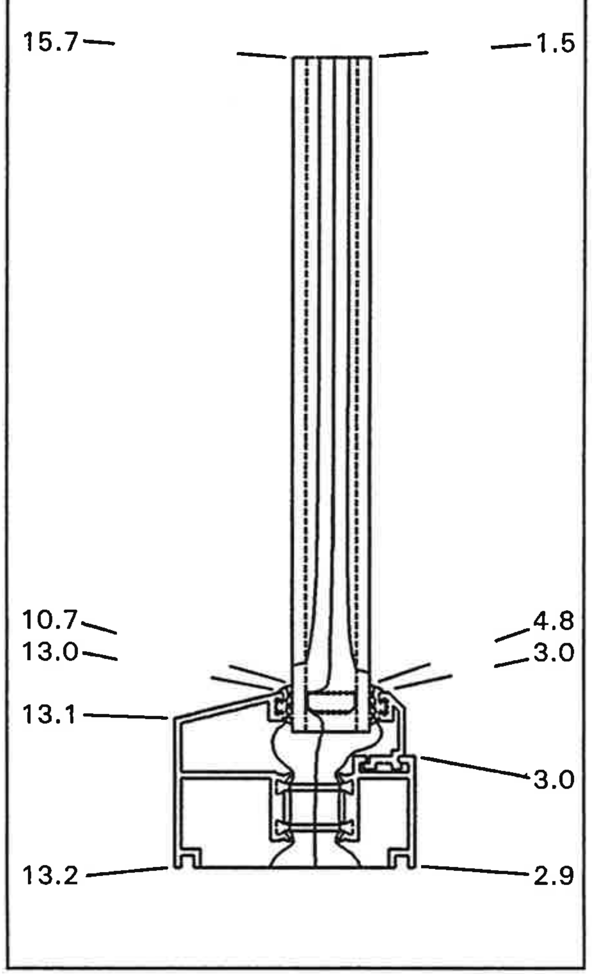
2.6 Dimensions



2.6 Ordinary 4/16/4 mm glazing



2.6 Low-e 4/16/4 mm glazing



2.7 Aluminium frame with long extruded polyamide thermal break, but reversed to appear internally beaded

This frame is reasonably symmetrical, and reversing the frame has little effect on the U-value.

With an aluminium frame it is the area of the exposed surfaces that is significant, and if the warm-side and cold-side surfaces have the same area then reversing the frame will have little effect.

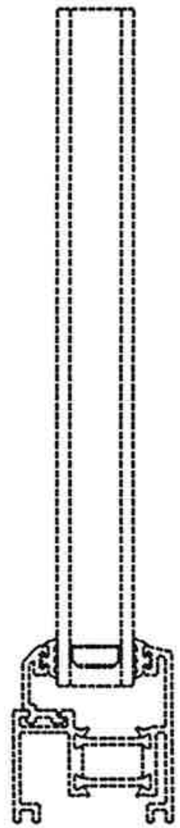
Performance

	Ordinary	Low-e	
Q_{total}	15.72	12.00	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.72	5.08	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.29	4.62	W/m²K

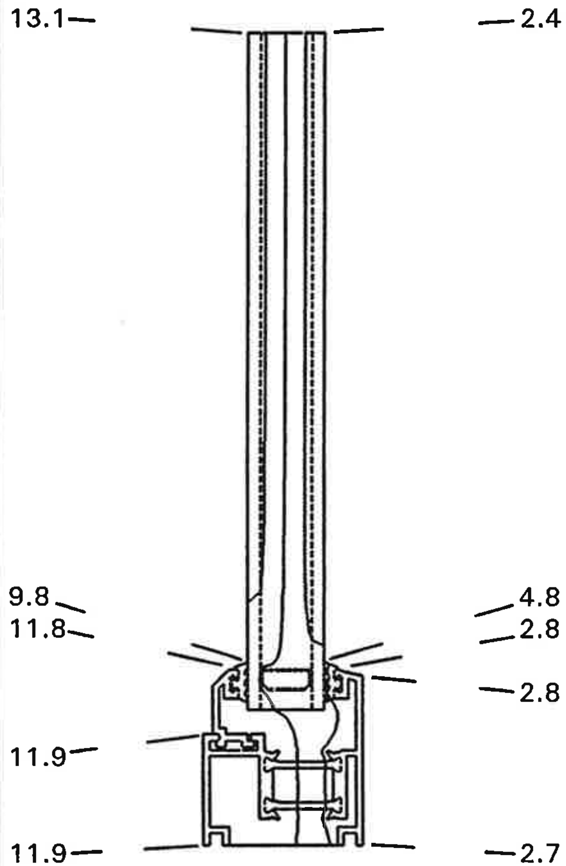
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.29	4.62	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.06	2.31	W/m²K

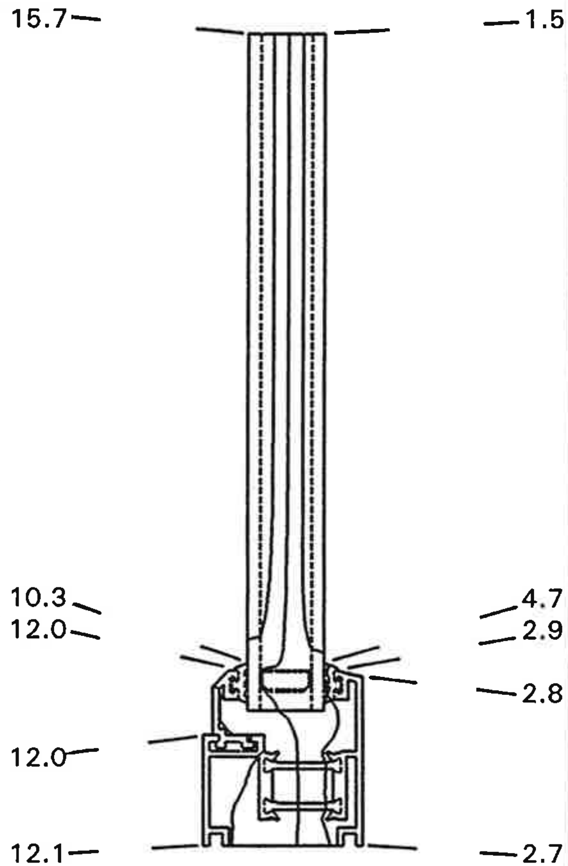
2.7 **Dimensions**



2.7 **Ordinary 4/16/4 mm glazing**



2.7 **Low-e 4/16/4 mm glazing**



2.8 Aluminium frame with long extruded polyamide thermal break and an extruded non-thermally-broken aluminium sill, underside of sill covered

The possible impact of a sill on heat loss should always be carefully considered. This sill is non-thermally-broken and so completely bypasses the thermal break in the frame. As a result the warm-side frame surface temperature is very low and prone to condensation. It is important to note that the warm-side surface temperatures are lower than for the non-thermally-broken window of example 2.1.

The calculated window U-value may be optimistically low, as the sides and top of the window are assumed to perform as predicted in example 2.5. In a real window the mechanical joint at the corners of the frame, combined with the excellent heat conduction properties of aluminium, will ensure that the effect of this sill reaches beyond the lowermost part of the frame - the sill may compromise the U-value of the whole window!

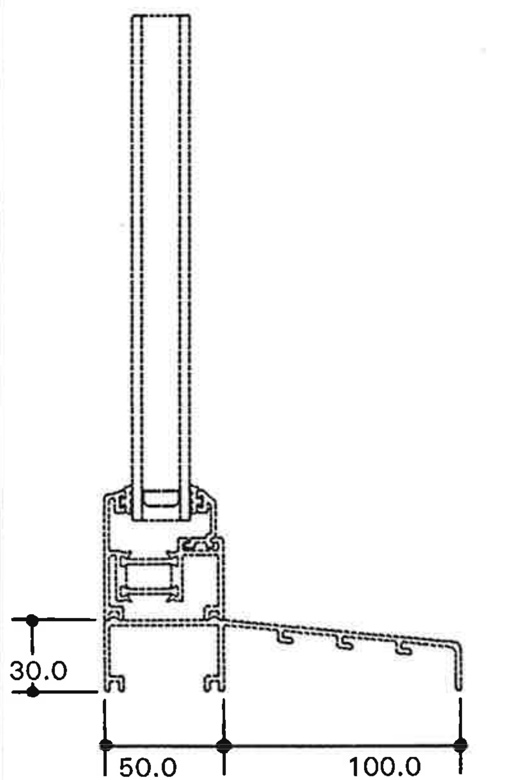
Performance

	Ordinary	Low-e	
Q_{total}	23.47	19.84	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	12.47	12.92	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.34	7.60	W/m^2K

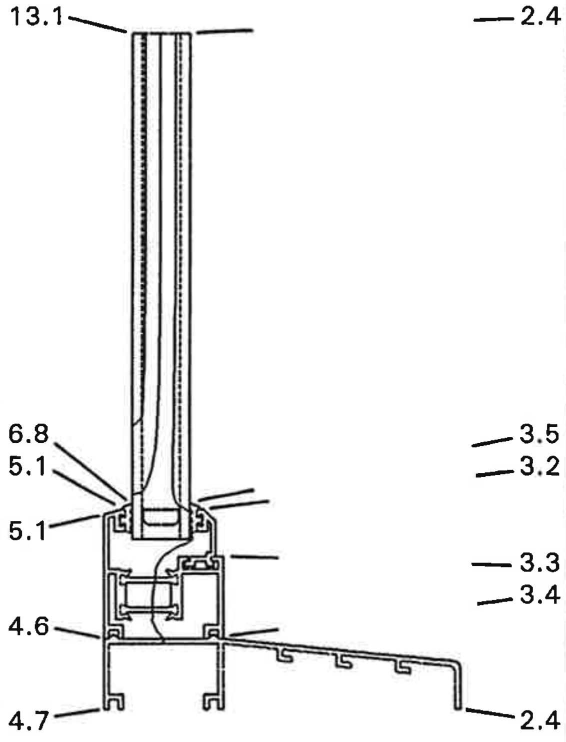
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 2.5

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.8769	0.8769	m^2
$U_{sides/top}$	4.28	4.61	W/m^2K
$A_{sides/top}$	0.1763	0.1763	m^2
U_{frame}	7.34	7.60	W/m^2K
A_{frame}	0.0718	0.0718	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.28	2.56	W/m^2K

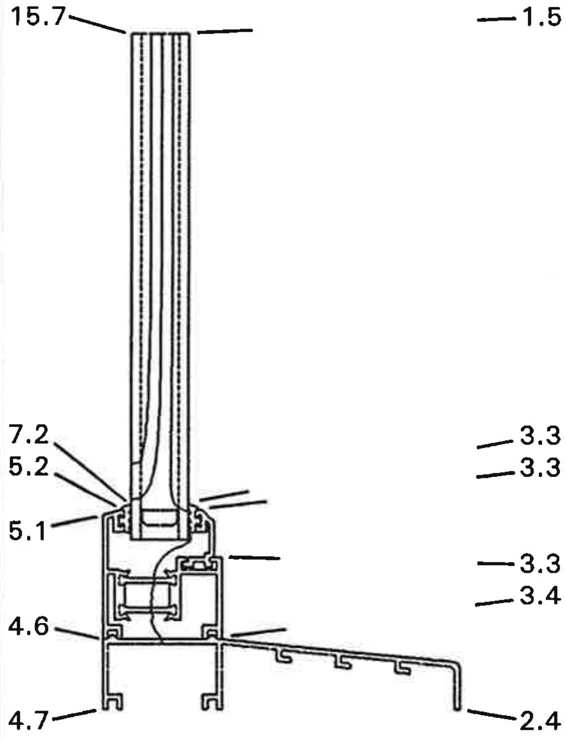
2.8 **Dimensions**



2.8 **Ordinary 4/16/4 mm glazing**



2.8 **Low-e 4/16/4 mm glazing**



2.9 Aluminium frame with long extruded polyamide thermal break and an extruded non-thermally-broken aluminium sill, underside of sill fully exposed

If the underside of this sill is fully exposed, with the window mounted close to the outside face of the wall, then the exposed cold-side surface area of the frame is almost doubled. The U-value of the frame is significantly higher than in example 2.8, and the warm-side surface temperatures are even lower.

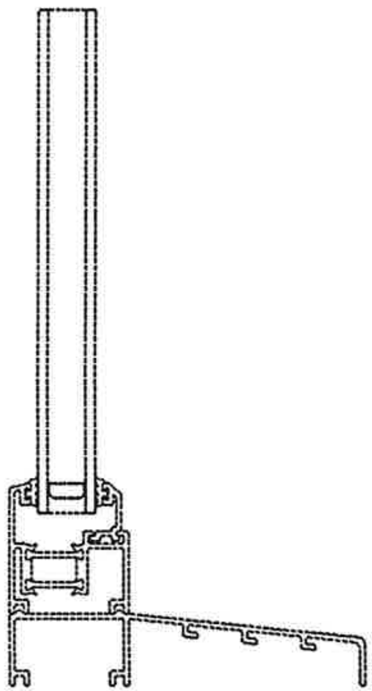
Performance

	Ordinary	Low-e	
Q_{total}	24.46	20.84	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	13.46	13.92	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.92	8.19	W/m^2K

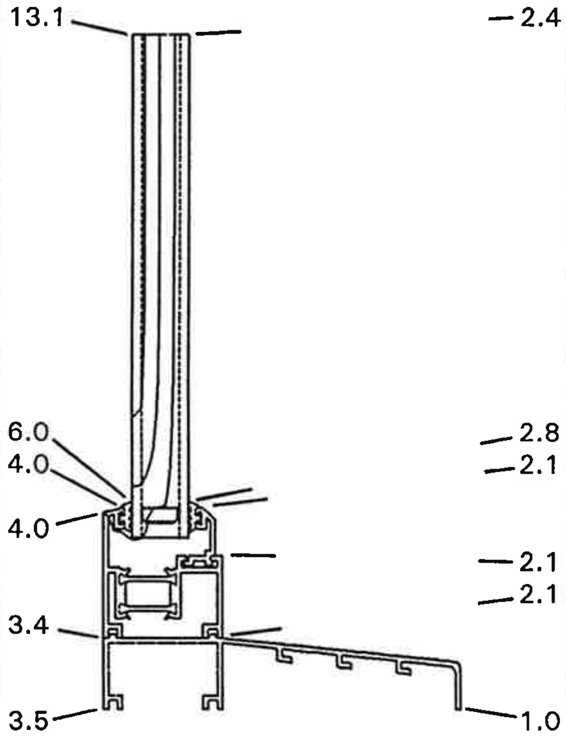
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 2.5

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.8769	0.8769	m^2
$U_{sides/top}$	4.28	4.61	W/m^2K
$A_{sides/top}$	0.1763	0.1763	m^2
U_{frame}	7.92	8.19	W/m^2K
A_{frame}	0.0718	0.0718	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.32	2.59	W/m^2K

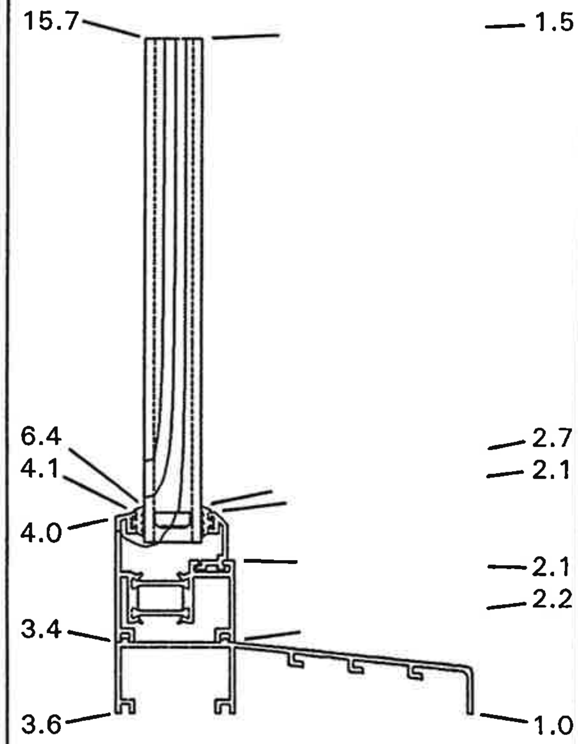
2.9 Dimensions



2.9 Ordinary 4/16/4 mm glazing



2.9 Low-e 4/16/4 mm glazing



2.10 Aluminium frame with long extruded polyamide thermal break and a non-thermally-broken pressed steel sill fixed to the warm-side profile, underside of sill fully exposed

This steel sill is also non-thermally-broken and again completely bypasses the thermal break in the frame proper. The warm-side frame surface temperature is again low and prone to condensation.

The choice of a thin pressed steel sill is usually made to avoid reducing the vision area of the window, whereas the sill considered in the previous example reduces the height of the glazed part of the window by 30 mm. Clearly however the decision to attach the sill to the warm-side frame surface has made a nonsense of the use of a thermally broken frame. Although mild steel has a thermal conductivity one-quarter that of aluminium it still conducts heat some 240 times more readily than polyamide!

It is important to note that the heat transfer per metre length of frame is about 20% lower than in the previous example, but the projected width of the frame plus sill is 35% lower, resulting in a higher frame U-value. The window U-value however clearly reflects the reduced heat transfer compared to the previous sill, but the increased condensation risk is the strongest reason for avoiding this type of sill.

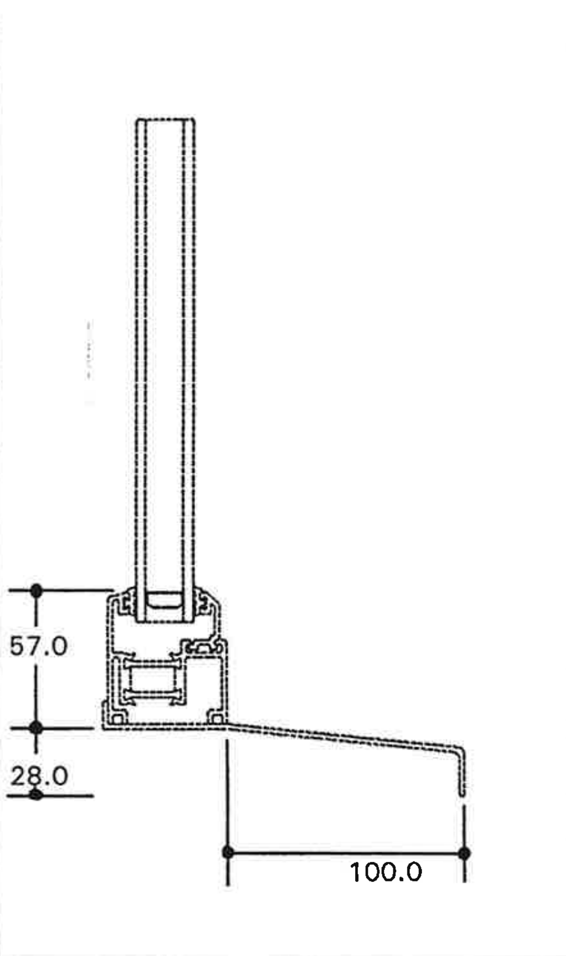
Performance

	Ordinary	Low-e	
Q_{total}	20.06	16.42	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	9.06	9.50	W
P_{frame}	0.057	0.057	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.95	8.33	W/m^2K

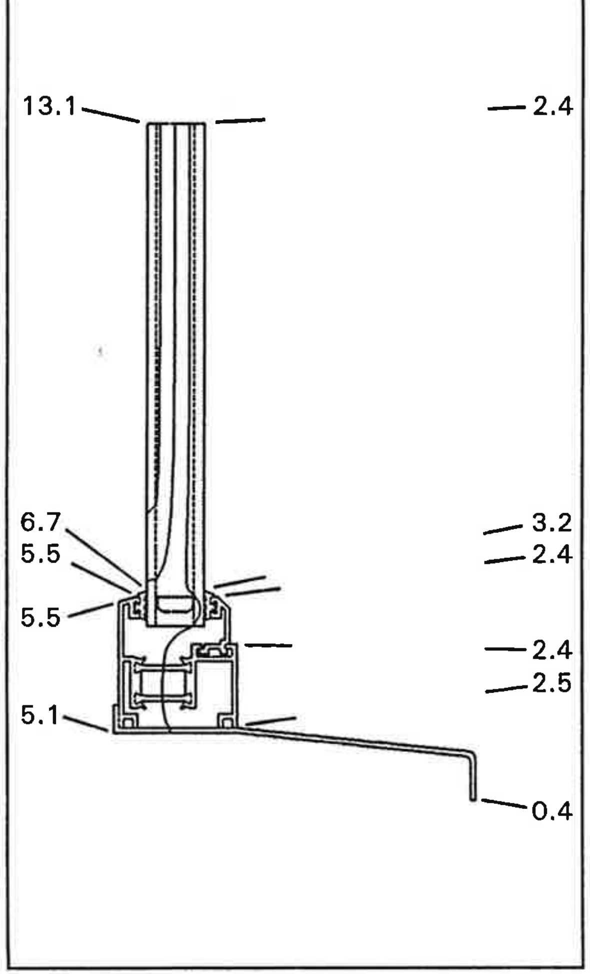
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 2.5

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.8990	0.8990	m^2
$U_{sides/top}$	4.28	4.61	W/m^2K
$A_{sides/top}$	0.1778	0.1778	m^2
U_{frame}	7.95	8.33	W/m^2K
A_{frame}	0.0482	0.0482	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.21	2.47	W/m^2K

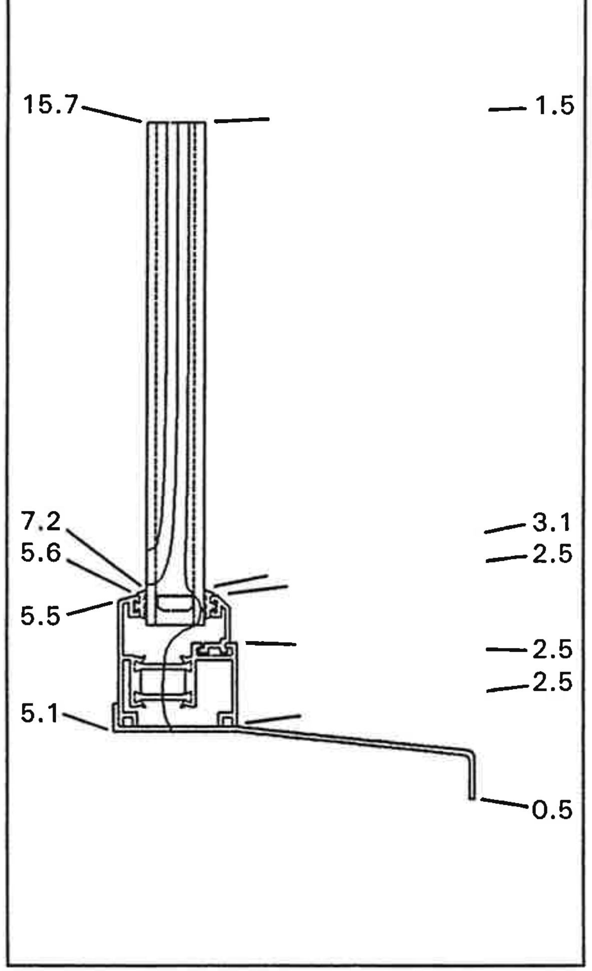
2.10 Dimensions



2.10 Ordinary 4/16/4 mm glazing



2.10 Low-e 4/16/4 mm glazing



2.11 Aluminium frame and sill with long extruded polyamide thermal breaks, underside of sill covered

This sill is thermally-broken with the same polyamide extrusions as the frame. The U-value of the modified frame is lower than without the sill (example 2.5), because the increase in frame projected area outstrips the additional heat loss. The frame warm-side surface temperature is reduced slightly, in a reverse of the phenomena shown in example 2.6 - the frame heat transfer has increased by 41%, but the warm-side surface area has increased by a similar 49%, cancelling out the effect.

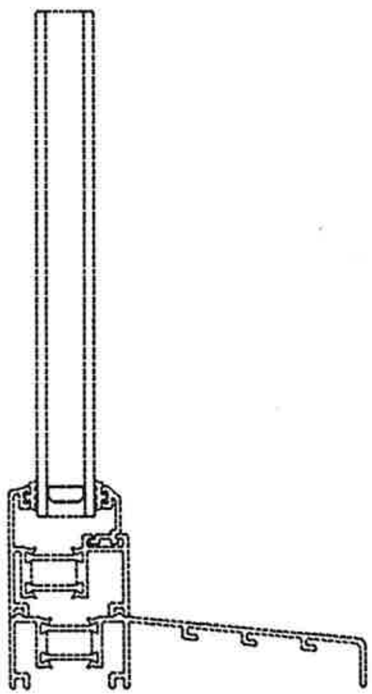
Performance

	Ordinary	Low-e	
Q_{total}	17.79	14.07	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	6.79	7.15	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.99	4.21	W/m²K

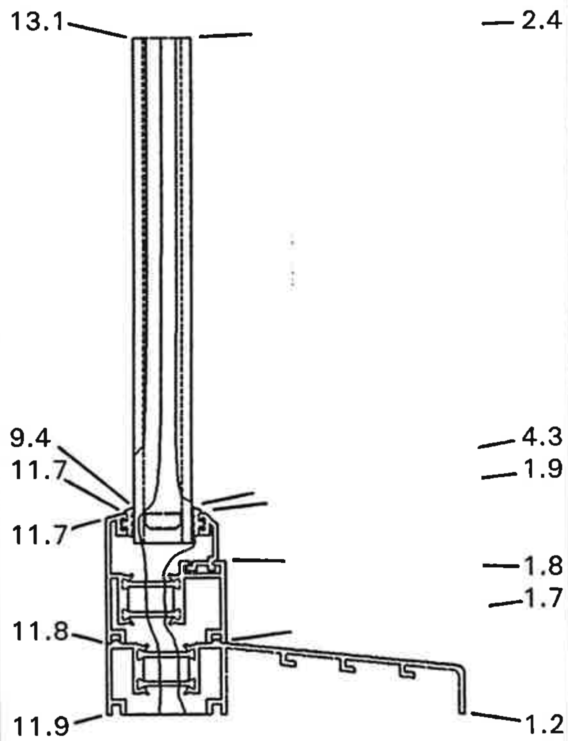
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 2.5

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	4.28	4.61	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	3.99	4.21	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.07	2.34	W/m²K

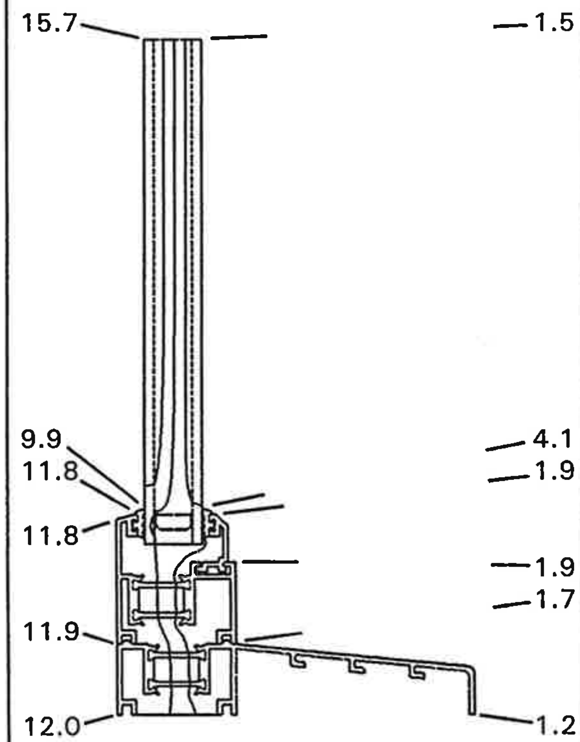
2.11 Dimensions



2.11 Ordinary 4/16/4 mm glazing



2.11 Low-e 4/16/4 mm glazing



2.12 Aluminium frame and sill with long extruded polyamide thermal breaks, underside of sill fully exposed

The effect of exposing the underside of a thermally-broken sill is less than with a non-thermally-broken sill. However, there is still a clear increase in the frame U-value and a reduction in the temperatures on the warm-side surface of the frame.

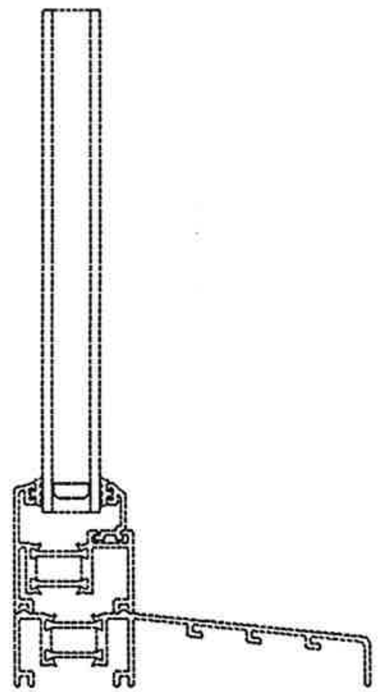
Performance

	Ordinary	Low-e	
Q_{total}	18.05	14.33	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	7.05	7.41	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.15	4.36	W/m²K

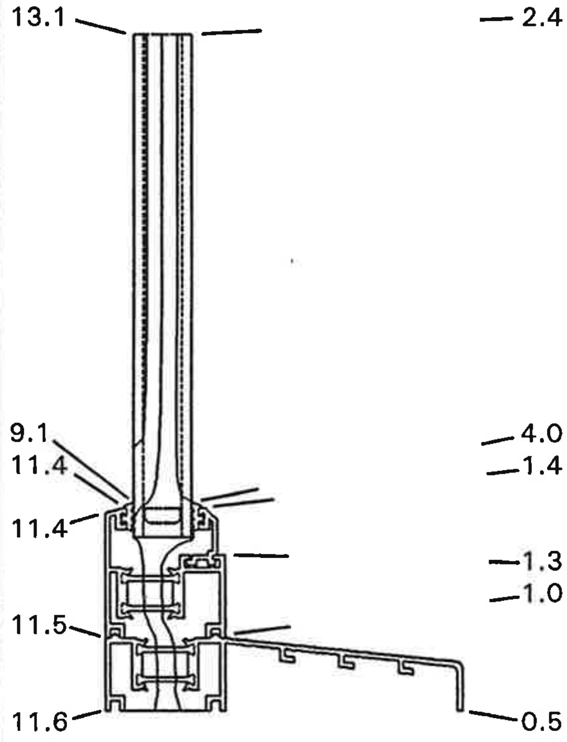
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 2.5

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	4.28	4.61	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	4.15	4.36	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.08	2.35	W/m²K

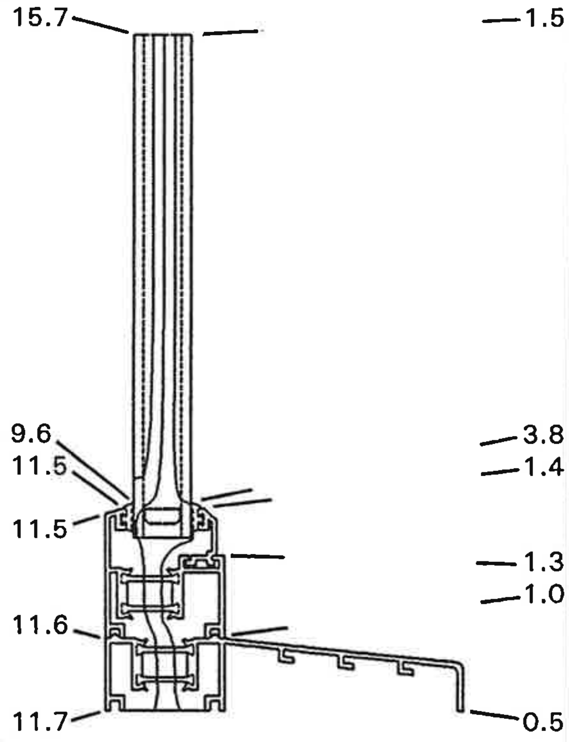
2.12 Dimensions



2.12 Ordinary 4/16/4 mm glazing



2.12 Low-e 4/16/4 mm glazing



2.13 Aluminium frame with long extruded polyamide thermal break and a non-thermally-broken pressed steel sill fixed to the cold-side profile, underside of sill fully exposed

This sill is non-thermally-broken but is just lapped under the cold-side edge of the frame. This represents an increase in the cold-side frame surface area and so the heat transfer and U-value are increased, but only slightly. A pressed steel sill can therefore be used, but it should not be continued past the plane of the thermal break.

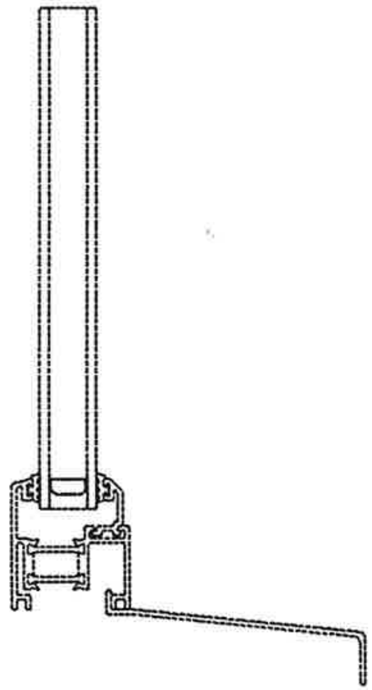
Performance

	Ordinary	Low-e	
Q_{total}	16.08	12.37	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.08	5.45	W
P_{frame}	0.057	0.057	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.46	4.78	W/m²K

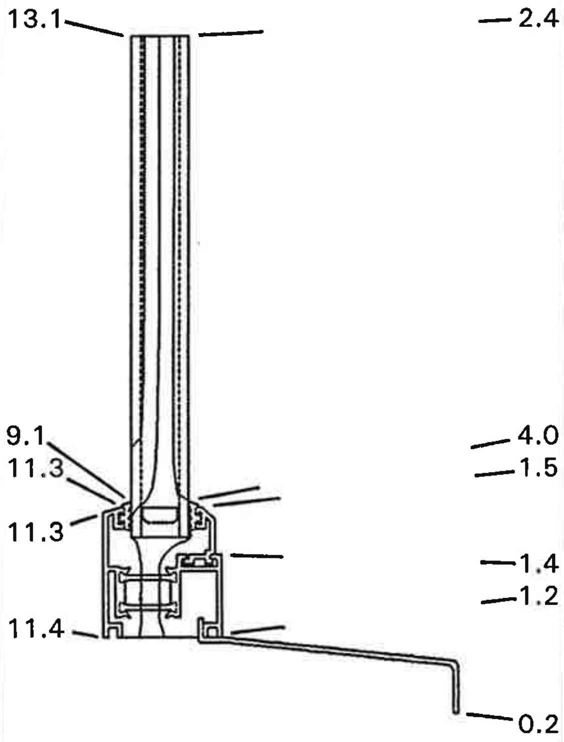
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 2.5

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8990	0.8990	m²
$U_{sides/top}$	4.28	4.61	W/m²K
$A_{sides/top}$	0.1778	0.1778	m²
U_{frame}	4.46	4.78	W/m²K
A_{frame}	0.0482	0.0482	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.07	2.32	W/m²K

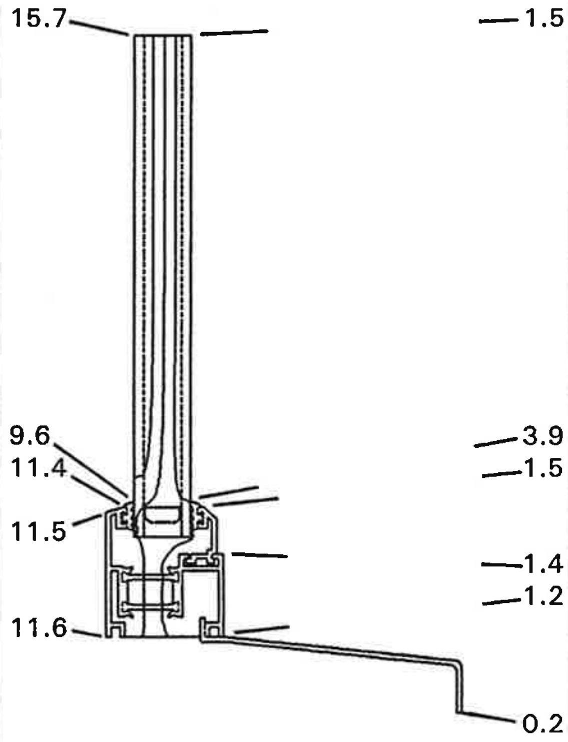
2.13 Dimensions



2.13 Ordinary 4/16/4 mm glazing



2.13 Low-e 4/16/4 mm glazing



2.14 Summary

Aluminium frames are unique in that heat is readily transferred along the aluminium to the weakest link in the frame, which is usually the glazing edge detail. Improving the thermal break alone is a costly and wasteful exercise, and yet this is a major part of mainland European development.

This chapter has emphasised several fundamental points:

i. metals are excellent conductors of heat and should be used carefully

ii. in general the heat transfer through a material will be minimised if the heat transfer paths are made longer and narrower

iii. the overall performance of the frame is not directly proportional to the thermal resistance of any one part of the frame - the overall impact of a design modification is always less than the magnitude of the modification

iv. frame U-values are not always a good way to compare frames - increasing the projected area of a frame will reduce the U-value whilst increasing the heat transfer; overall window U-values are a much better means of comparison

v. the interaction between the frame and the glazing is instrumental in defining the overall performance - heat transfer is complex and two-dimensional between the frame and glazing, and the glazing edge detail is often the weakest part of the assembly; the reduction in window U-value is not proportional to the reduction in centre-glazing U-value

vi. a low U-value does not necessarily mean a low risk of condensation - condensation risk can actually be reduced by increasing the U-value!

3 Timber and timber/aluminium composite windows

Timber is a natural insulating material. The fibrous nature of timber increases the resistance to heat transfer across the grain. However, timber differs from other framing materials in that it must be cut and machined to form a frame profile, and different glazing techniques have therefore evolved. In general rubber gaskets are not used, the preferred alternatives including adhesive glazing tapes, preformed sealant strips and gun-applied sealants.

The low thermal conductivity of timber results in very different properties for timber frames. In particular heat transfer tends to occur directly through the frame, rather then being channelled towards the part of the frame with the lowest thermal resistance. However, the addition of an aluminium extrusion to create a composite frame must be considered carefully. A timber frame with a simple aluminium casing on the cold-side, to provide weather protection, can offer good thermal performance. However, it is also possible to produce a composite window using an aluminium extrusion with a warm-side timber cladding. This type of window may have somewhat poorer thermal performance.

The addition of a timber sill to a timber window has a very different effect to the addition of an aluminium sill to an aluminium window. An aluminium sill behaves as a fin, with an increased surface area exposed to the cold-side environment but little benefit from the extra length of the sill. However, with a timber sill the extra length of the sill means an increased distance for heat to travel.

The thermal conductivity of timber is remarkably similar for many softwoods and hardwoods. The value taken here is typical for European redwood, and is determined across the grain. For heat transfer along the grain a higher thermal conductivity would be expected. The basic timber frame considered here uses an identical glazing unit to the aluminium frames, but the unit is installed using a non-setting butyl sealant tape.

The frames in this chapter do not show any internal construction lines. The frames may be machined from a single timber, with an added glazing bead, or laminated from several pieces of timber. In either case the internal detail does not affect the heat transfer through the frame.

3.1 Simple timber window frame

This is a basic timber window frame. The frame is not particularly bulky, when compared to some Scandinavian frames, but the British climate does not require frames with a particularly high thermal resistance. However, demands for thicker glazing units is leading to bulkier frames with better thermal properties.

The U-value is significantly lower than for a thermally-broken aluminium frame. Importantly the frame warm-side surface temperatures are higher than for the aluminium frames considered in the previous chapter, although there is a clear reduction in the frame surface temperature near the edge of the glazing unit. The lower thermal conductivity of the frame material isolates the majority of the frame from the poor performance of the glazing edge, but the glazing edge still has a significant local effect.

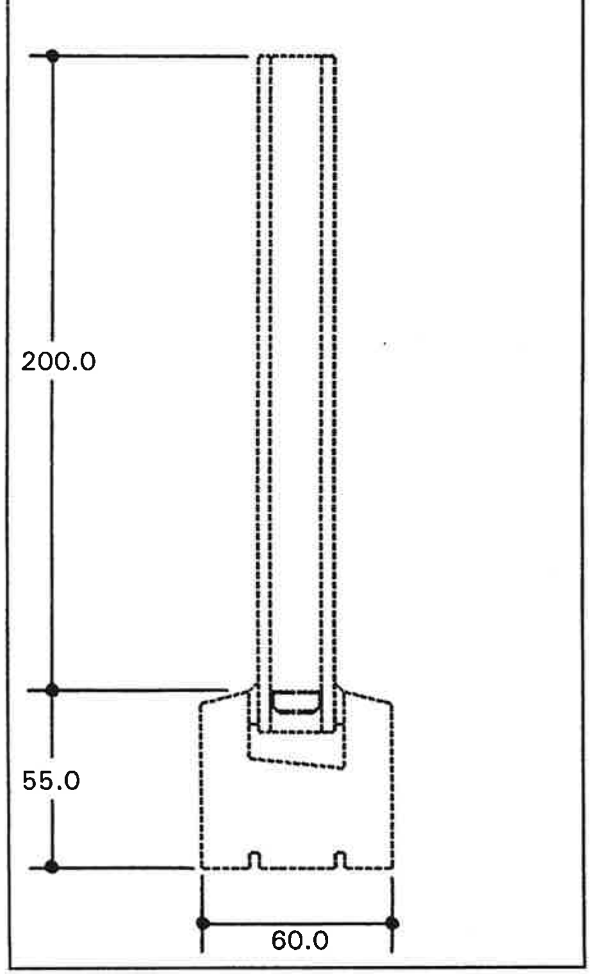
Performance

	Ordinary	Low-e	
Q_{total}	14.09	10.39	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.09	3.47	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.81	3.15	W/m²K

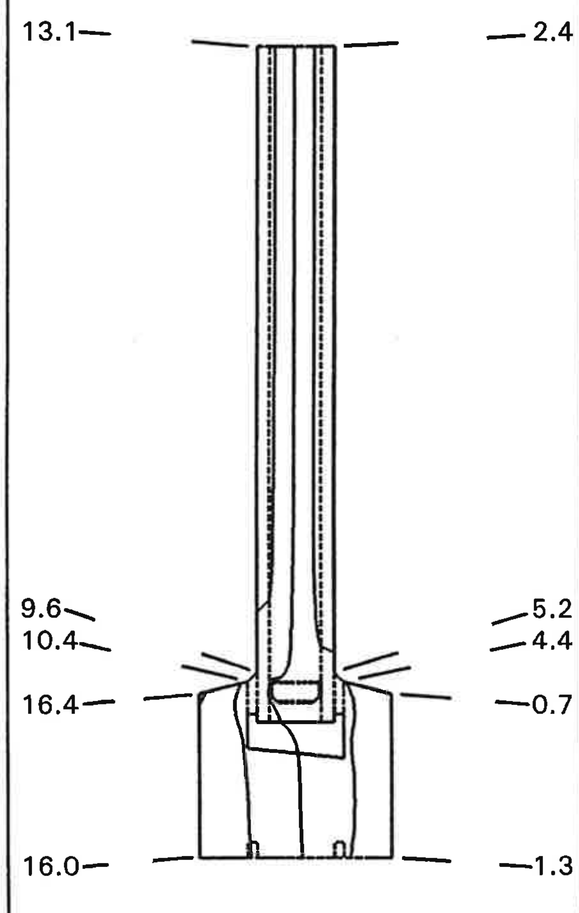
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	2.81	3.15	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.76	2.01	W/m²K

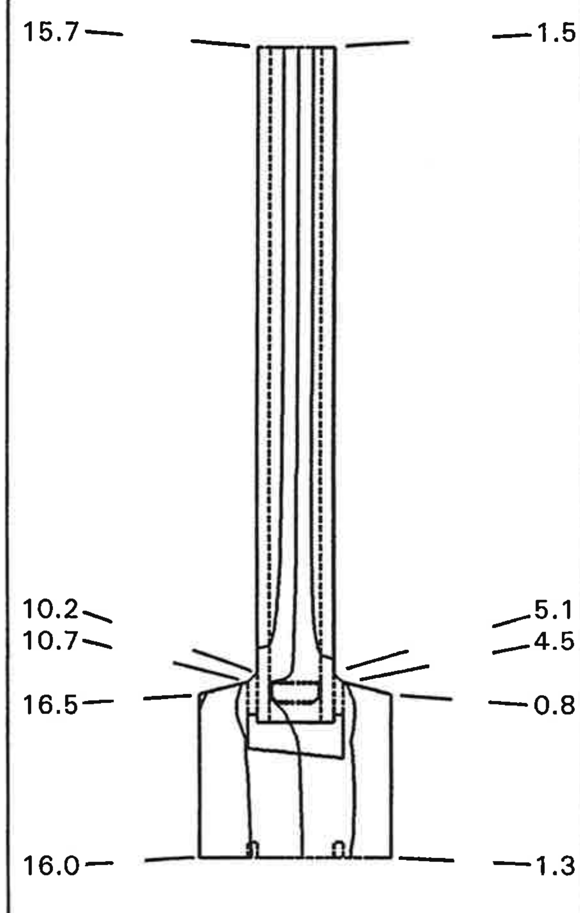
3.1 **Dimensions**



3.1 **Ordinary 4/16/4 mm glazing**



3.1 **Low-e 4/16/4 mm glazing**



3.2 Simple timber window frame with sill extension, underside of sill covered

This frame has been made thicker, over the lower portion, to form a sill. The projected width is the same but the average thickness of the frame is greatly increased. The result, despite the greater cold-side surface area, is less heat transfer and a lower U-value.

Although not used for practical reasons this modification has been used to demonstrate that if a greater thickness of a low thermal conductivity material is used then the U-value must decrease because the path for heat transfer has become longer. The increase in surface area is clearly not as significant, because the cold-side surface resistance is almost negligible to start with.

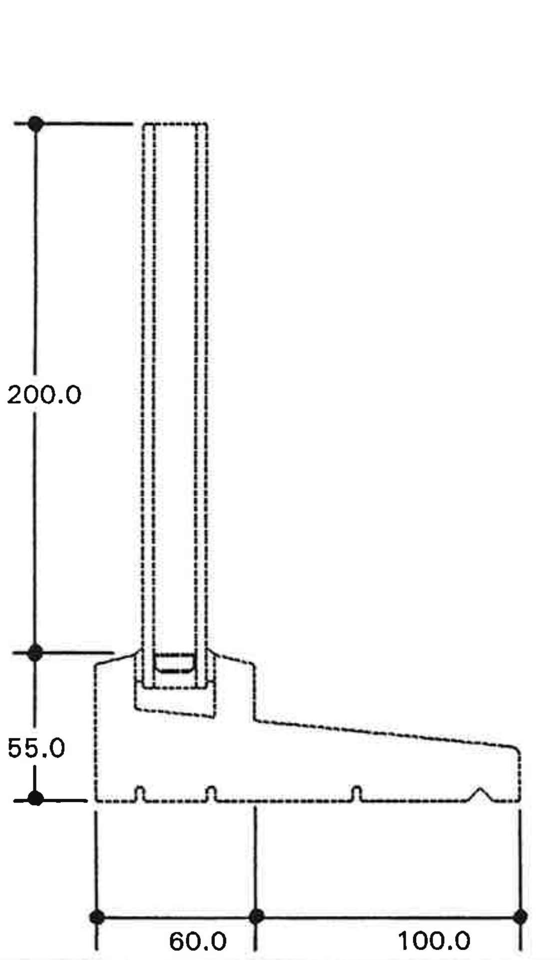
Performance

	Ordinary	Low-e	
Q_{total}	13.99	10.29	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	2.99	3.37	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.72	3.06	W/m²K

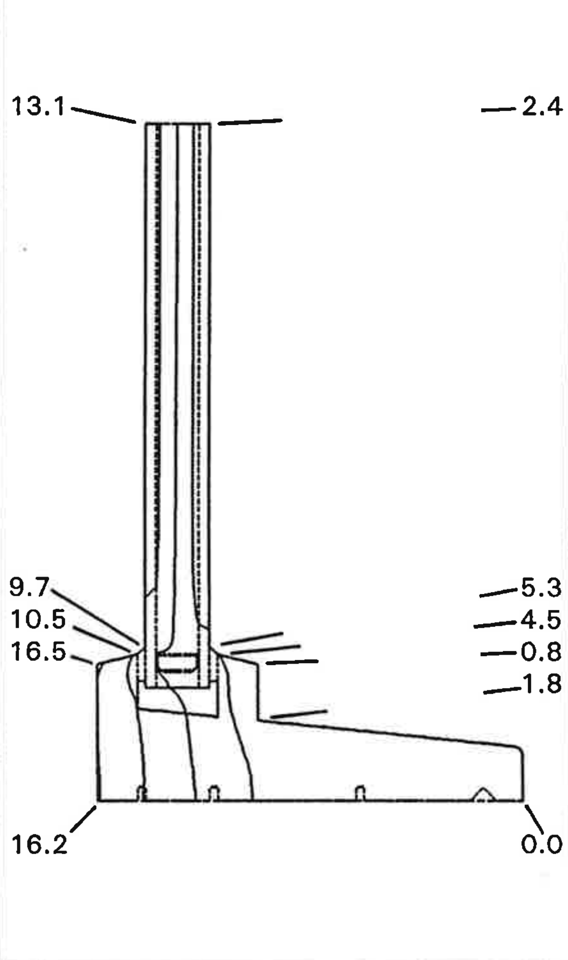
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 3.1

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
$U_{sides/top}$	2.81	3.15	W/m²K
$A_{sides/top}$	0.1779	0.1779	m²
U_{frame}	2.72	3.06	W/m²K
A_{frame}	0.0465	0.0465	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.76	2.01	W/m²K

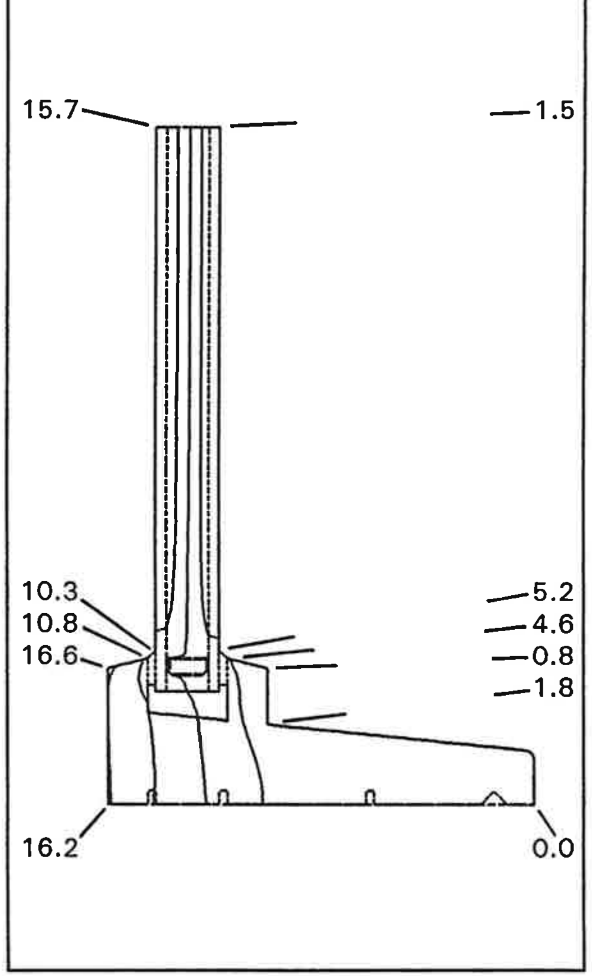
3.2 Dimensions



3.2 Ordinary 4/16/4 mm glazing



3.2 Low-e 4/16/4 mm glazing



3.3 Simple timber window frame with sill extension, underside of sill fully exposed

With a sill made from an insulating material the effect of exposing the underside of the sill to heat transfer is negligible. The U-values given here are barely different from those for the previous example. The heat loss per unit length of frame is still less than for the basic frame of example 3.1.

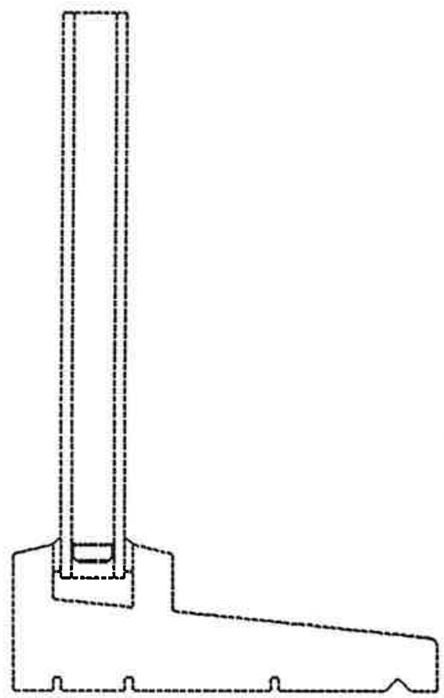
Performance

	Ordinary	Low-e	
Q_{total}	14.04	10.34	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.04	3.42	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.76	3.11	W/m²K

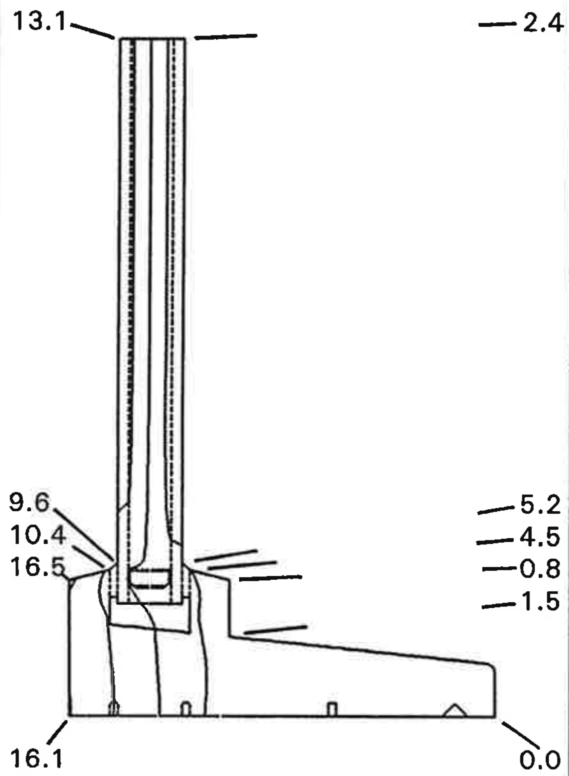
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 3.1

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
$U_{sides/top}$	2.81	3.15	W/m²K
$A_{sides/top}$	0.1779	0.1779	m²
U_{frame}	2.76	3.11	W/m²K
A_{frame}	0.0465	0.0465	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.76	2.01	W/m²K

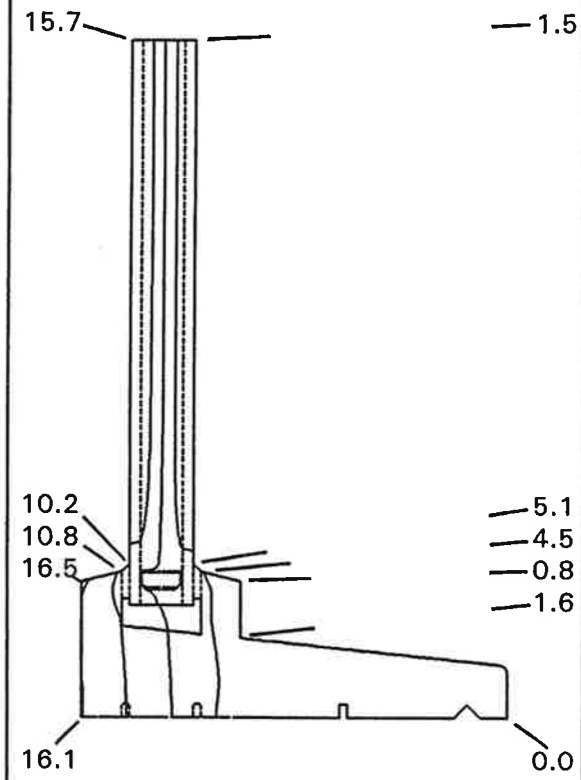
3.3 Dimensions



3.3 Ordinary 4/16/4 mm glazing



3.3 Low-e 4/16/4 mm glazing



3.4 Simple timber window frame with added sill, underside of sill covered

This added sill increases the frame heat transfer, but the U-value decreases, due to the effect of the increased projected area. The warm-side surface temperature is slightly increased, compared to the frame without sill.

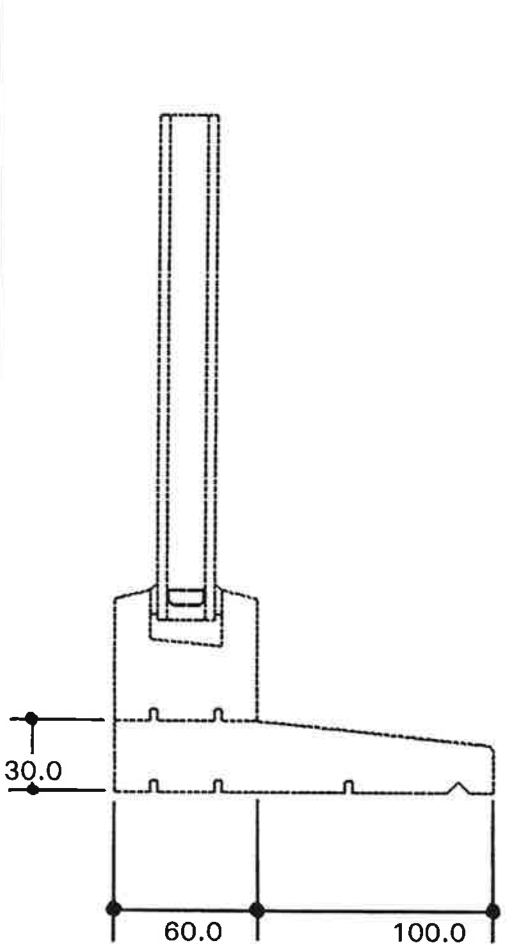
Performance

	Ordinary	Low-e	
Q_{total}	14.94	11.23	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.94	4.31	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.32	2.54	W/m²K

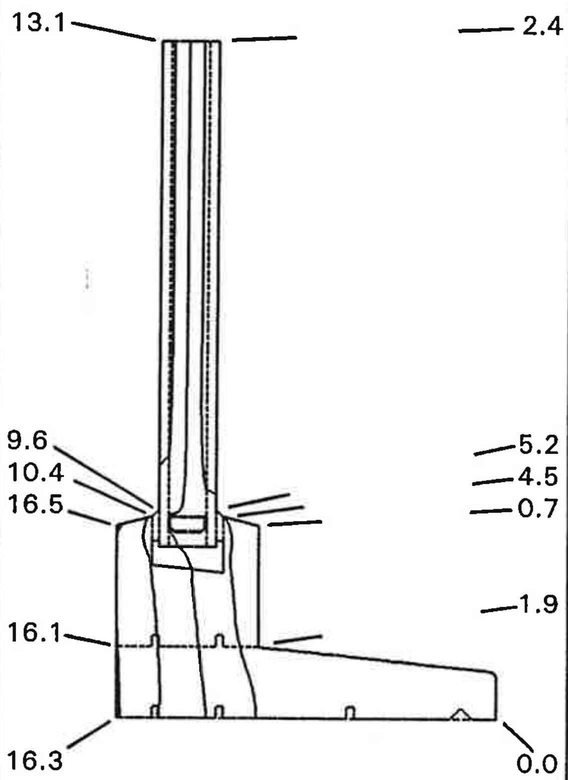
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 3.1

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	2.81	3.15	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	2.32	2.54	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.73	2.00	W/m²K

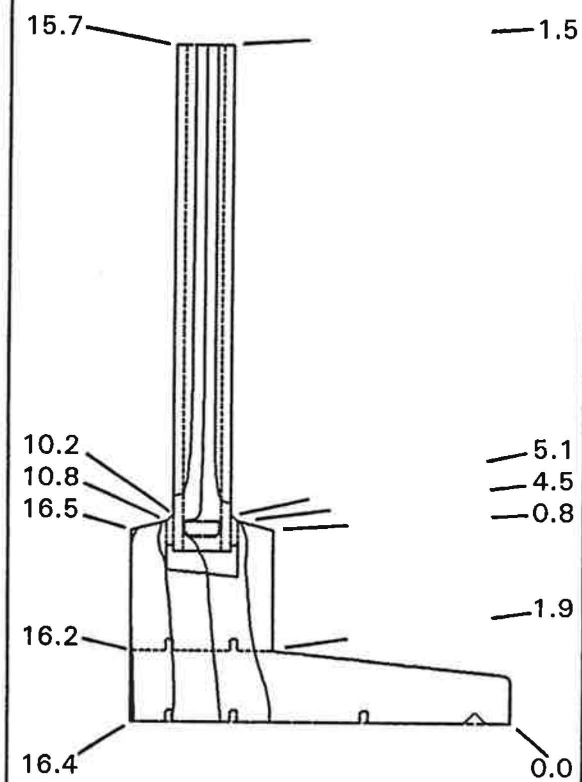
3.4 Dimensions



3.4 Ordinary 4/16/4 mm glazing



3.4 Low-e 4/16/4 mm glazing



3.5 Simple timber window frame with added sill, underside of sill fully exposed

As with the previous type of sill the effect of exposing the underside of the sill is negligible.

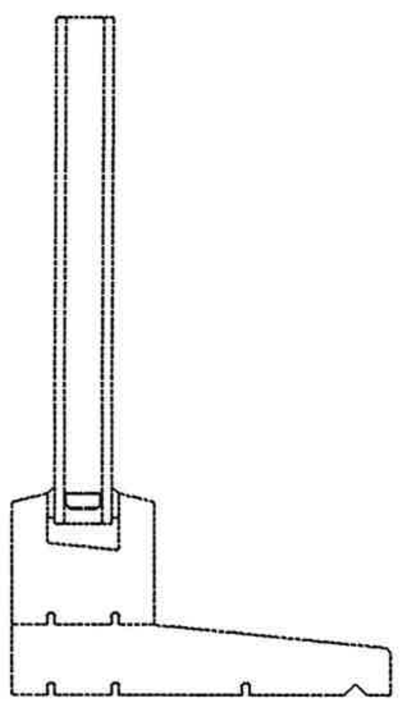
Performance

	Ordinary	Low-e	
Q_{total}	14.99	11.29	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.99	4.37	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.35	2.57	W/m²K

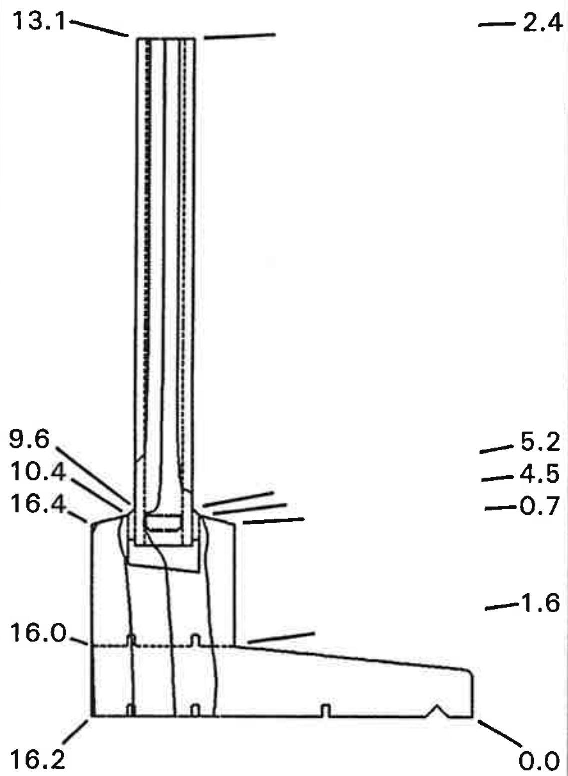
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 3.1

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	2.81	3.15	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	2.35	2.57	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.73	2.01	W/m²K

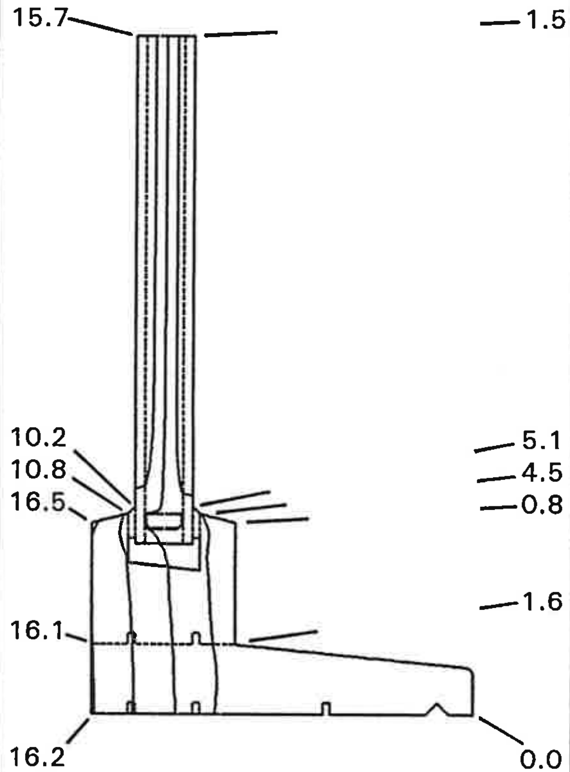
3.5 Dimensions



3.5 Ordinary 4/16/4 mm glazing



3.5 Low-e 4/16/4 mm glazing



3.6 Timber window frame with secondary glazing on the warm-side

An added pane of single glazing may be used to reduce the overall U-value, provide additional sound insulation or to protect blinds placed within the newly created air gap.

The use of secondary triple glazing must be considered carefully. In this case the extra pane of glass is on the warm-side of the window. The outcome is an improved centre-glazing U-value, and an improved frame U-value by virtue of the increased thickness of the frame. However, the condensation performance must be examined more closely.

Without the secondary glazing the temperature on the inside glass surface is just 13.1°C, with ordinary glazing. With the added pane of glass the temperature of the warmest surface of the sealed unit is now only 8.7°C. However, the newly created cavity cannot be regarded as vapour-tight, being open to the warm room environment whenever the secondary sash is opened. The risk of condensation on the warm-side of the insulated glazing unit is therefore greater.

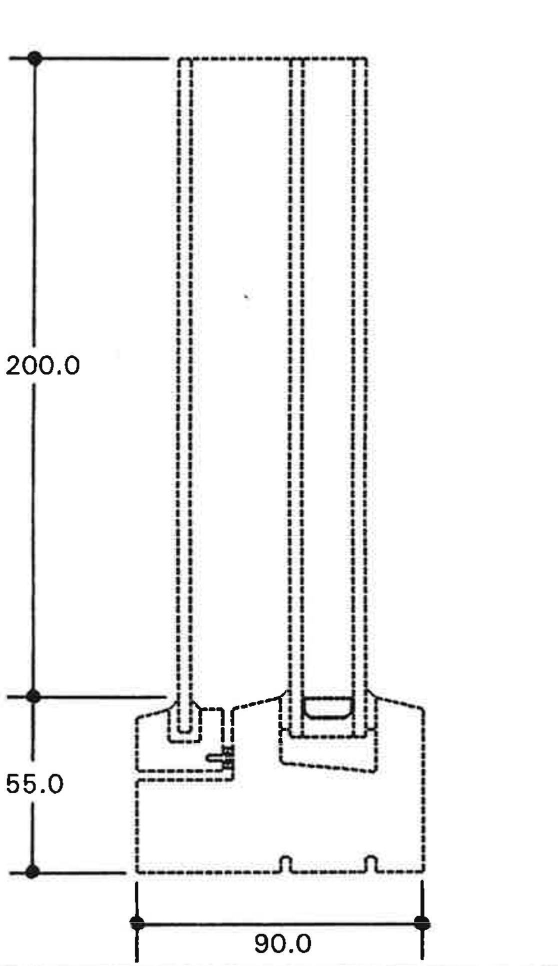
Performance

	Ordinary	Low-e	
Q_{total}	9.14	7.38	W
U_{glass}	1.82	1.31	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	7.28	5.24	W
Q_{frame}	1.86	2.14	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	1.69	1.95	W/m^2K

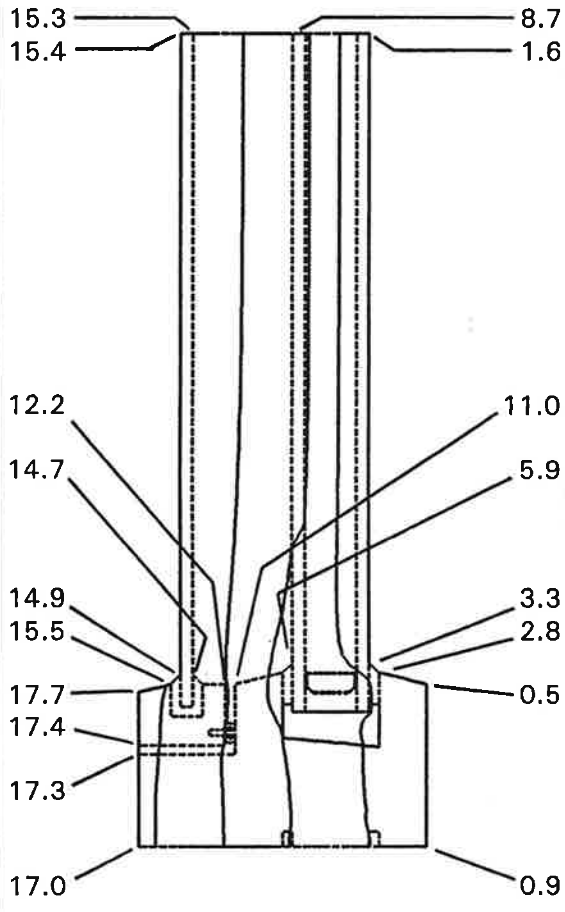
Typical window, 900 mm wide × 1250 mm high

U_{glass}	1.82	1.31	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	1.69	1.95	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	1.79	1.44	W/m^2K

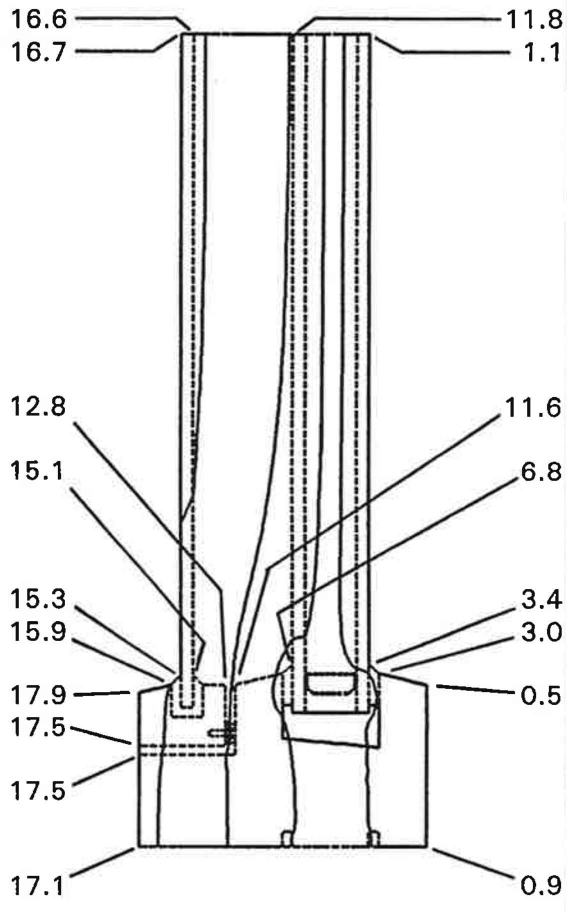
3.6 **Dimensions**



3.6 **4 + 31 + Ordinary 4/16/4 mm glazing**



3.6 **4 + 31 + Low-e 4/16/4 mm glazing**



3.7 Timber window frame with secondary glazing on the cold-side

This is the secondary glazed window from the previous example, but reversed, so that the secondary glazing pane is on the cold-side of the window.

The frame U-values are identical to those predicted above. However, the large air cavity is now likely to have a low moisture content, since it is open to the cold-side environment, and so the condensation risk has been eliminated. Furthermore the edge detail of the sealed double glazing unit is now closer to the warm-side of the frame and so will experience a smaller variation in temperature throughout the year and the edge seal is less likely to be affected by water penetration.

The addition of secondary glazing is a simple method to improve the performance of a window. However, the UK practice of adding additional glazing to the warm-side of the window may lead to problems if the new glazing cavity is not at least vented to the outside. This might then introduce problems if the vents are sufficiently large to allow pressure equalisation - wind loads would be transferred to the secondary glazing!

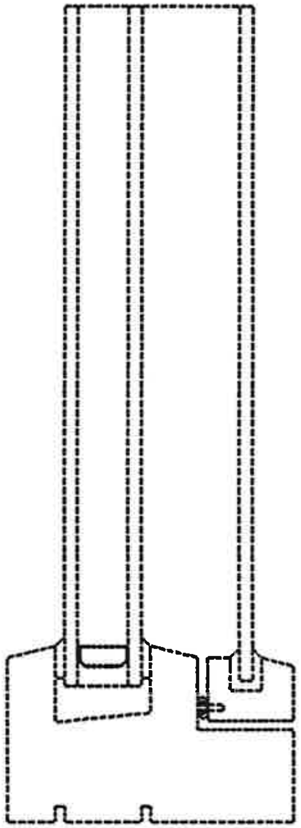
Performance

	Ordinary	Low-e	
Q_{total}	9.14	7.36	W
U_{glass}	1.82	1.31	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	7.28	5.24	W
Q_{frame}	1.86	2.12	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	1.69	1.93	W/m²K

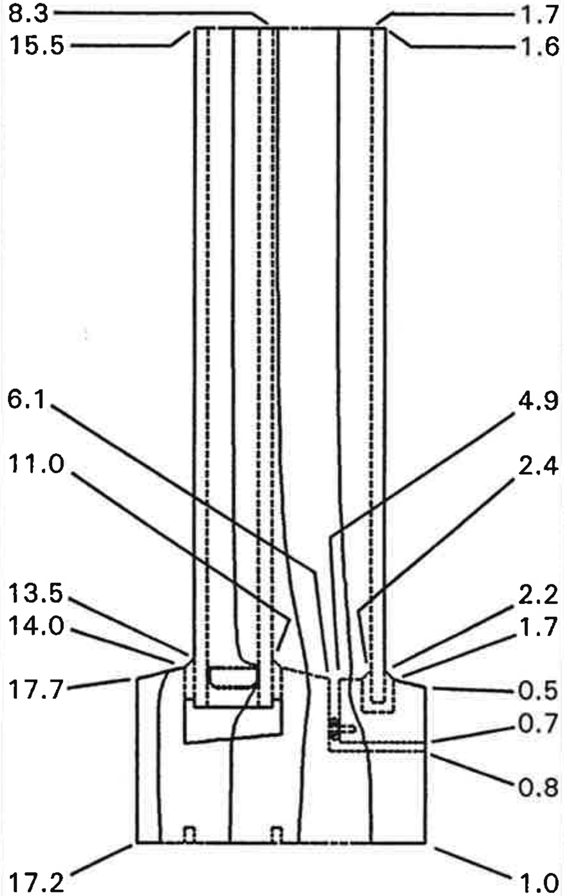
Typical window, 900 mm wide × 1250 mm high

U_{glass}	1.82	1.31	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	1.69	1.93	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	1.79	1.43	W/m²K

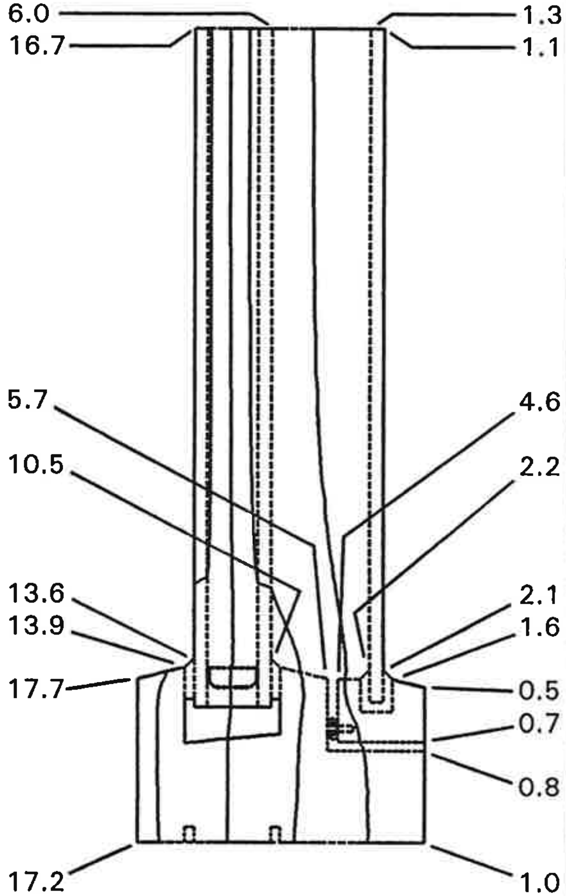
3.7 Dimensions



3.7 Ordinary 4/16/4 mm glazing + 31 + 4



3.7 Low-e 4/16/4 mm glazing + 31 + 4



3.8 Aluminium clad timber frame

A simple maintenance-free method of protecting the exterior of a timber window frame from the elements is to introduce a simple aluminium cladding, as shown here. Aluminium is however an excellent conductor of heat.

The U-value is clearly higher than for the basic timber frame of example 3.1. The aluminium serves to draw heat out of the window through the glazing edge detail. Most significantly the warm-side edge-of-glazing temperature is lower than for even a thermally-broken aluminium window; with the timber having a high thermal resistance very little heat is conducted into the edge of the glazing from the frame and so the warm-side glass edge temperature is lower.

This example again illustrates the complex balance between heat flow and temperature. The temperature at a point depends on the net amount of heat that can flow into the point. A simple analogy is that of water flowing into a basin - if water is drawn out of the basin faster than it is poured in then the water level will drop. The final level depends on the difference between the resistance to flow in and the resistance to flow out.

It is interesting to note that the 4°C isotherm skirts around the aluminium cladding, which is acting as a cold-finger into the frame.

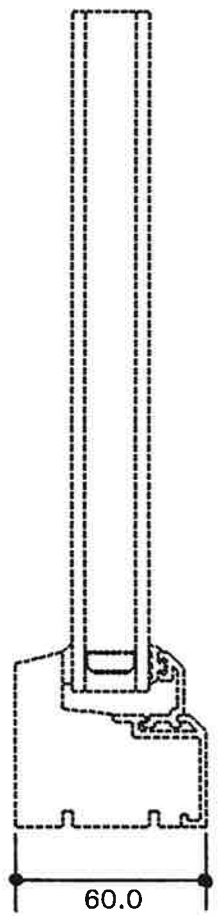
Performance

	Ordinary	Low-e	
Q_{total}	14.77	11.09	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.77	4.17	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.43	3.79	W/m²K

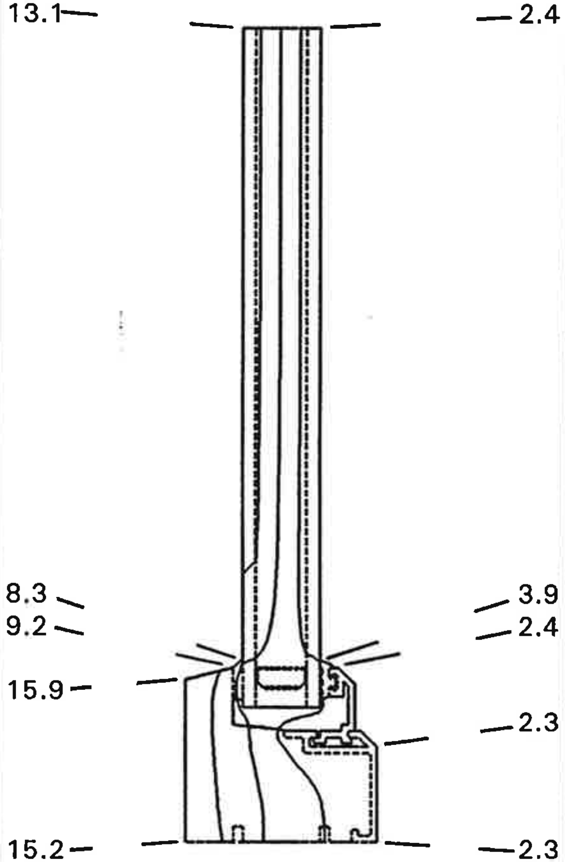
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.43	3.79	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.89	2.14	W/m²K

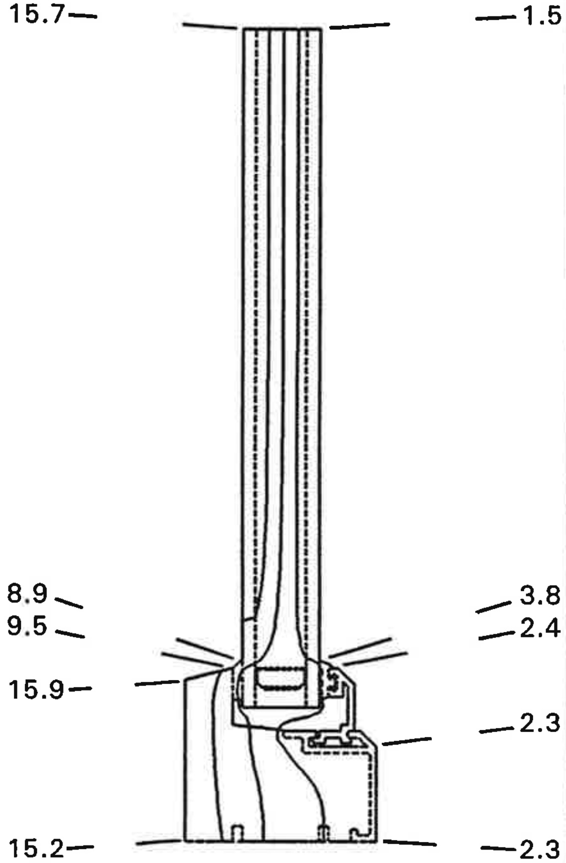
3.8 Dimensions



3.8 Ordinary 4/16/4 mm glazing



3.8 Low-e 4/16/4 mm glazing



3.9 Aluminium/timber composite frame

The previous frame was described as an aluminium-clad timber frame. This example might more properly be called a 'composite' timber/aluminium frame.

The use of a deeper aluminium section than in example 3.8 increases heat transfer through the frame, because the thickness of the thermally resistive timber has been reduced. The U-value of this frame is still lower than for a thermally-broken aluminium window however.

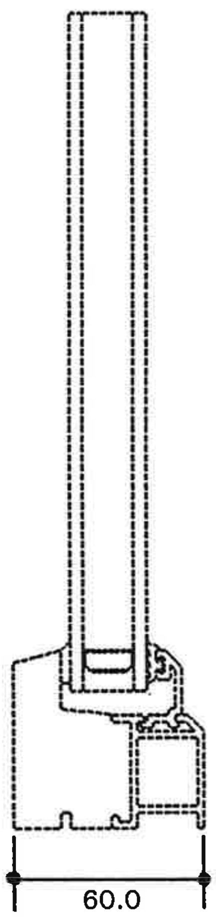
Performance

	Ordinary	Low-e	
Q_{total}	14.94	11.26	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.94	4.34	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.58	3.95	W/m²K

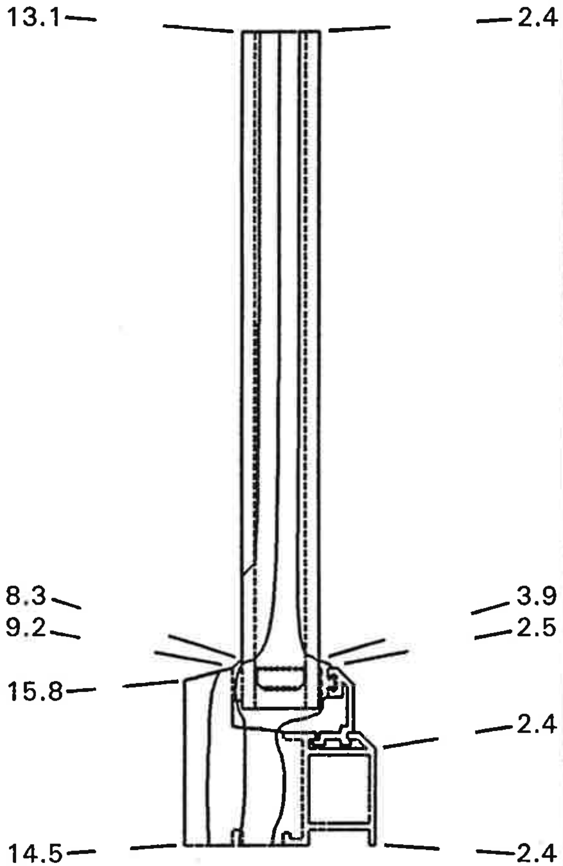
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.58	3.95	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.92	2.17	W/m²K

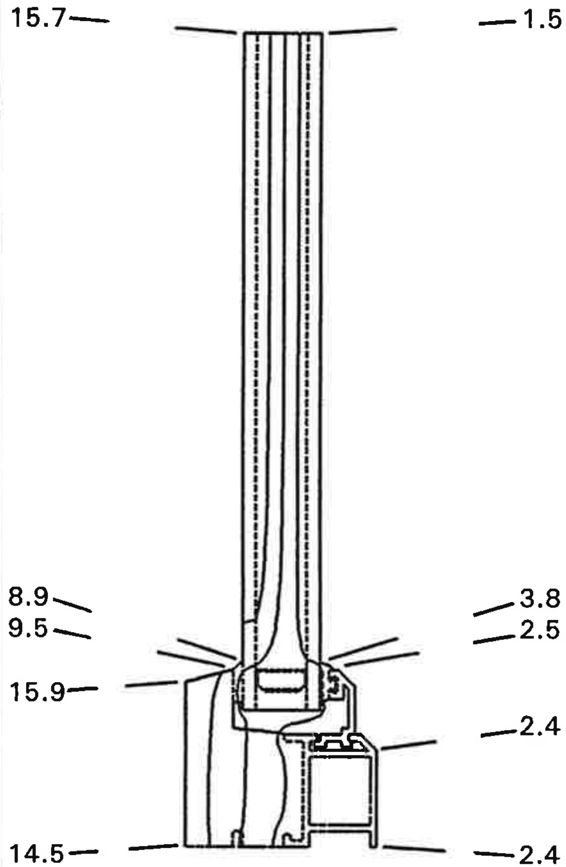
3.9 Dimensions



3.9 Ordinary 4/16/4 mm glazing



3.9 Low-e 4/16/4 mm glazing



3.10 Timber clad aluminium frame

This frame has been taken to the other extreme of a non-thermally-broken aluminium frame with a timber cladding applied to the warm-side surface for cosmetic purposes. The frame U-value is comparable to that of a thermally-broken aluminium frame, although the glazing edge temperature is now lower on the warm-side.

Consideration must be given to the possibility of condensation at the interface between the timber and aluminium, which would be trapped in contact with the timber and lead to rot. An interesting solution to this problem is found in frames which incorporate a plastic element between the aluminium and the timber. Any condensation will occur between the plastic and the aluminium, and so will not affect the timber. This approach also allows the plastic and aluminium to be extruded with a simpler clip-together method of fixing - the plastic can be screwed or glued to the timber before assembly.

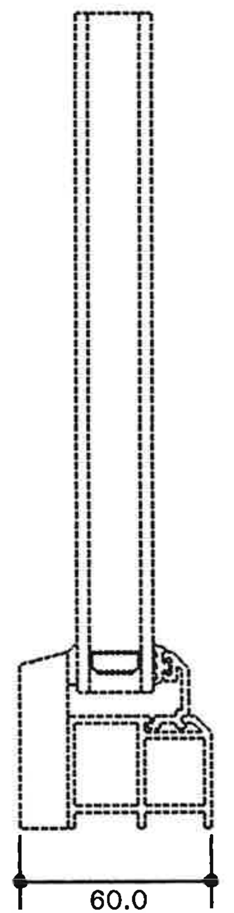
Performance

	Ordinary	Low-e	
Q_{total}	16.05	12.38	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.05	5.46	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.59	4.96	W/m²K

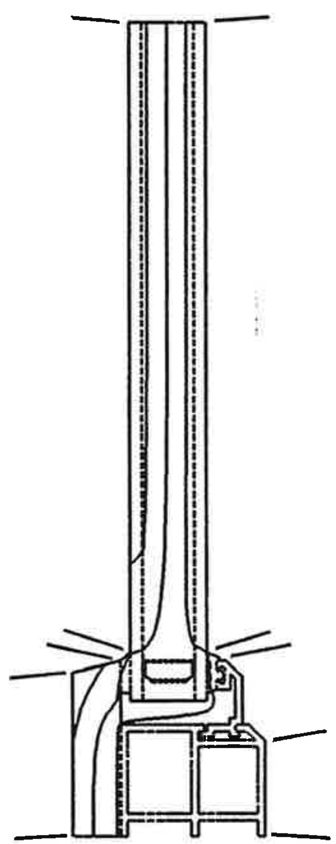
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.59	4.96	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.12	2.37	W/m²K

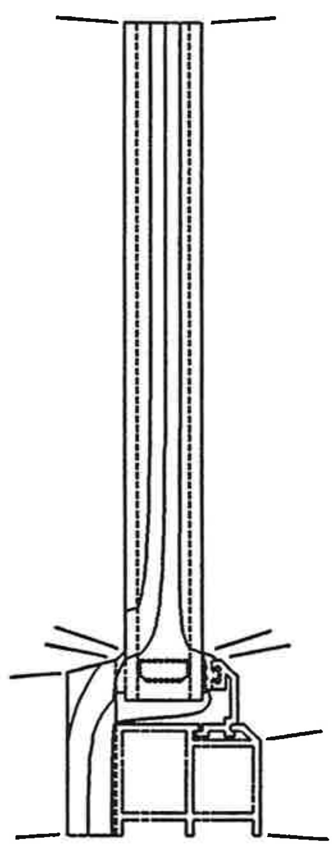
3.10 Dimensions



3.10 Ordinary 4/16/4 mm glazing



3.10 Low-e 4/16/4 mm glazing



3.11 Aluminium clad timber frame with reduced contact

This frame is similar to that of example 3.8, but the degree of contact between the aluminium cladding and the timber has been reduced.

There is a small improvement in performance, but the majority of the additional heat loss through this frame (compared to the basic timber frame of example 3.1) is due to the proximity of the large continuous aluminium surface to the glazing edge detail. Reducing the contact between the timber and the aluminium therefore has little effect.

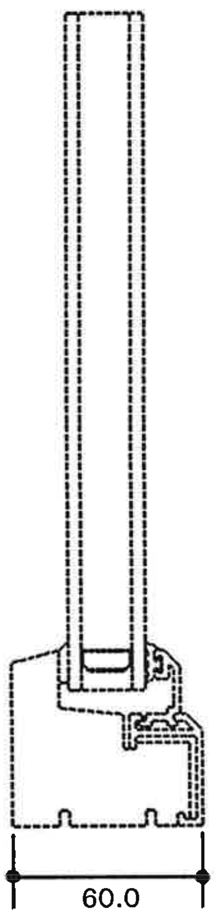
Performance

	Ordinary	Low-e	
Q_{total}	14.65	10.96	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.65	4.04	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.32	3.67	W/m²K

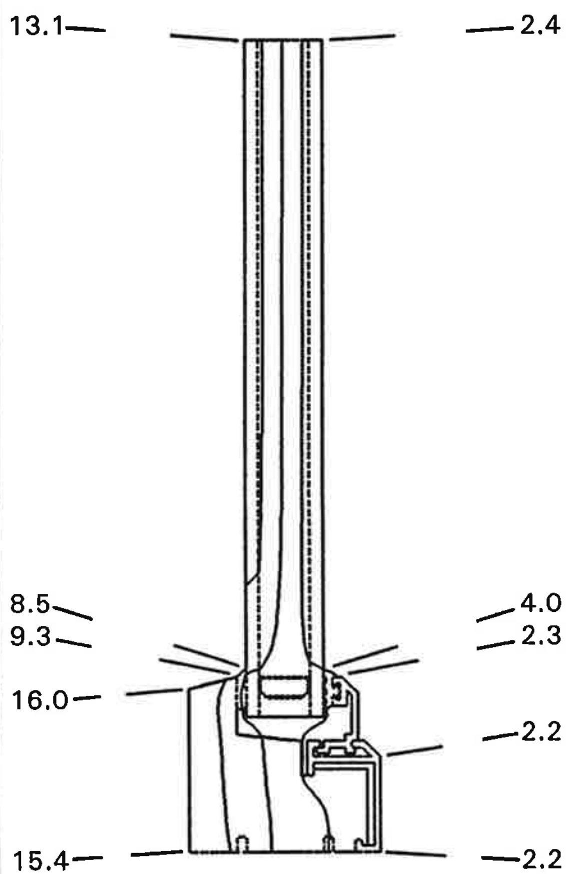
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.32	3.67	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.86	2.12	W/m²K

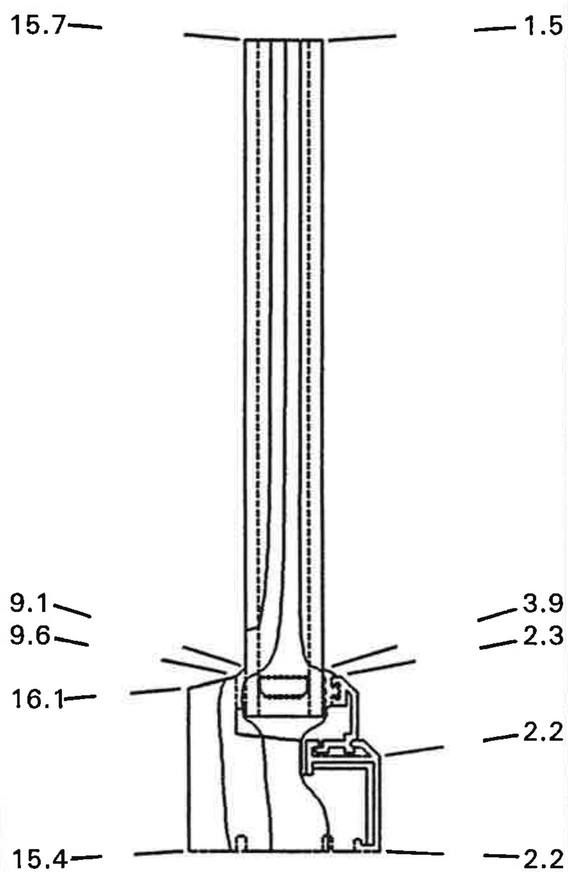
3.11 Dimensions



3.11 Ordinary 4/16/4 mm glazing



3.11 Low-e 4/16/4 mm glazing



3.12 Aluminium clad timber frame, with reduced contact and split cladding

In this version of the aluminium clad timber frame the cladding is split into two distinct sections. The surface area of the aluminium in contact with the cold-side glazing gasket is much reduced, and the lower part of the cladding is now much colder, signifying that a higher thermal resistance has been achieved. The U-value of the frame is lower than for example 3.11.

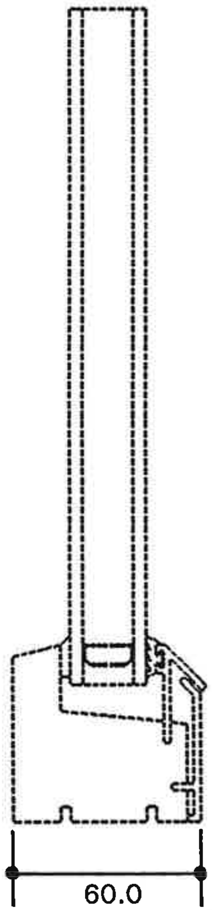
Performance

	Ordinary	Low-e	
Q_{total}	14.44	10.75	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.44	3.83	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.13	3.48	W/m²K

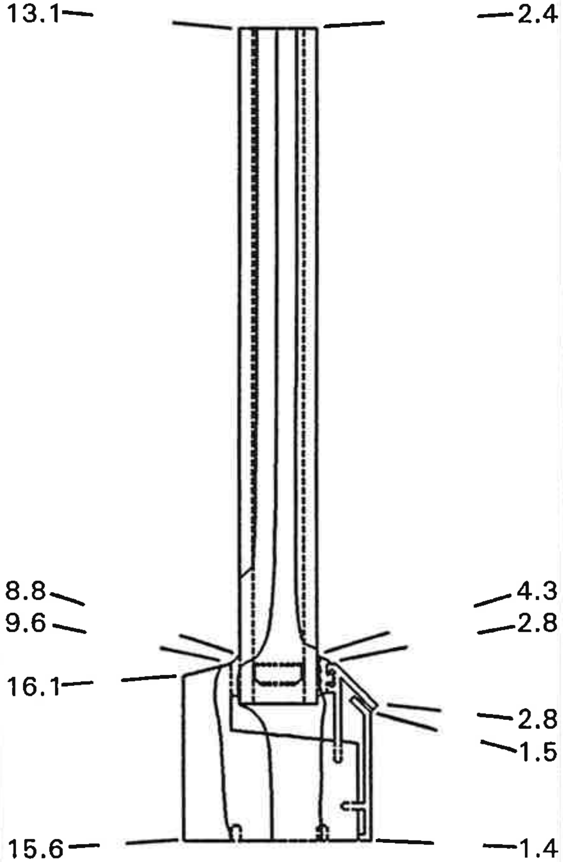
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.13	3.48	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.83	2.08	W/m²K

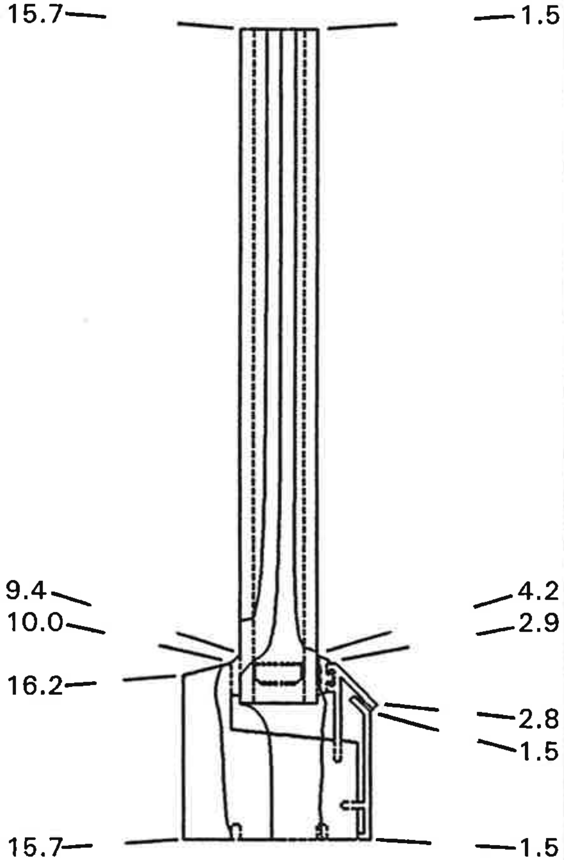
3.12 Dimensions



3.12 Ordinary 4/16/4 mm glazing



3.12 Low-e 4/16/4 mm glazing



3.13 Summary

Timber and timber/aluminium composite frames generally have better U-values than aluminium frames. However, the range of U-values is large when timber/aluminium composite frames are considered. It is important to ascertain how much aluminium has been used in composite frames, and to determine whether the aluminium section is a continuous piece in good thermal contact with the glazing edge or a number of pieces with some degree of thermal isolation from the glazing edge.

The use of additional panes of glass to improve the overall U-value has been shown to increase the risk of condensation if placed on the warm-side of the window. However, this practice is commonplace in the UK, and demonstrates a poor understanding of the principles of heat transfer and vapour transmission. Placing the extra pane on the cold-side of the construction is common practice in mainland Europe and elsewhere, and also serves to protect the sealed glazing unit from extremes of temperature, water penetration and impact.

4 PVC-U and PVC-U/aluminium composite windows

PVC-U has a thermal conductivity comparable with that of timber but with the advantage that PVC-U frames can be formed by extrusion, allowing thermally resistive air-filled cavities to be introduced. However, PVC-U is a flexible material and may require reinforcement in the form of steel or aluminium sections inserted into one or more of the larger frame cavities. This reinforcement is a thermal bridge and may increase heat transfer through the frame. This chapter initially considers different options for the use of reinforcement in PVC-U frames.

The application of aluminium cladding to give a surface with better weathering properties on the cold-side of a frame has already been discussed. This chapter considers PVC-U windows with various aluminium profiles added to the cold-side of the frame. These composite frames may range from a basically aluminium frame with a PVC-U cladding on the warm-side to a PVC-U frame with an aluminium cladding on the cold-side. In practice most of these frames are of the former type.

The addition of a sill to a composite frame raises an interesting question. Should the sill be aluminium or PVC-U? Both of these alternatives are considered here.

The frames considered in this chapter use the same glazing unit as previously, but whilst the cold-side glazing gasket is EPDM (identical to that used for the aluminium window frames) the warm-side glazing gasket is a thermoplastic wedge.

4.1 Basic PVC-U frame without reinforcement

This frame is un-reinforced. With fixed frames this may be normal practice for some window systems - the fixing into the wall is considered to provide sufficient strength. However, this example is used to demonstrate the relative difference between standard and reinforced frames. As the reinforcement is generally hidden it is always wise to check for the presence of reinforcement when measuring the U-value of PVC-U windows - it might be deliberately omitted in an attempt to produce an advantageous result.

Without reinforcement this frame has a lower U-value than the basic timber frame (example 3.1) due to the presence of air cavities within the frame. This frame is also slightly thicker.

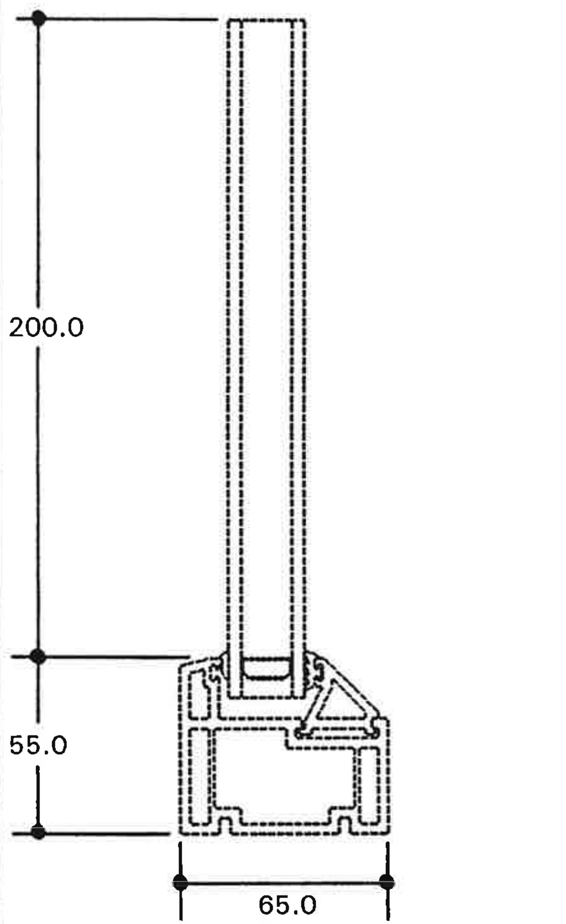
Performance

	Ordinary	Low-e	
Q_{total}	13.84	10.14	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	2.84	3.22	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.58	2.93	W/m²K

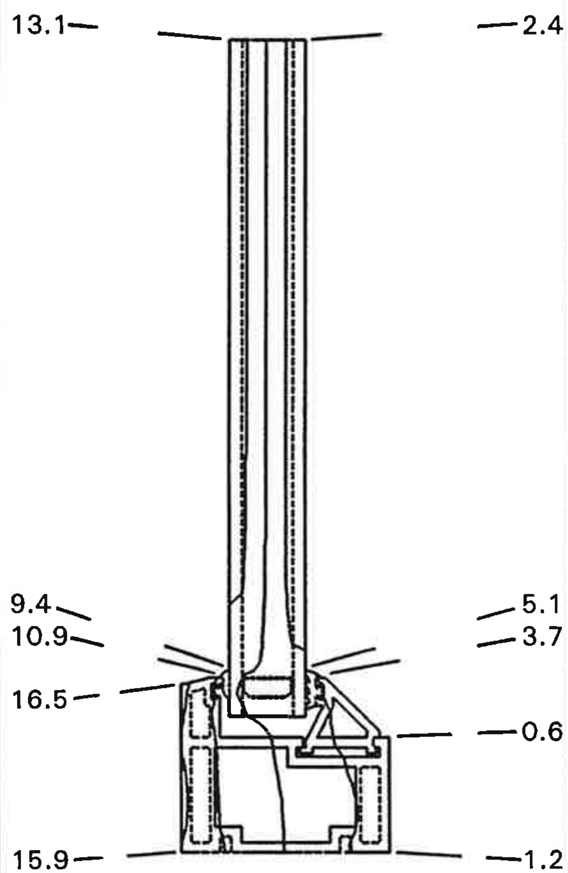
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	2.58	2.93	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.72	1.97	W/m²K

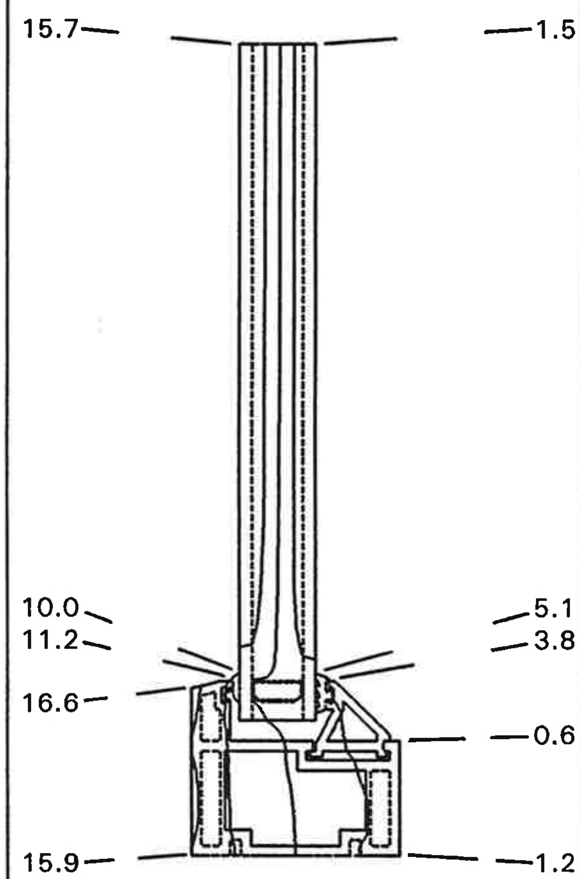
4.1 Dimensions



4.1 Ordinary 4/16/4 mm glazing



4.1 Low-e 4/16/4 mm glazing



4.2 Basic PVC-U frame with tight-fitting steel reinforcement

Reinforcement generally takes two forms. This is the first, in which a cold-rolled steel profile is forced into the main frame cavity. This type of reinforcement either relies on a tight fit to hold the reinforcement in place and provide additional strength (as shown here) or uses fixing screws to secure the steel profile (example 4.3).

The U-value of the frame is now slightly worse than for the basic timber frame. The reinforcement acts as a thermal bridge within the frame, and allows greater heat transfer through the main frame cavity. Note that the reinforcement is only in contact with small protrusions in the frame cavity. A fuller contact may result in a higher U-value.

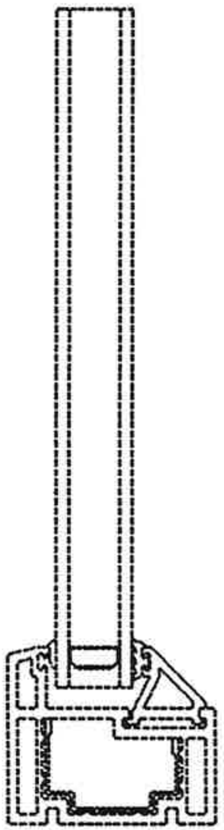
Performance

	Ordinary	Low-e	
Q_{total}	14.30	10.61	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.30	3.69	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.00	3.35	W/m²K

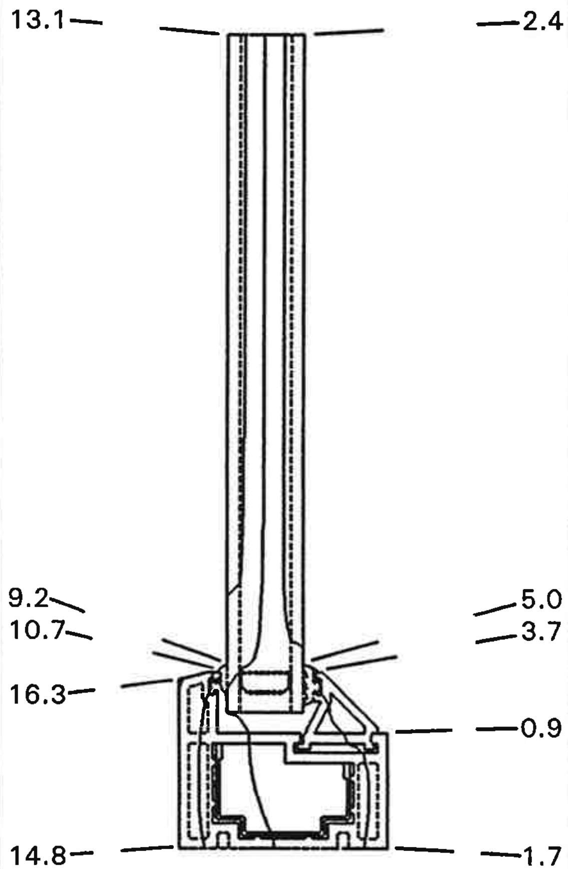
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.00	3.35	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.80	2.05	W/m²K

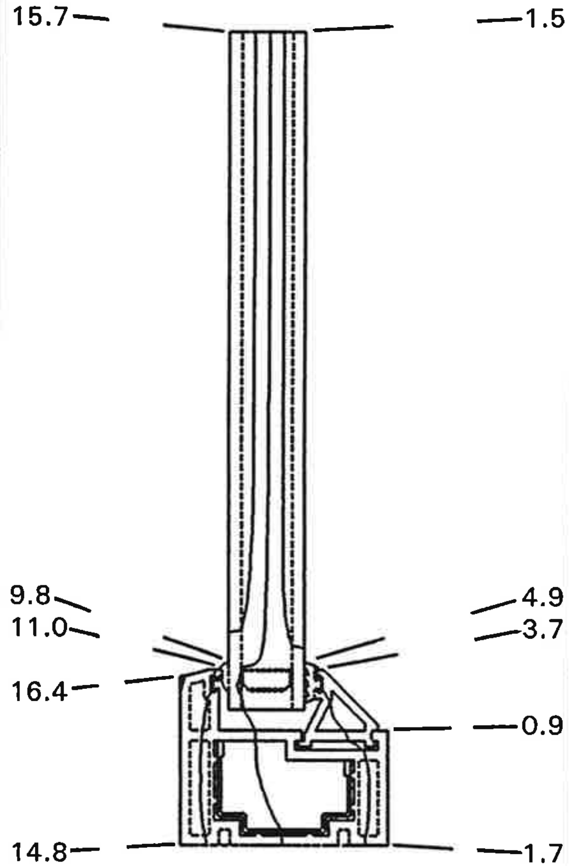
4.2 Dimensions



4.2 Ordinary 4/16/4 mm glazing



4.2 Low-e 4/16/4 mm glazing



4.3 Basic PVC-U frame with loose-fitting steel reinforcement

The alternative option for reinforcement is to use a strong steel tube or aluminium extrusion, fitted loosely within the frame and held in place with fixing screws at intervals along the length of the frame.

The performance of this frame is better than with the tight-fitting reinforcement of example 4.2. The U-value is almost identical to that of the basic timber frame.

It is clear from these first three examples that the use of reinforcement may remove some of the advantages of PVC-U over timber and in a real PVC-U window reinforcement might only be used in parts of the frame that span the full height or width of the frame and are too far from the perimeter to rely on the glazing for additional strength. It is also clear that a seemingly simple addition to a frame can make a significant change to the frame U-value. Care must always be taken that frame U-values are determined for the frame as it will actually be used.

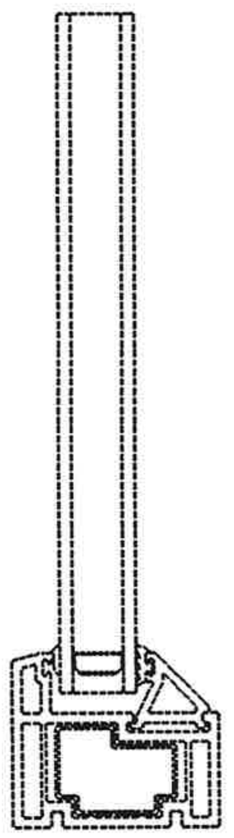
Performance

	Ordinary	Low-e	
Q_{total}	14.10	10.42	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.10	3.50	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.82	3.18	W/m^2K

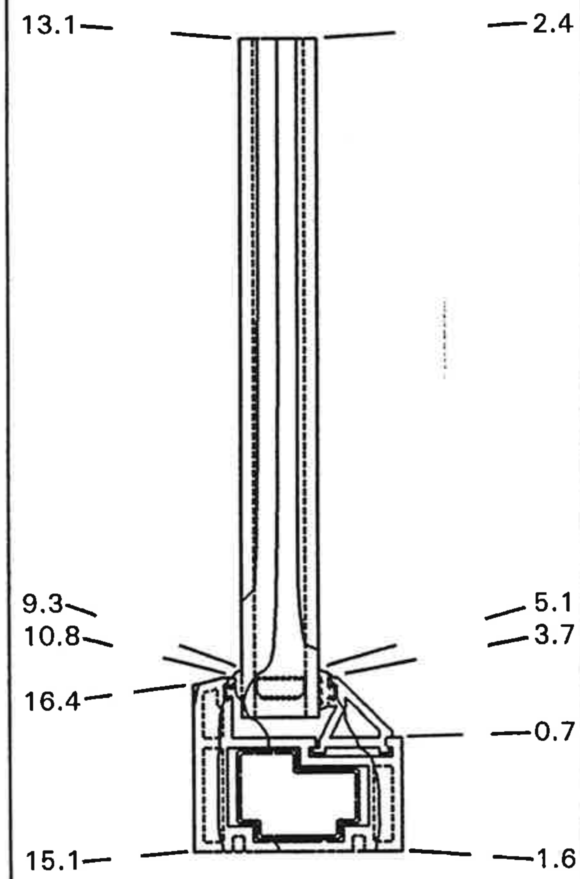
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	2.82	3.18	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	2.76	2.02	W/m^2K

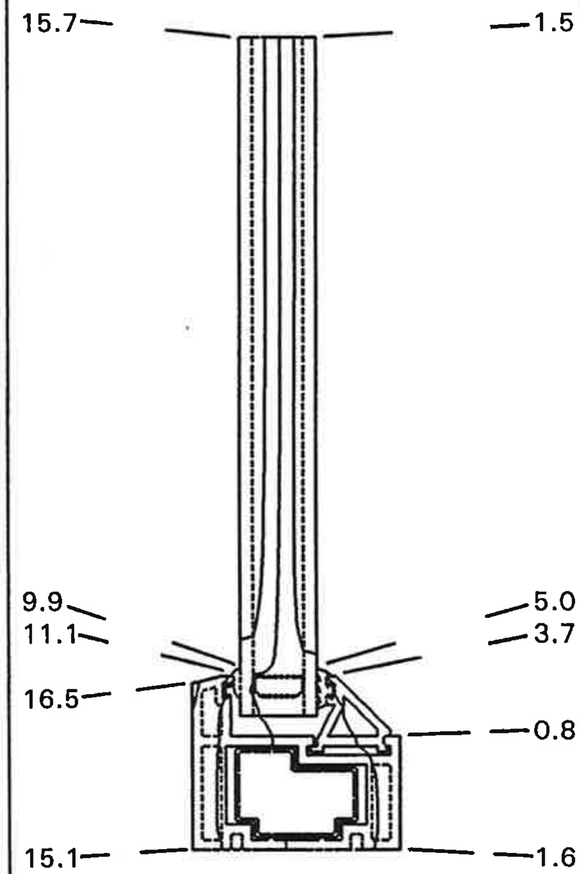
4.3 Dimensions



4.3 Ordinary 4/16/4 mm glazing



4.3 Low-e 4/16/4 mm glazing



4.4 Basic PVC-U frame with loose-fitting steel reinforcement and a similarly reinforced add-on sill, underside of sill covered

Although with the add-on sill there is more heat loss per unit length of frame the U-value is lower due to the increased projected area.

The PVC-U sill behaves in much the same way as the timber sill - although there is a greater surface area the extra distance for heat to travel is usually sufficient to limit the additional heat loss.

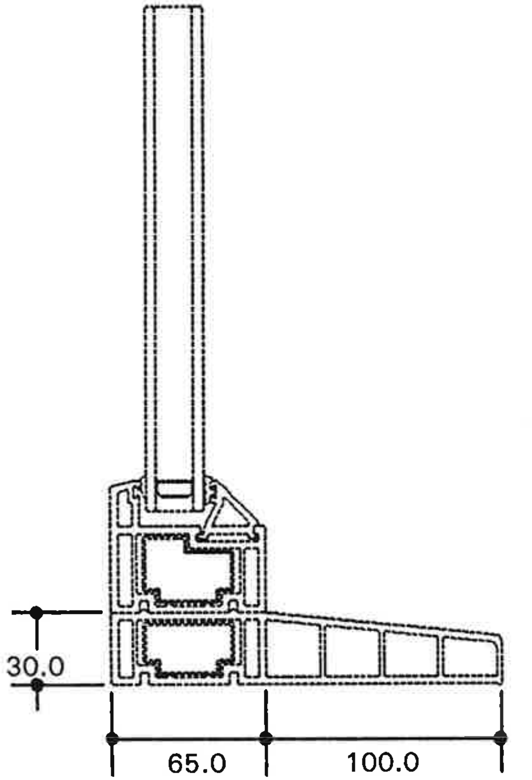
Performance

	Ordinary	Low-e	
Q_{total}	15.06	11.36	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.06	4.44	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.39	2.61	W/m²K

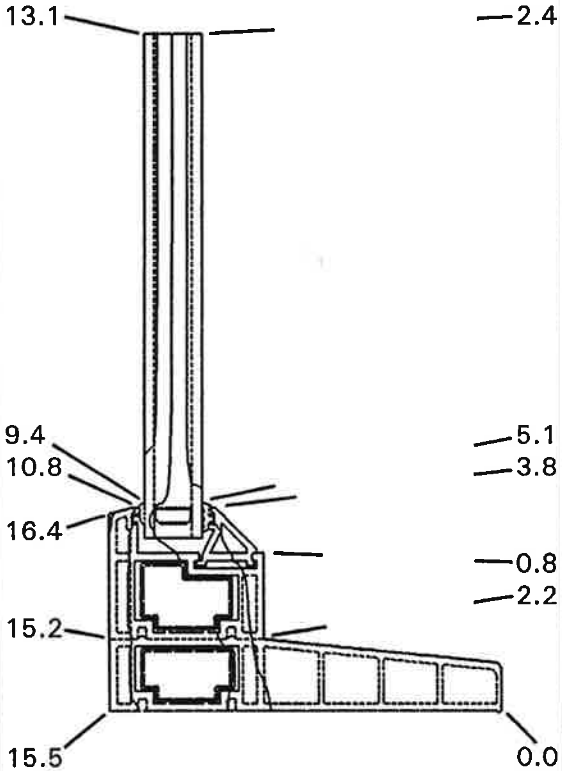
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.3

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	2.82	3.18	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	2.39	2.61	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.74	2.01	W/m²K

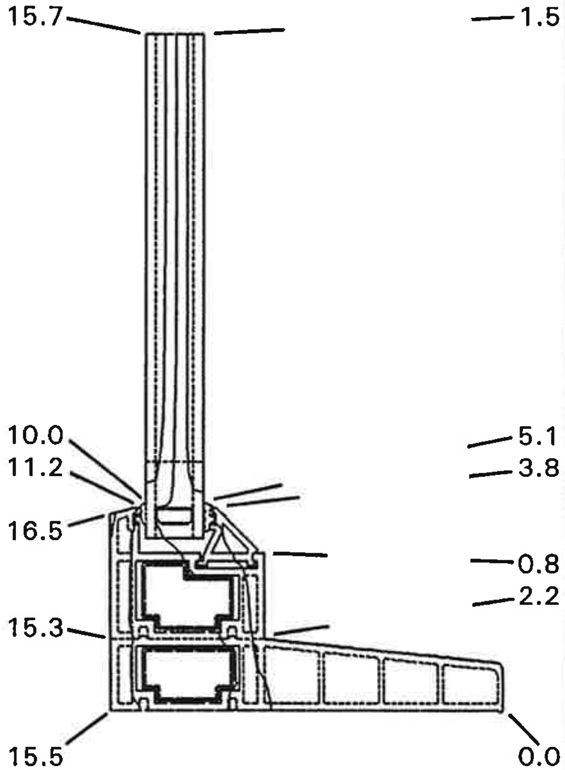
4.4 Dimensions



4.4 Ordinary 4/16/4 mm glazing



4.4 Low-e 4/16/4 mm glazing



4.5 Basic PVC-U frame with loose-fitting steel reinforcement and a similarly reinforced add-on sill, underside of sill fully exposed

As with the examples of chapter 3 a sill made from an insulating material performs equally with the underside of the sill sheltered or exposed. The cold-side surface thermal resistance, although reducing as the surface area is increased, is already a negligible part of the overall thermal resistance of the frame.

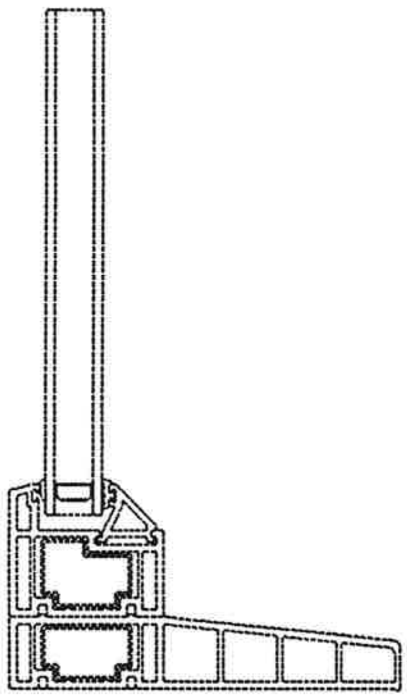
Performance

	Ordinary	Low-e	
Q_{total}	15.13	11.43	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.13	4.51	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.43	2.65	W/m²K

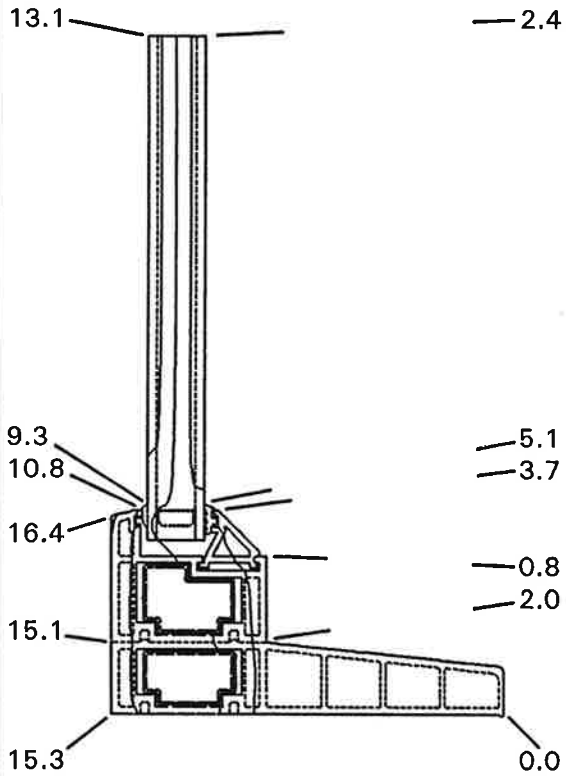
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.3

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	2.82	3.18	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	2.43	2.65	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.74	2.02	W/m²K

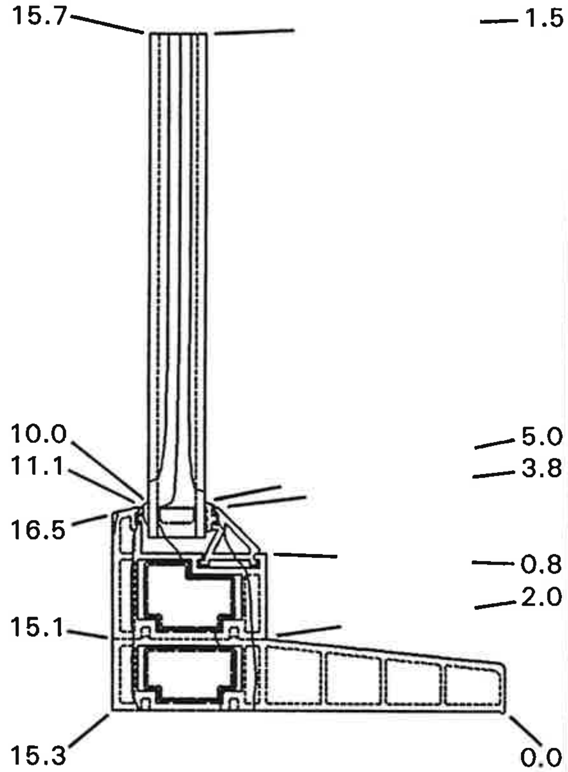
4.5 Dimensions



4.5 Ordinary 4/16/4 mm glazing



4.5 Low-e 4/16/4 mm glazing



4.6 Aluminium frame with PVC-U cladding on the warm-side

This is a typical composite PVC-U/aluminium frame. The PVC-U profile has been kept to a minimum thickness, and the overall thickness of the frame is similar to that of the aluminium frames of chapter 2. Consequently the U-value is closer to that of a thermally-broken aluminium frame, although the thermal break is now on the surface of the frame. However, by eliminating the aluminium warm-side surface the heat flow into the glazing edge detail has been reduced, with the result that the warm-side surface of the glass is 1.5°C colder than for an aluminium frame with a higher U-value (see example 2.5).

The relationship between heat transfer and point temperature is again shown to be a complex one where two-dimensional heat transfer is occurring. The temperature at a point depends on the balance between heat flow into and out of the point. If the heat flow into a point is reduced then the point temperature will reduce to establish a new heat flow balance.

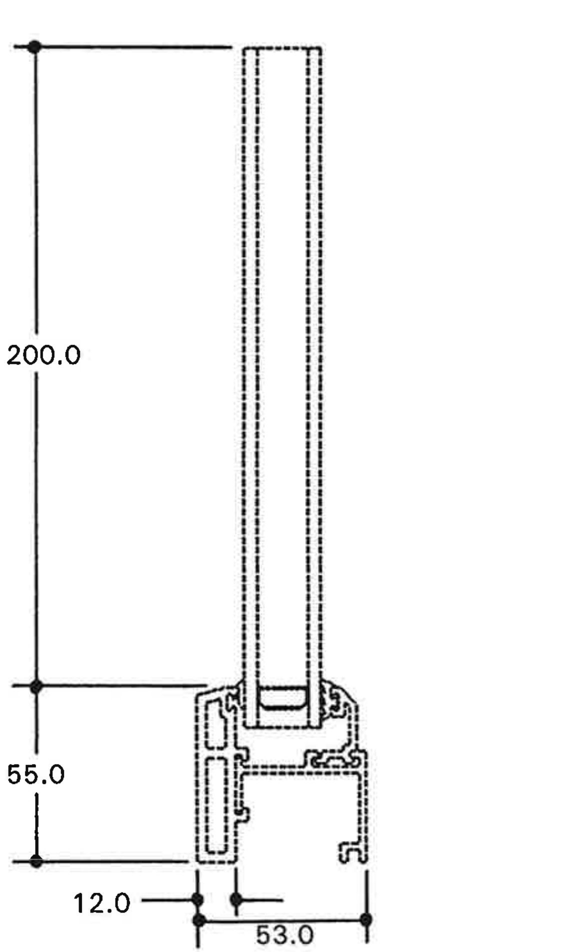
Performance

	Ordinary	Low-e	
Q_{total}	15.44	11.77	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.44	4.85	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.04	4.41	W/m²K

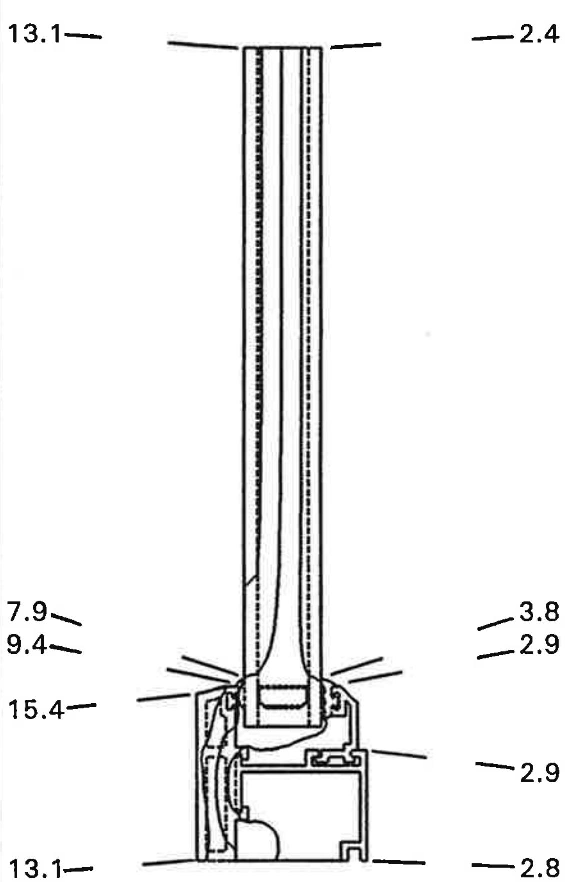
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.04	4.41	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.01	2.26	W/m²K

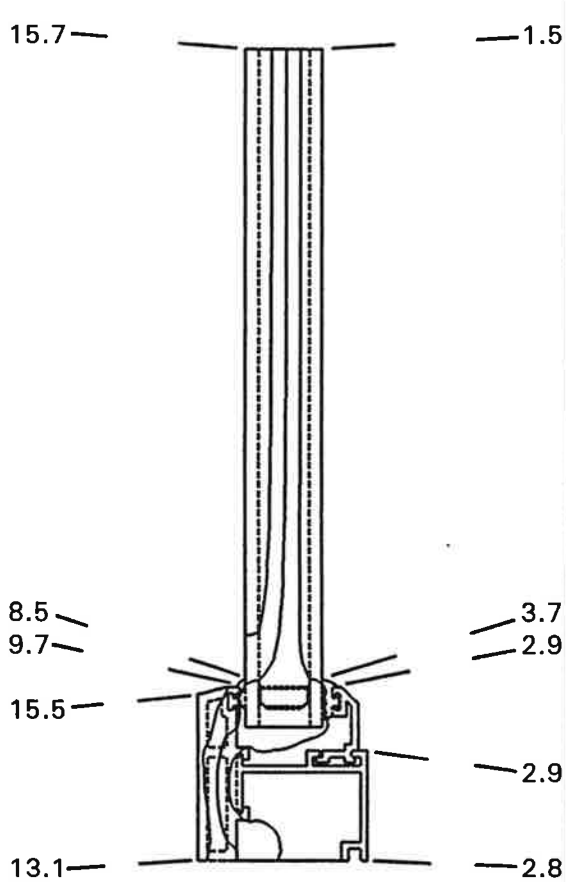
4.6 **Dimensions**



4.6 **Ordinary 4/16/4 mm glazing**



4.6 **Low-e 4/16/4 mm glazing**



4.7 Aluminium frame with a deep PVC-U cladding on the warm-side

In this frame the PVC-U section has been increased in depth. This is similar to introducing an additional thermal break into the frame.

The U-value has been reduced significantly, and the glazing edge temperature is slightly higher. This example shows that the heat flow distribution (and hence the temperature distribution) is a function of the relative thermal resistances of the various heat flow paths through the frame. Improving the thermal resistance of the frame proper has increased the temperature of the frame warm-side surface, and pushed more heat into the glazing edge, even though the thermal resistance of the glazing edge has not changed.

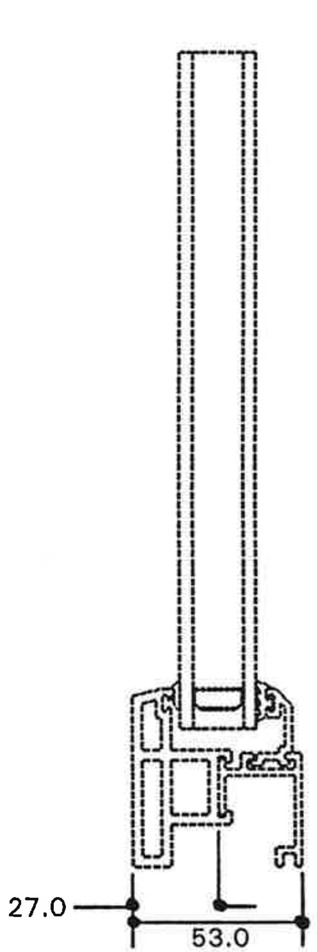
Performance

	Ordinary	Low-e	
Q_{total}	14.62	10.94	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.62	4.02	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.29	3.65	W/m²K

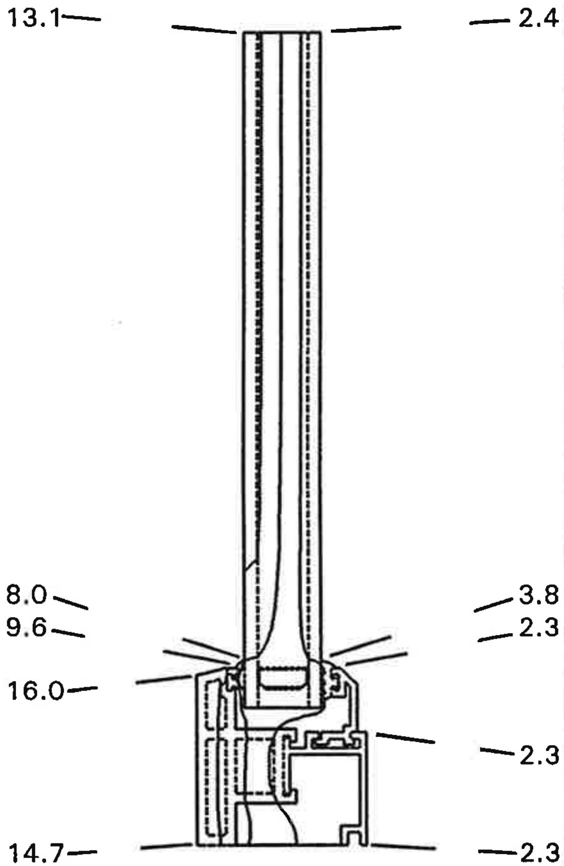
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.29	3.65	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.86	2.11	W/m²K

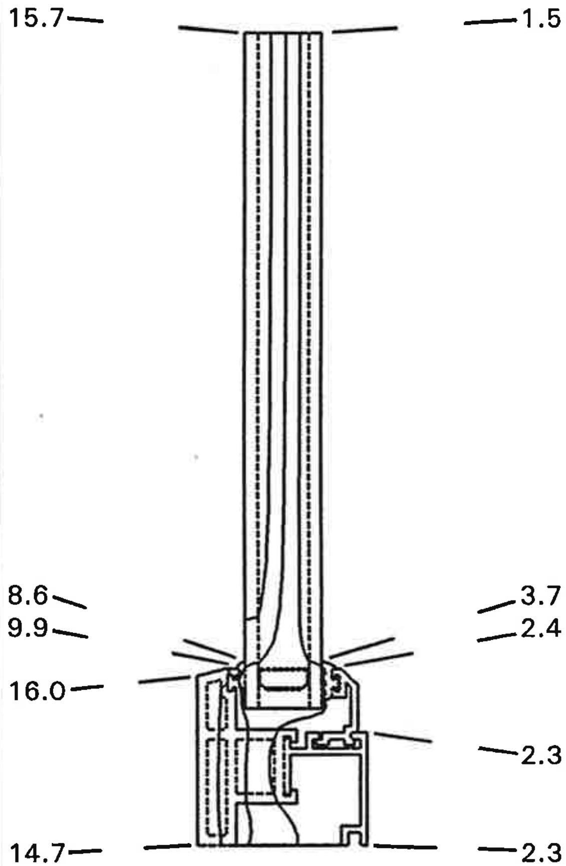
4.7 Dimensions



4.7 Ordinary 4/16/4 mm glazing



4.7 Low-e 4/16/4 mm glazing



4.8 Aluminium frame with a deep PVC-U cladding, but reversed

Reversing the frame of example 4.7 increases the frame U-value. With this frame orientation the cold-side frame surface is colder, indicating less heat loss from this part of the surface. However, near the glazing edge the PVC-U profile and the glazing are considerably warmer than in example 4.7. Reversing the frame has increased the relative thermal resistance of the cold-side of the frame, thereby raising the cold-side glass surface temperature and causing greater heat loss from the glazing. This frame orientation makes it easier for heat transfer to occur through the warm-side of the frame, and harder for heat transfer to occur through the cold-side of the frame.

It is noticeable that with the aluminium surface on the inside there is a smaller variation in warm-side surface temperature, reflecting the ease with which the aluminium conducts heat into the edge detail, raising the glass edge temperature. It is apparent that in this form of composite window the lowest condensation risk will be achieved with the aluminium profile to the inside!

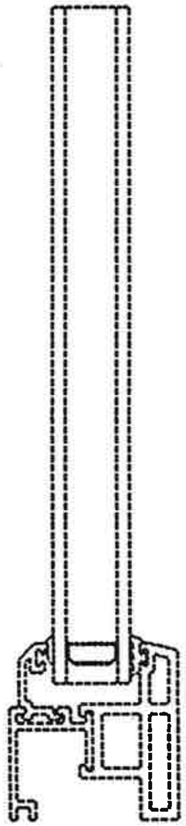
Performance

	Ordinary	Low-e	
Q_{total}	14.86	11.10	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.86	4.18	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.51	3.80	W/m^2K

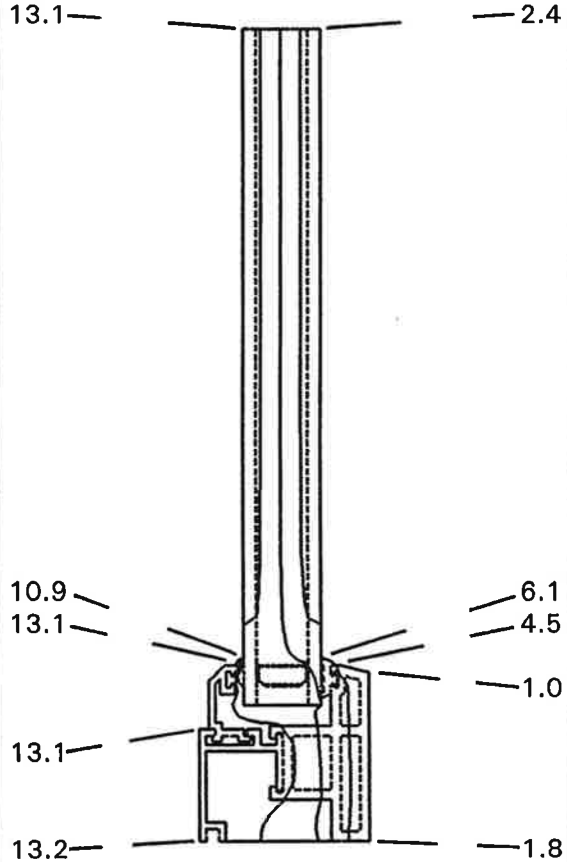
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	3.51	3.80	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	2.90	2.14	W/m^2K

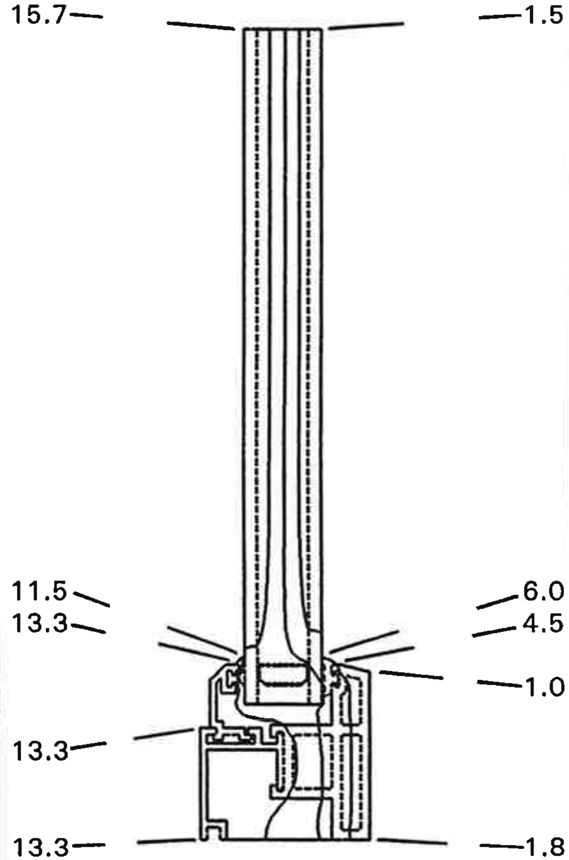
4.8 Dimensions



4.8 Ordinary 4/16/4 mm glazing



4.8 Low-e 4/16/4 mm glazing



4.9 Aluminium frame with a deep PVC-U cladding on the warm-side, and a reinforced PVC-U sill, underside of sill covered

This frame is identical to the frame of example 4.7, but with the PVC-U section extended to include a sill (N.B. it is unlikely that the sill will be part of the same extrusion as the PVC-U part of the frame, but the results will be identical if the sill is a separate PVC-U 'add-on').

The window U-value is identical to that without the sill. The sill introduces an extra heat loss of 1.03 W, which over the 30 mm projected width of the sill is equivalent to a U-value of 1.72 W/m²K - the same as the low-e glazing. It is important to note that the lowest temperature isotherm is significantly closer to the warm-side in the composite part of the profile, and that this isotherm always passes close to the interface with the aluminium section. The aluminium is clearly a cold-finger, pushing into the frame.

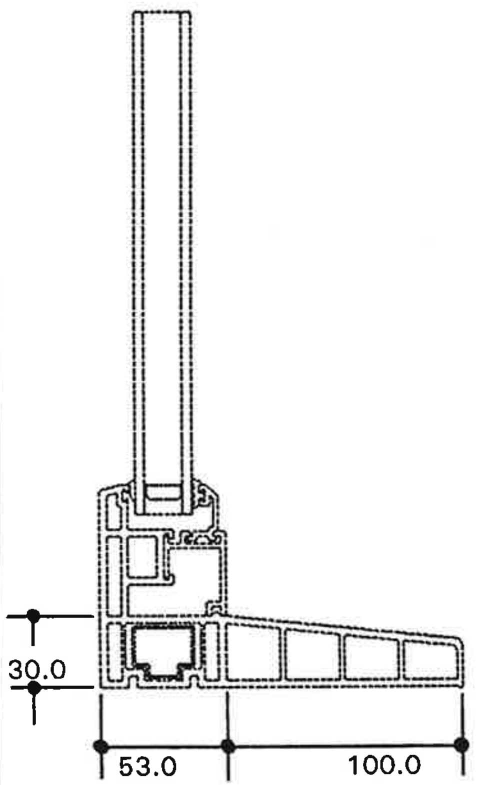
Performance

	Ordinary	Low-e	
Q_{total}	15.65	11.98	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.65	5.06	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.74	2.98	W/m²K

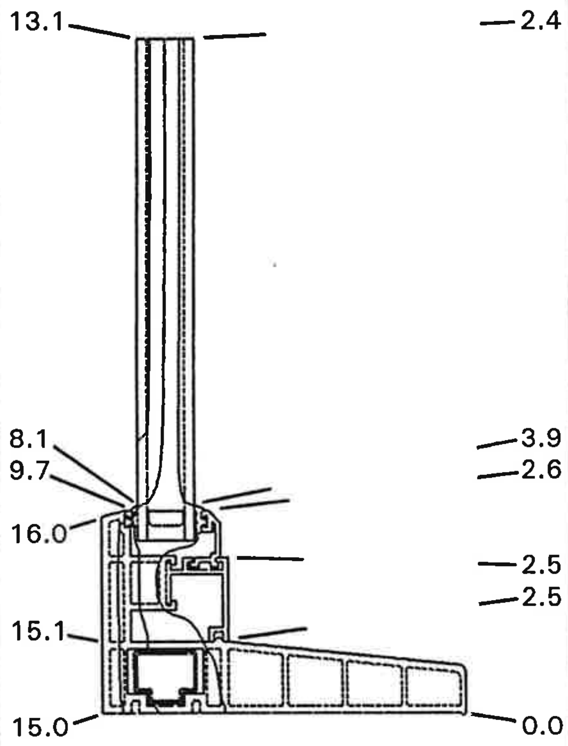
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.7

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	3.29	3.65	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	2.74	2.98	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.83	2.11	W/m²K

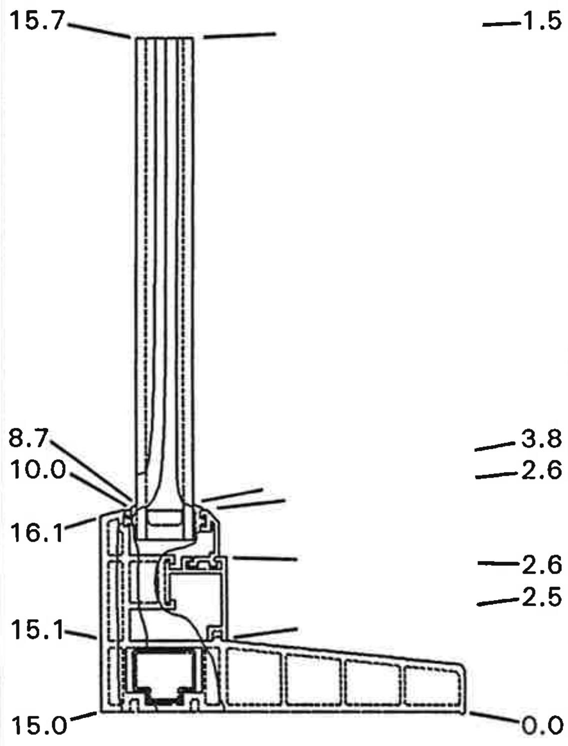
4.9 Dimensions



4.9 Ordinary 4/16/4 mm glazing



4.9 Low-e 4/16/4 mm glazing



4.10 Aluminium frame with a deep PVC-U cladding on the warm-side, and a reinforced PVC-U sill, underside of sill fully exposed

The results of this example are entirely as expected - the good thermal properties of the sill material result in a high thermal resistance, such that surface effects become negligible.

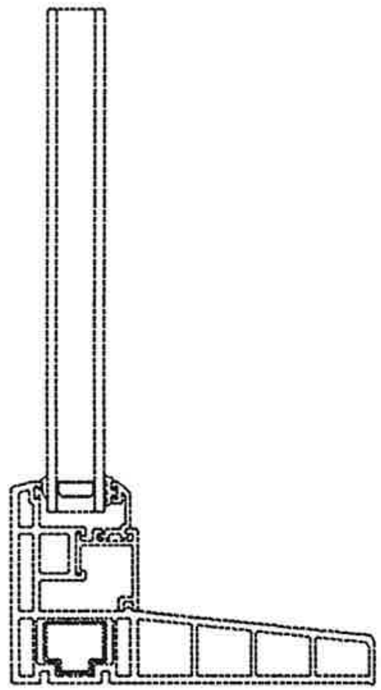
Performance

	Ordinary	Low-e	
Q_{total}	15.71	12.03	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.71	5.11	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.77	3.01	W/m²K

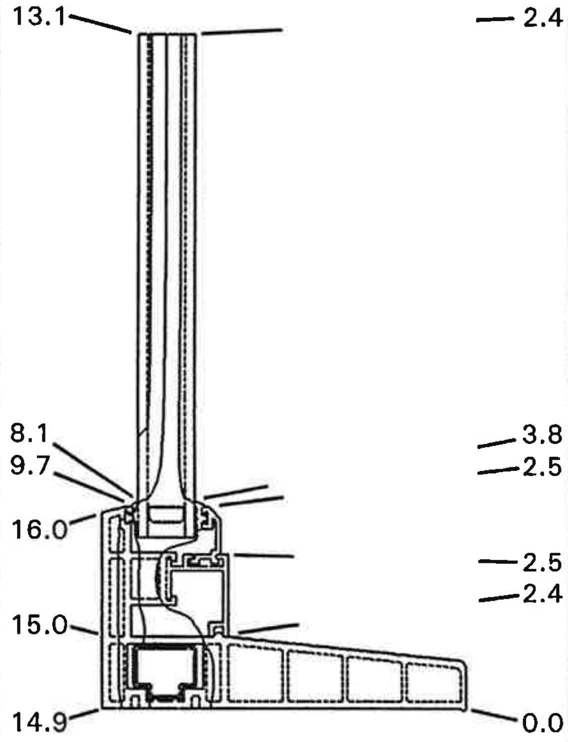
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.7

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	3.29	3.65	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	2.77	3.01	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.84	2.11	W/m²K

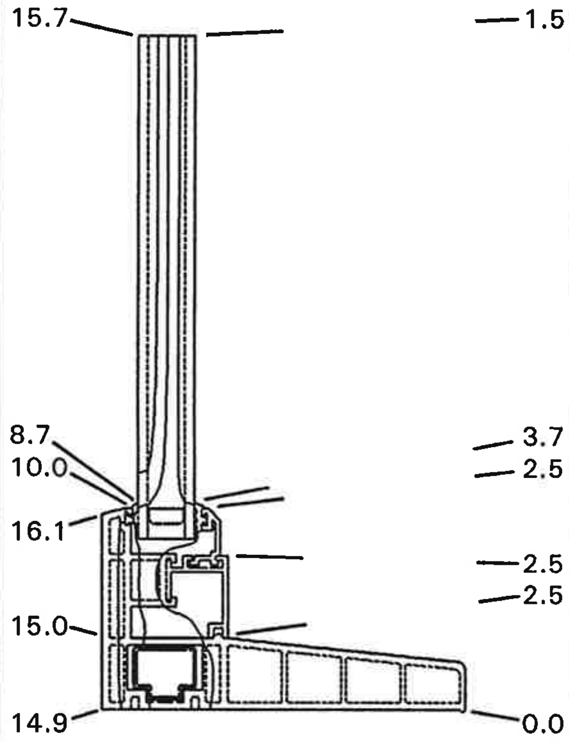
4.10 Dimensions



4.10 Ordinary 4/16/4 mm glazing



4.10 Low-e 4/16/4 mm glazing



4.11 Aluminium frame with a deep PVC-U cladding on the warm-side, and a thermally-broken aluminium sill, underside of sill covered

The addition of a good thermally broken aluminium sill gives a higher U-value than with the PVC-U sill. The thermal break in the aluminium sill does not provide as good a level of insulation as the PVC-U cladding on the main frame. The warm-side surface temperatures are all lower, but particularly on the warm-side of the sill.

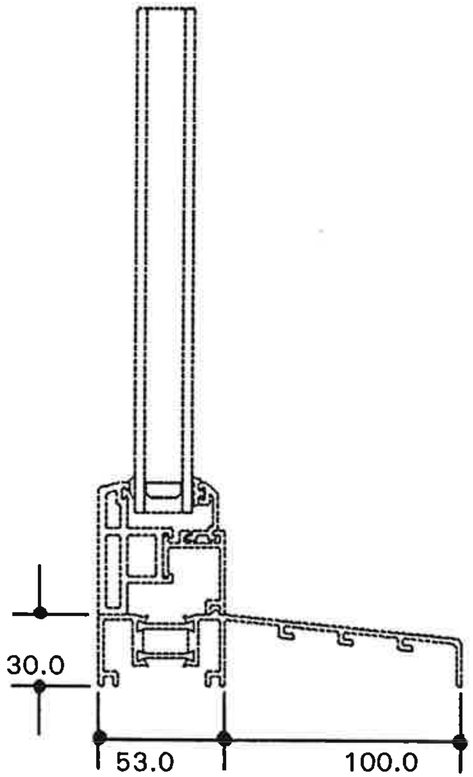
Performance

	Ordinary	Low-e	
Q_{total}	16.71	13.04	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.71	6.12	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.36	3.60	W/m²K

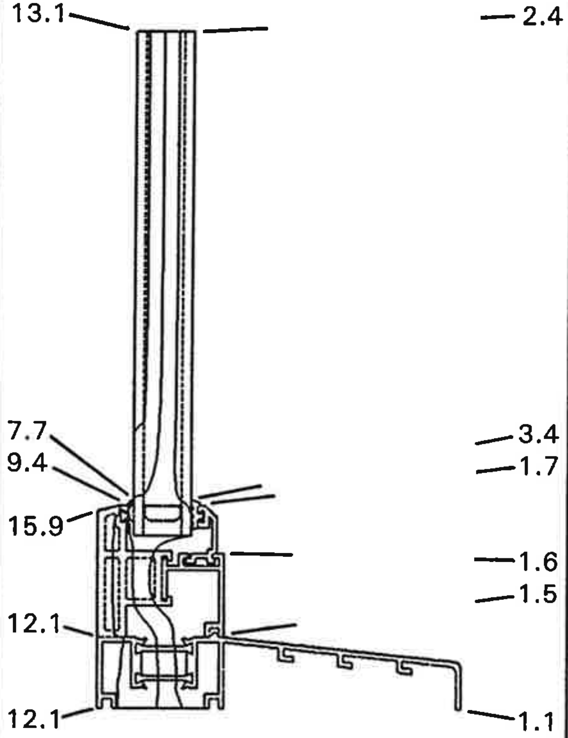
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.7

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	3.29	3.65	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	3.36	3.60	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.87	2.15	W/m²K

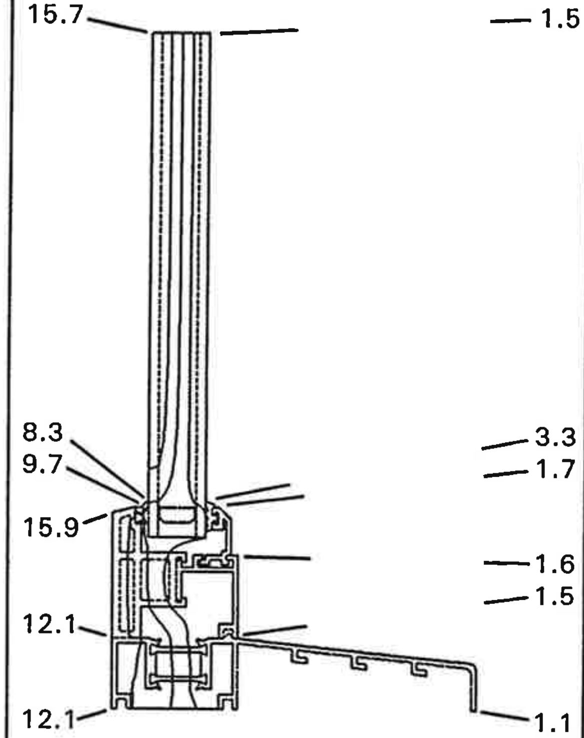
4.11 Dimensions



4.11 Ordinary 4/16/4 mm glazing



4.11 Low-e 4/16/4 mm glazing



4.12 Aluminium frame with a deep PVC-U cladding on the warm-side, and a thermally-broken aluminium sill, underside of sill fully exposed

Exposing the underside of this sill, as in example 2.11, has a more significant effect. The thermal resistance of the cold-side of the frame and sill is negligible, due to the high thermal conductivity of aluminium, and so the thermal resistance of the heat flow paths through the sill thermal break, PVC-U cladding and glazing edge detail becomes critical, with the least resistive path being most important.

In this case the warm-side surface temperatures show that the greatest reduction (compared to example 4.11) occurs for the sill, indicating that this is the weakest part of this frame. The glazing edge detail is not as significant because heat cannot flow easily into the glazing edge from the warm-side of the frame, whereas the warm-side of the sill is low resistance aluminium.

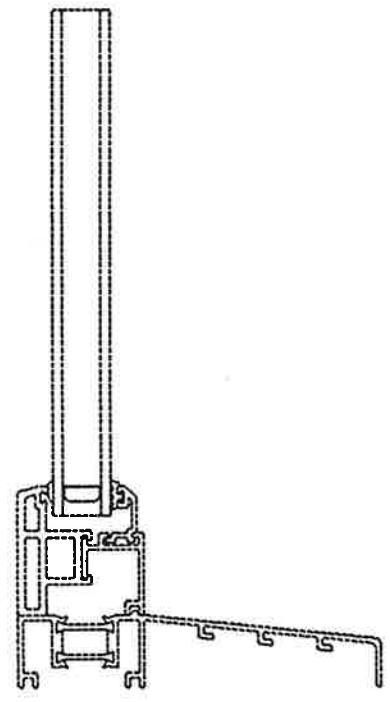
Performance

	Ordinary	Low-e	
Q_{total}	16.91	13.24	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.91	6.32	W
P_{frame}	0.085	0.085	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.48	3.72	W/m²K

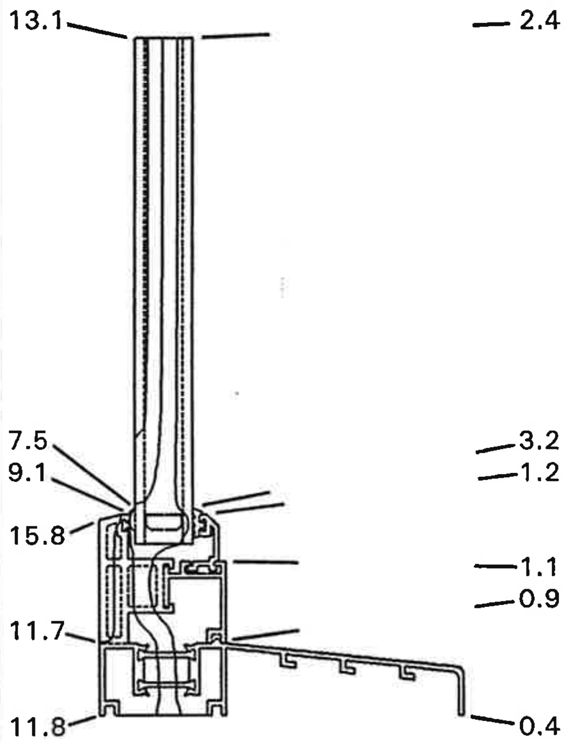
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.7

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8769	0.8769	m²
$U_{sides/top}$	3.29	3.65	W/m²K
$A_{sides/top}$	0.1763	0.1763	m²
U_{frame}	3.48	3.72	W/m²K
A_{frame}	0.0718	0.0718	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.88	2.16	W/m²K

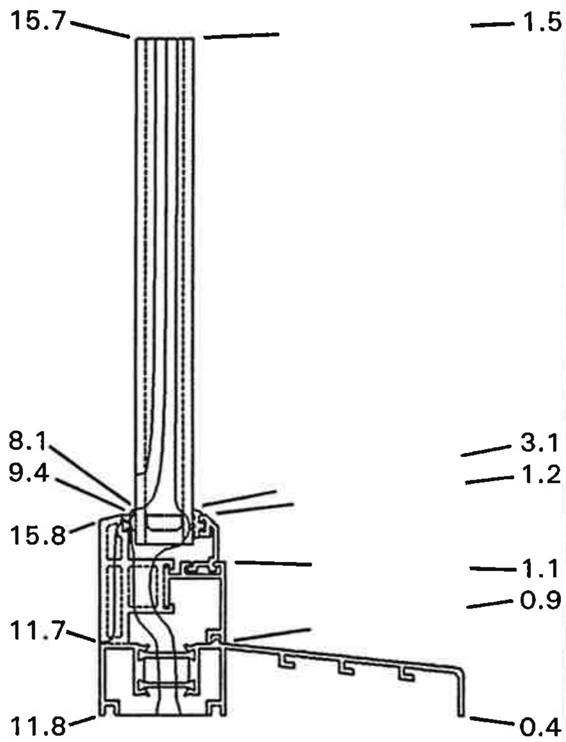
4.12 Dimensions



4.12 Ordinary 4/16/4 mm glazing



4.12 Low-e 4/16/4 mm glazing



4.13 Aluminium frame with a deep PVC-U cladding on the warm-side, and a pressed steel sill, underside of sill fully exposed

With a simple sill attached to the aluminium section of the frame the U-value is only slightly worse than for the basic frame. The main thermal resistance of the frame is still the PVC-U cladding, and the only effect of the sill is to increase the heat loss from the cold-side surface. The overall heat transfer has increased by only 0.2 Watts per metre of frame, although the exposed surface area has been increased by 400%.

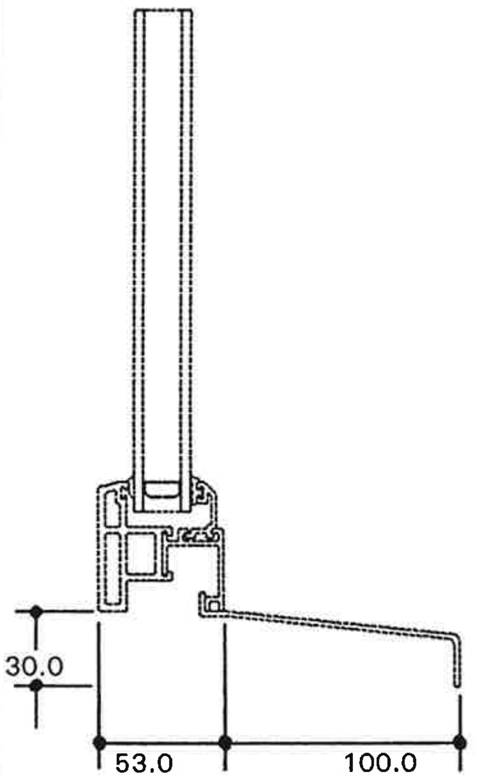
Performance

	Ordinary	Low-e	
Q_{total}	14.87	11.20	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.87	4.28	W
P_{frame}	0.057	0.057	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.39	3.75	W/m²K

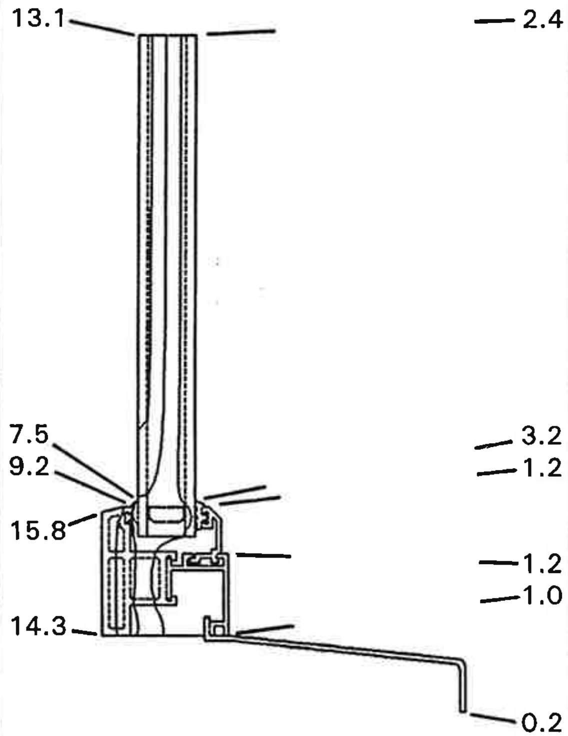
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 4.7

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.8990	0.8990	m²
$U_{sides/top}$	3.29	3.65	W/m²K
$A_{sides/top}$	0.1778	0.1778	m²
U_{frame}	3.39	3.75	W/m²K
A_{frame}	0.0482	0.0482	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.86	2.12	W/m²K

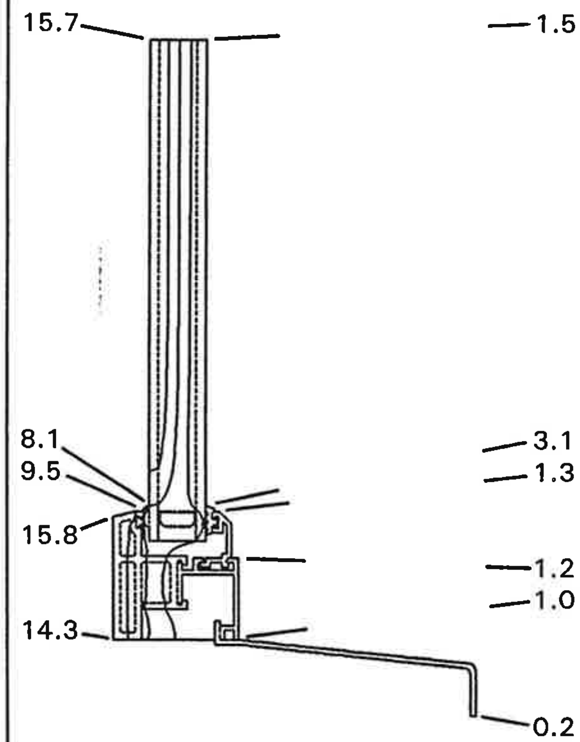
4.13 Dimensions



4.13 Ordinary 4/16/4 mm glazing



4.13 Low-e 4/16/4 mm glazing



4.14 Summary

The performance of PVC-U and PVC-U/aluminium composite frames is not dissimilar to that of timber and timber/aluminium composite frames. However, the introduction of air-filled voids within the frame can provide a better U-value.

The only drawback with timber or PVC-U frames is that the temperature at the edge of the glazing is reduced, and condensation risk at the edge of glazing is therefore greater, than when compared to an aluminium frame with a higher U-value. This demonstrates the complex nature of heat flow through a glazing frame.

An important observation of chapters 3 and 4 is that the use of any aluminium cladding on the cold-side of the frame will certainly increase the frame U-value if it is introduced at the expense of thermally-resistive timber or PVC-U. Furthermore, aluminium conducts heat so well that even a thin aluminium cladding can have a detrimental effect by eliminating the thermal resistance between any point on the aluminium surface and the edge of the glazing unit, which is often the weak link in timber and PVC-U frames.

5 Steel windows

Steel is the strongest of the window framing materials, but also the heaviest, and steel windows cannot be produced by extrusion. Steel window frames are generally made using two processes - hot rolling and cold rolling.

Hot-rolled steel frames are produced by gradually shaping a hot steel billet through a series of rollers. The cost of the rolling dies means that hot-rolled frames are based on a limited number of profiles. The profiles have a thick cross-section and are not thermally-broken. The method of fixing for these windows is different, as the steel must be factory prepared for installation, and the mounting detail is often non-symmetrical, with unequal legs on the cold-side and warm-side. The glazing unit thickness is limited by the size of the frame profile, unless special glazing platforms are used.

Cold-rolled steel profiles are formed by folding thin sheets of steel. These frames are lighter, and may be thermally-broken by the introduction of a plastic insert or the use of a rigid foam block. The profiles are similar to thermally-broken aluminium frames, although the frame cross-section is often simpler to suit the cold-rolling process. The glazing unit thickness is not limited.

Steel windows in the UK are generally based on a standard set of hot-rolled profiles which are defined in the British Standard BS 6510:1984 "Specification for Steel windows, sills, window boards and doors" as the W20 and F ranges of frames. However, the principal UK supplier of hot-rolled profiles, Darlington and Simpson Rolling Mills Plc, also produce a "500 series" of profiles, and it is a frame based on one of these profiles that has been assessed in the first examples of this chapter.

Steel windows in mainland Europe are based on cold-rolled profiles, and so the second part of this chapter examines a typical design of thermally-broken cold-rolled window frame. Note that for the hot-rolled frame the glazing edge is fully bedded in a non-setting butyl sealant, whilst the cold-rolled frame uses a butyl tape sealant on the cold-side and an EPDM wedge gasket on the warm-side.

5.1 Hot-rolled steel frame in timber sub-frame, with 4/8/4 mm glazing

This frame has been based on the dimensions of the DSRM Plc 537 profile. This particular profile allows the direct use of glazing units up to 16 or 18 mm in thickness - for thicker glazing units it is necessary to introduce some form of extended glazing platform. A timber sub-frame has been introduced to compensate for the unequal leg length of this frame, and to increase the projected width of the frame to the standard 55.0 mm used in this study.

The thinner glazing unit has a higher centre-glazing U-value. However, the non-thermally-broken frame also has a high U-value. Importantly the use of a timber sub-frame in this example artificially lowers the U-value. If the sub-frame were omitted then the heat transfer would not be substantially reduced, and the U-value based on the smaller projected frame width would be somewhat higher. This demonstrates the inherent difficulties in comparing frames of different sizes when only considering the frame U-value.

Significantly, the temperature on the warm-side surface of the steel frame is low, and there is a greater risk of condensation. Most noticeably the edge-of-glazing is warmer than the frame, indicating that heat transfer occurs from the inner pane of glass to the frame, and from the frame to the outer pane of glass, as with the non-thermally-broken aluminium frame of example 2.1.

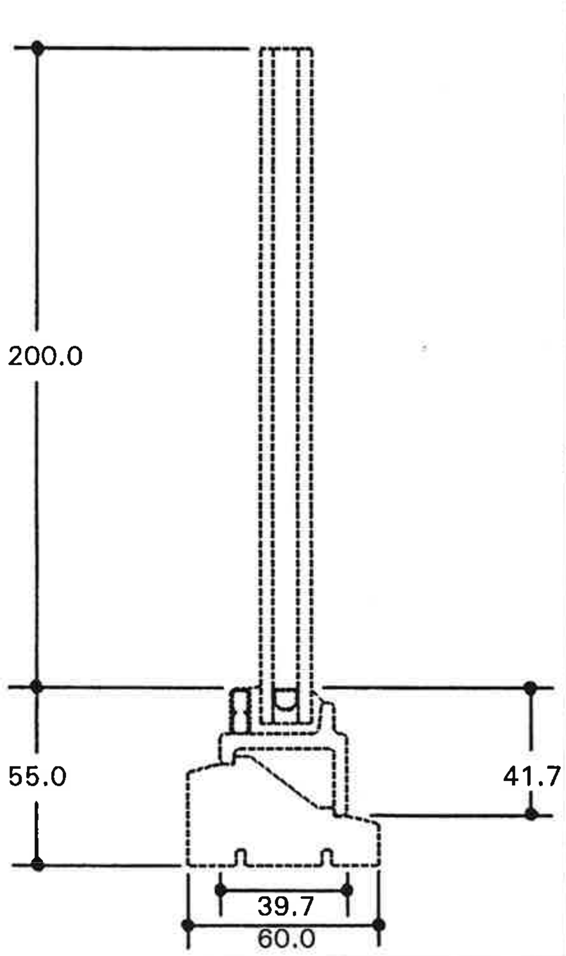
Performance

	Ordinary	Low-e	
Q_{total}	18.93	16.17	W
U_{glass}	3.11	2.34	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	12.44	9.36	W
Q_{frame}	6.49	6.81	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	5.90	6.19	W/m²K

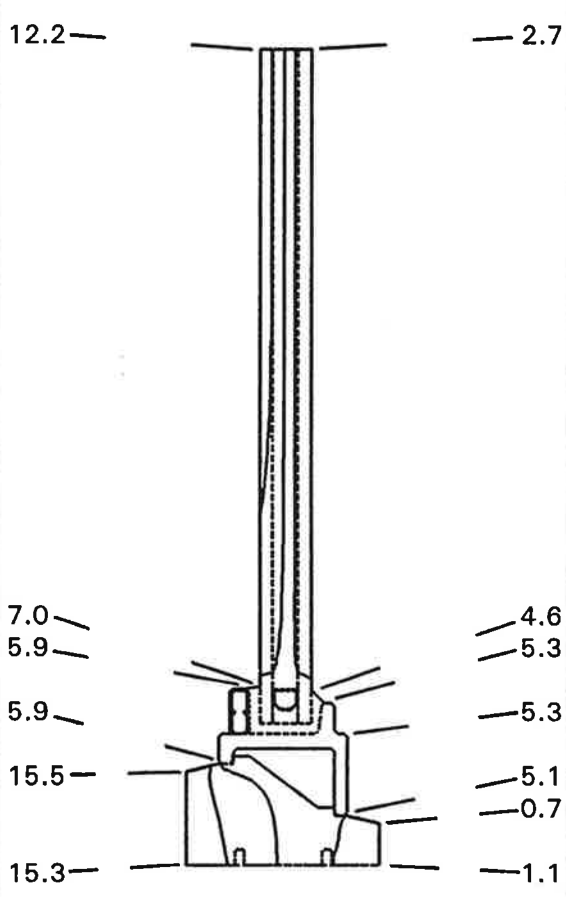
Typical window, 900 mm wide × 1250 mm high

U_{glass}	3.11	2.34	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	5.90	6.21	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.67	3.11	W/m²K

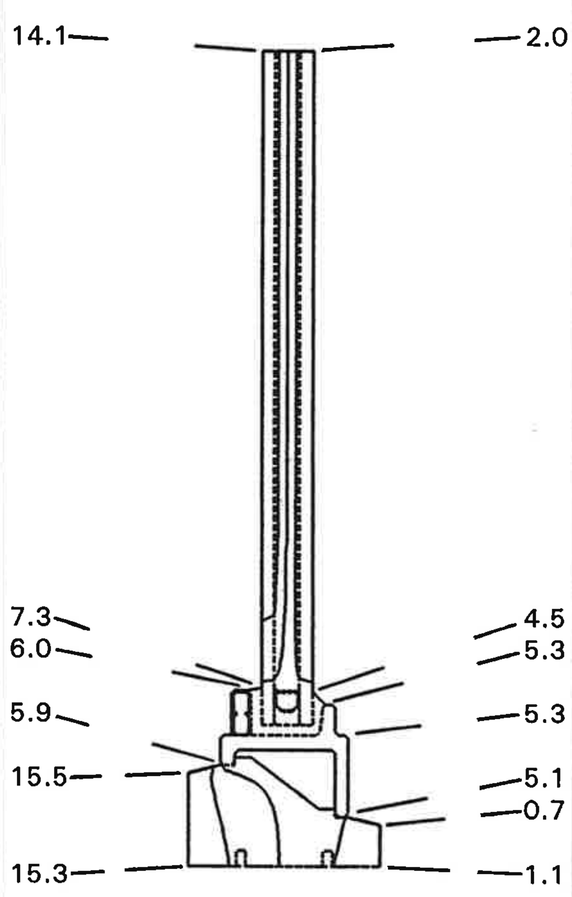
5.1 Dimensions



5.1 Ordinary 4/8/4 mm glazing



5.1 Low-e 4/8/4 mm glazing



5.2 Hot-rolled steel frame in timber sub-frame, with 4/8/4 mm glazing and PVC-U cold-side cladding

It is not essential that thermal breaks are placed between the warm-side and cold-side frame sections. A suitable material can be placed over one of the exposed surfaces, as demonstrated with the composite frames of examples 3.10 and 4.6. However, placing an insulating material on the warm-side of a steel frame may trap condensation in contact with the steel, with a risk of corrosion in the long term. This example considers the alternative of a PVC-U cladding on the cold-side surface of the frame, similar to example 4.8.

It is clear that the U-value is reduced, as is the condensation risk on the warm-side frame surface. The use of a frame with a greater warm-side surface area may improve the condensation performance even further, although at the risk of increasing the U-value, as demonstrated in example 2.6.

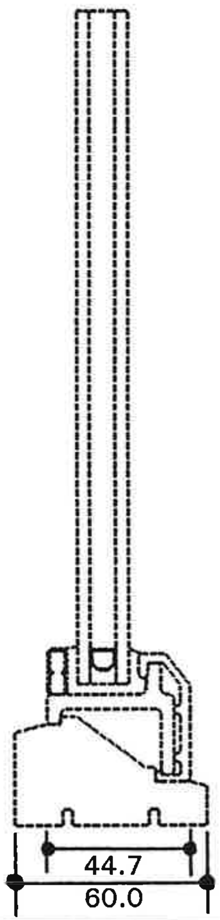
Performance

	Ordinary	Low-e	
Q_{total}	17.75	14.97	W
U_{glass}	3.11	2.34	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	12.44	9.36	W
Q_{frame}	5.31	5.61	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.83	5.10	W/m^2K

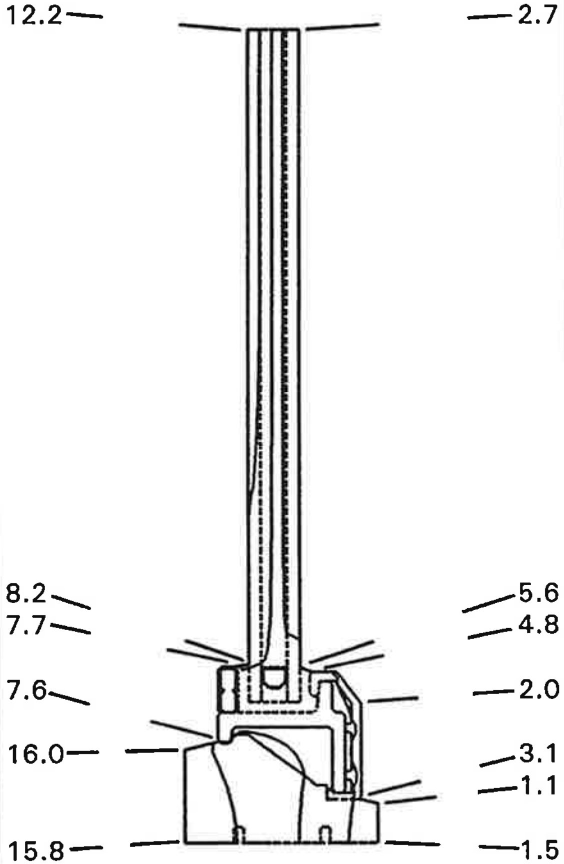
Typical window, 900 mm wide × 1250 mm high

U_{glass}	3.11	2.34	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	4.83	5.10	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.45	2.89	W/m^2K

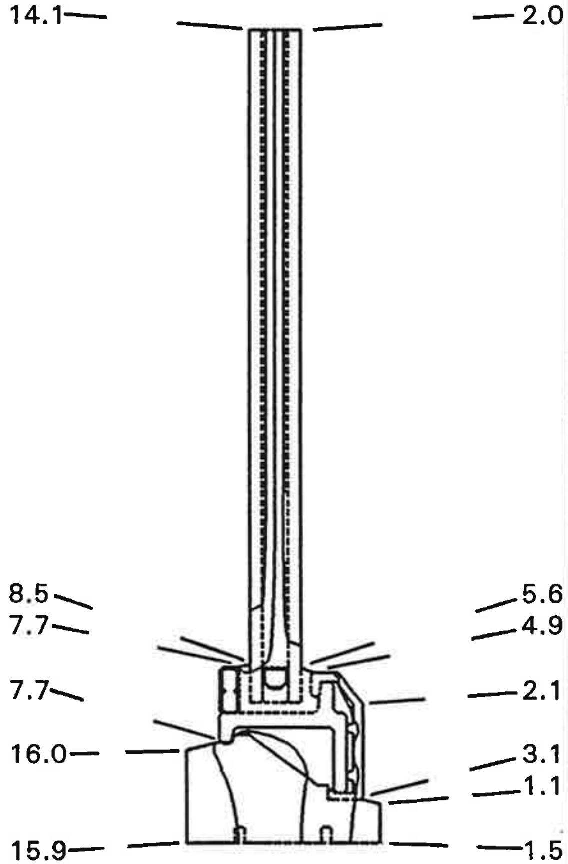
5.2 Dimensions



5.2 Ordinary 4/8/4 mm glazing



5.2 Low-e 4/8/4 mm glazing



5.3 Cold-rolled steel frame with extruded PVC-U thermal break

Cold-rolled steel frames may incorporate a variety of thermal breaks. In this case a simple extruded PVC-U thermal break is used. This frame uses a standard 4/16/4 mm glazing unit, and is internally beaded.

The U-value of this frame is seen to be identical to a thermally-broken aluminium frame, such as those of examples 2.2 and 2.3. Note that the warm-side surface area is increased, giving a good resistance to condensation.

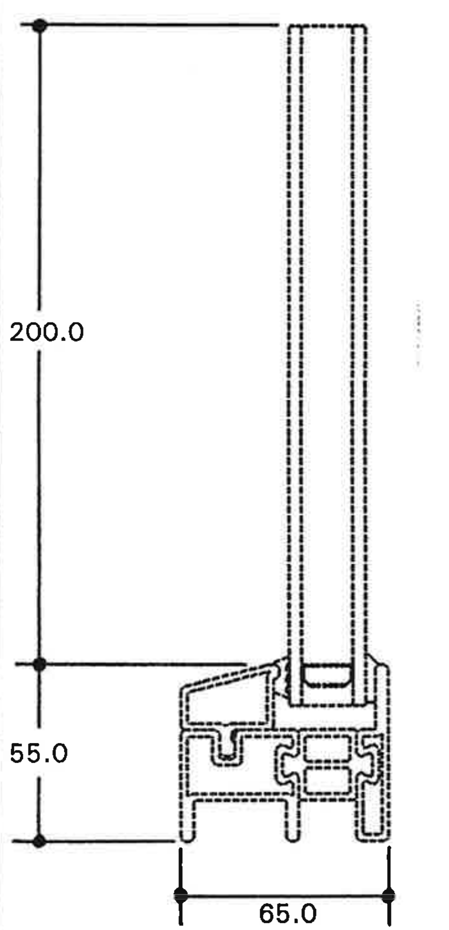
Performance

	Ordinary	Low-e	
Q_{total}	16.04	12.31	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.04	5.39	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.58	4.90	W/m²K

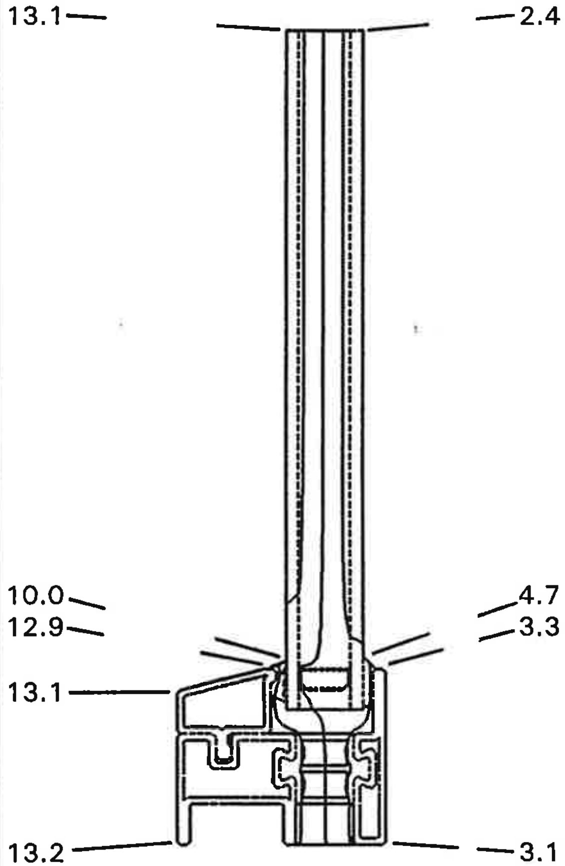
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.58	4.90	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.12	2.36	W/m²K

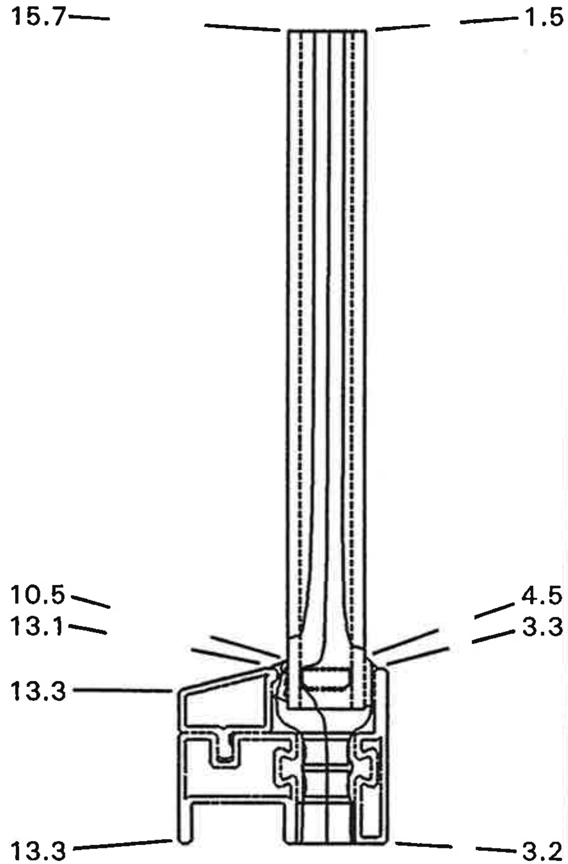
5.3 Dimensions



5.3 Ordinary 4/16/4 mm glazing



5.3 Low-e 4/16/4 mm glazing



5.4 Cold-rolled steel frame with extruded PVC-U thermal break and pressed steel sill, underside of sill fully exposed

A simple pressed steel sill is readily added to this type of frame, but the sill must be attached to the cold-side of the frame, as demonstrated in chapter 2.

The addition of the sill increases the heat loss through the frame. The warm-side surface temperatures are also slightly reduced. Although the cold-side surface area has been increased by about 400% this has a comparatively small effect on overall performance. The cold-side surface resistance is already very low, and so an increase in the surface area has a reduced effect on heat loss.

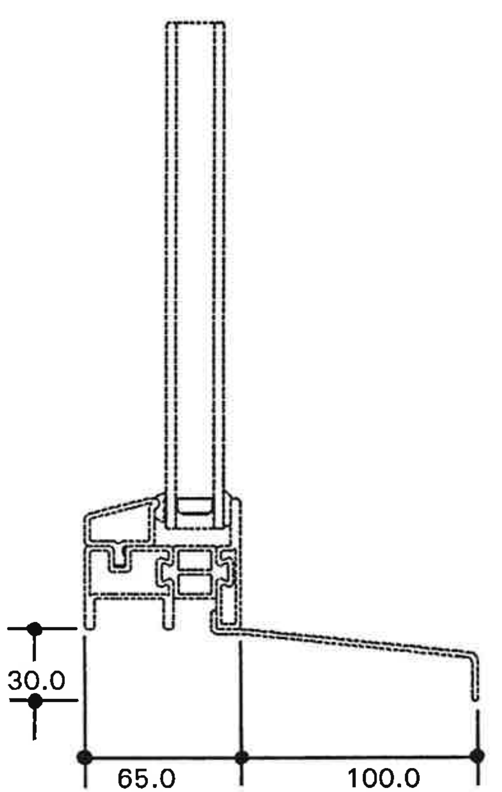
Performance

	Ordinary	Low-e	
Q_{total}	16.52	12.80	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	5.52	5.88	W
P_{frame}	0.057	0.057	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.84	5.16	W/m^2K

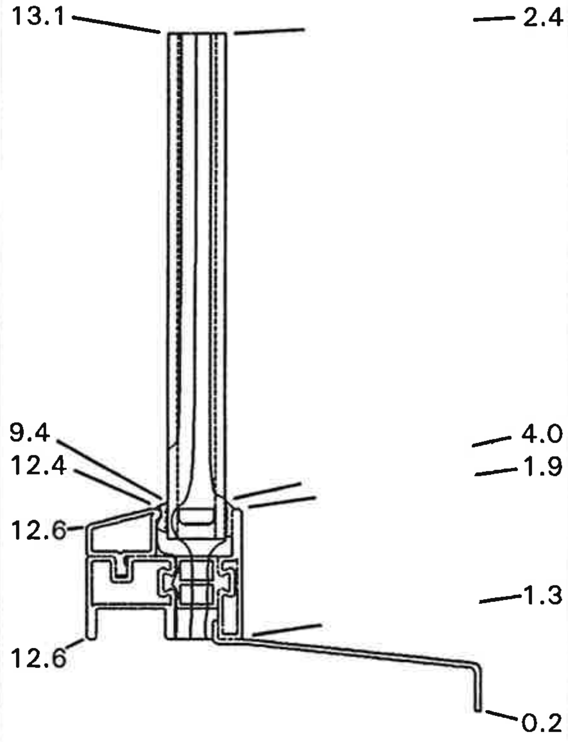
Typical window, 900 mm wide × 1250 mm high, sides and top as basic frame of example 5.3

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.8990	0.8990	m^2
$U_{sides/top}$	4.58	4.90	W/m^2K
$A_{sides/top}$	0.1778	0.1778	m^2
U_{frame}	4.84	5.16	W/m^2K
A_{frame}	0.0482	0.0482	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	3.13	2.38	W/m^2K

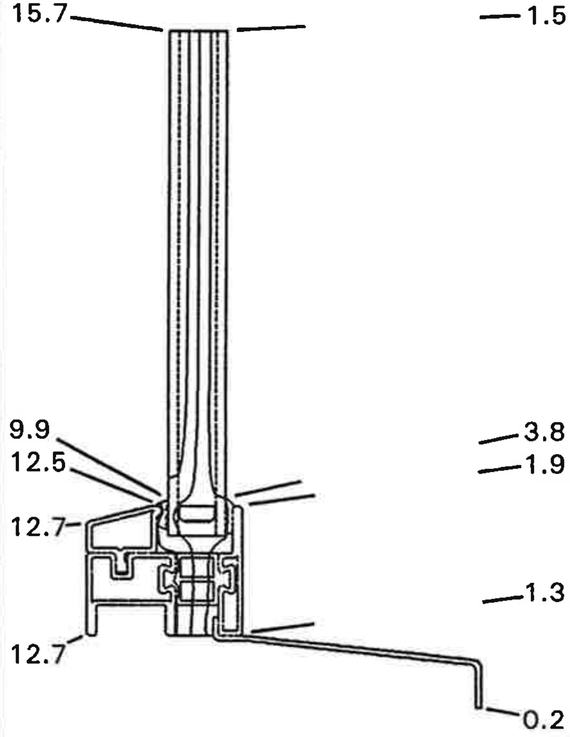
5.4 Dimensions



5.4 Ordinary 4/16/4 mm glazing



5.4 Low-e 4/16/4 mm glazing



5.5 Summary

Traditional British steel windows, based on non-thermally-broken hot-rolled frames, have the highest heat loss of any type of frame considered here. However, it is shown here that thermally-broken cold-rolled steel frames have U-values comparable to thermally broken aluminium frames. This type of frame is already used in other European countries, and there are several manufacturers using a range of thermal breaks.

The use of steel highlights the same issues of thermal performance as for aluminium frames. However, steel is considerably stronger than aluminium and offers advantages in other areas of performance.

A wider consideration of aluminium and steel frame performance demonstrates that there are many performance issues which influence the selection of frame material, and compromise is often essential. However, there are simple design rules which can be used to minimise heat loss through metal-based frames.

6 Warm edge technology glazing spacers used in windows

A common observation of several examples in this study is that the edge detail of the glazing unit is often a weak link in the performance of the window frame. The application of thermally-resistant glazing spacers, referred to as "warm edge technology", was developed to improve the performance of the glazing near the frame, with the principal intention of increasing surface temperatures and reducing the incidence of condensation at the edge of the glazing. It has also been shown in this study that the use of a low-emissivity coating on the glass increases heat transfer through the edge of the glazing unit, and that as the centre glazing U-value is improved further then the performance of the glazing edge becomes even more critical.

There are several different types of warm edge spacer, and most are based on polymer materials with a low thermal conductivity, although there are thin-walled stainless steel spacers which provide a warm edge function.

The objective of this chapter is to examine the performance of various types of warm edge spacer, and to show that they do provide an improvement in performance over a traditional aluminium spacer. However, it should be noted that better aluminium spacers may be developed, in which the length of the heat transfer path is increased.

It is not the intention in this chapter to identify any one spacer as the best. The pace of development is rapid, and the user must bear in mind that there are several other performance criteria that must be considered, most significantly durability, thermal expansion and reaction to long term exposure to solar radiation.

As might be expected with any new technology there is some reluctance to make use of warm edge spacers until questions of durability have been answered. However, an extensive Canadian and North American experience of warm edge technology is already providing relevant data, and some warm edge spacers have already been shown in standard tests, for glazing edge details, to equal the performance of aluminium spacers.

The first examples in this chapter are based on the thermally-broken aluminium frame of example 2.7, which was shown to have a frame U-value of 4.29 W/m^2K with ordinary glazing, and 4.62 W/m^2K with low-e glazing, when using a traditional all-aluminium glazing spacer. To provide a more rapid means of reference the results of example 2.7 are repeated overleaf.

The remaining examples of this chapter take the warm edge spacer considered in example 6.1 and examine its effect in various frames taken from previous chapters of this study.

2.7 Aluminium frame with long extruded polyamide thermal break, internally beaded

This example is repeated here as an aid to reference. Comments relating to this frame are given in example 2.7.

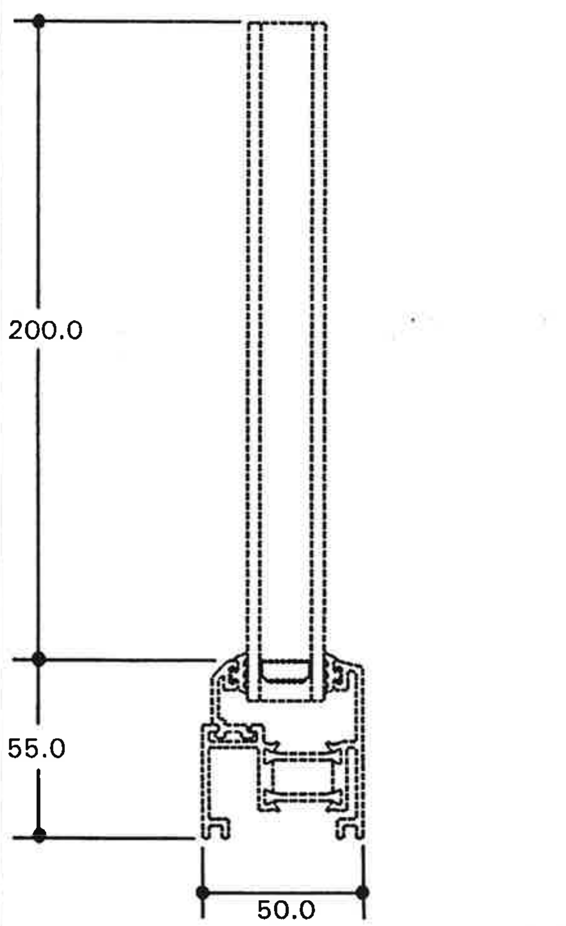
Performance

	Ordinary	Low-e	
Q_{total}	15.72	12.00	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.72	5.08	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.29	4.62	W/m²K

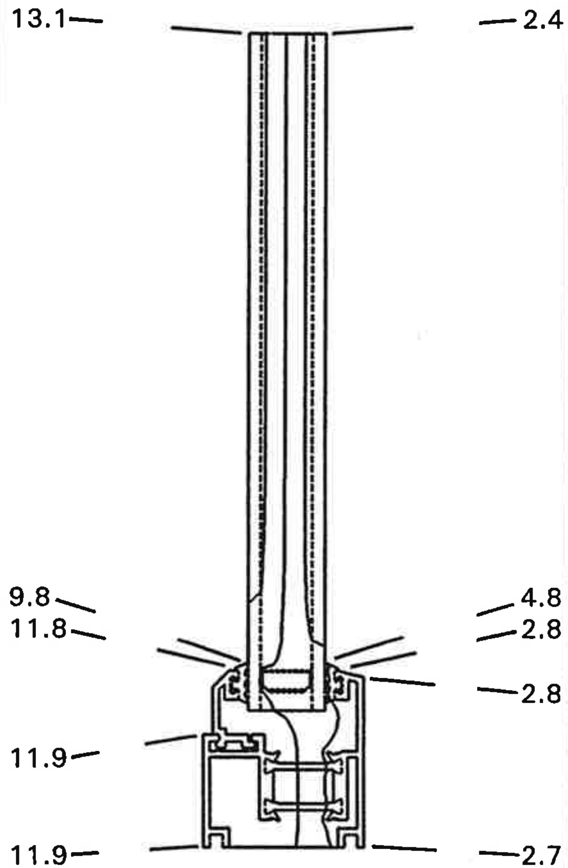
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.29	4.62	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.06	2.31	W/m²K

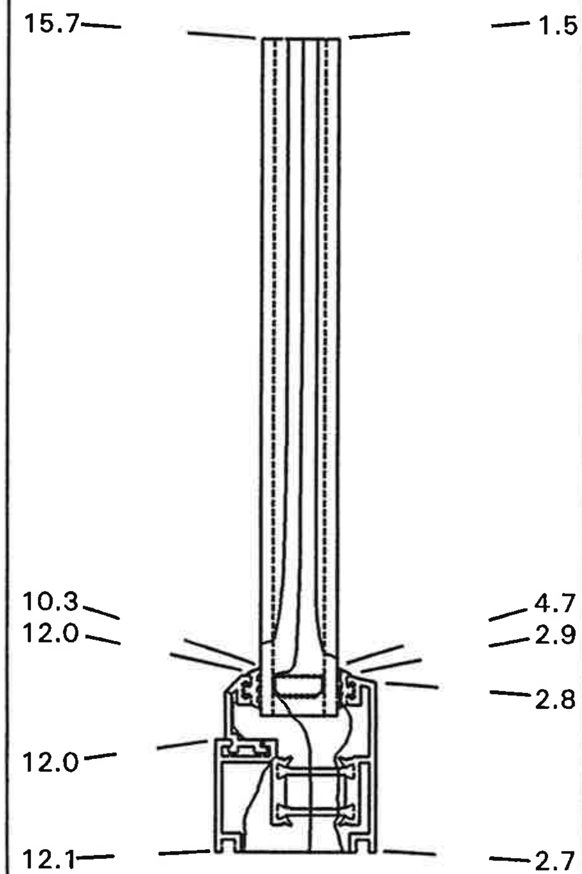
2.7 **Dimensions**



2.7 **Ordinary 4/16/4 mm glazing**



2.7 **Low-e 4/16/4 mm glazing**



6.1 Aluminium spacer with simple pour-and-de-bridge thermal break

The idea of introducing a resin pour-and-de-bridge thermal break to an aluminium spacer is a simple one, based on tried and tested technology. Initial designs of this type of spacer had a narrow de-bridging cut, typically 1.5 mm as in the example shown here.

It is clear that the U-value of the frame has been reduced by 10% simply by using this basic warm edge spacer. The minimum temperature on the warm-side of the glazing has been increased by 1.1°C, and the warm-side of the frame is increased in temperature by 0.6°C. The temperature difference across the warm-side gasket has therefore decreased from 2.0°C to 1.5°C (with ordinary glazing), representing a reduction of 25% in the local heat transfer through the glazing gasket.

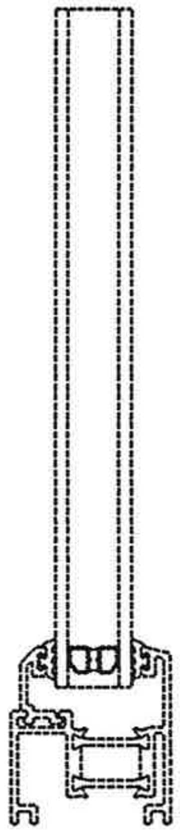
Performance

	Ordinary	Low-e	
Q_{total}	15.26	11.46	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.26	4.54	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.87	4.13	W/m²K

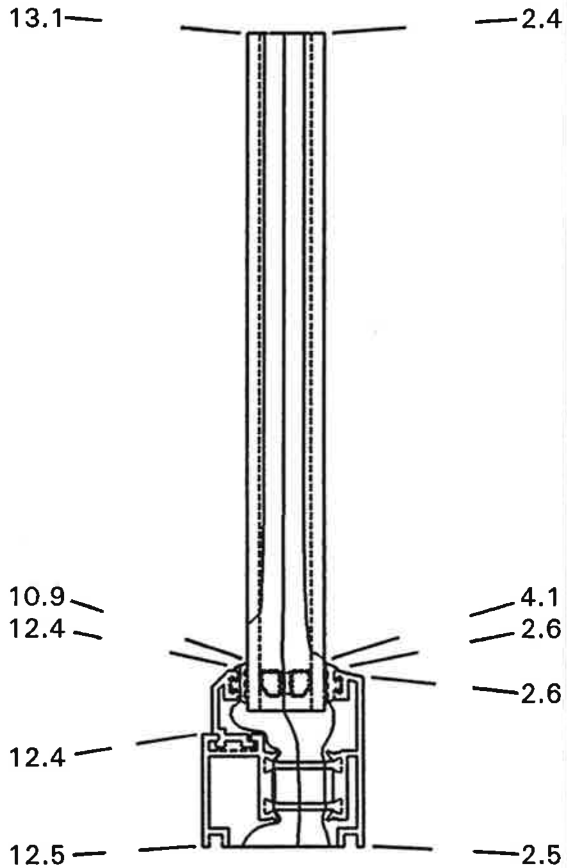
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.87	4.13	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.97	2.21	W/m²K

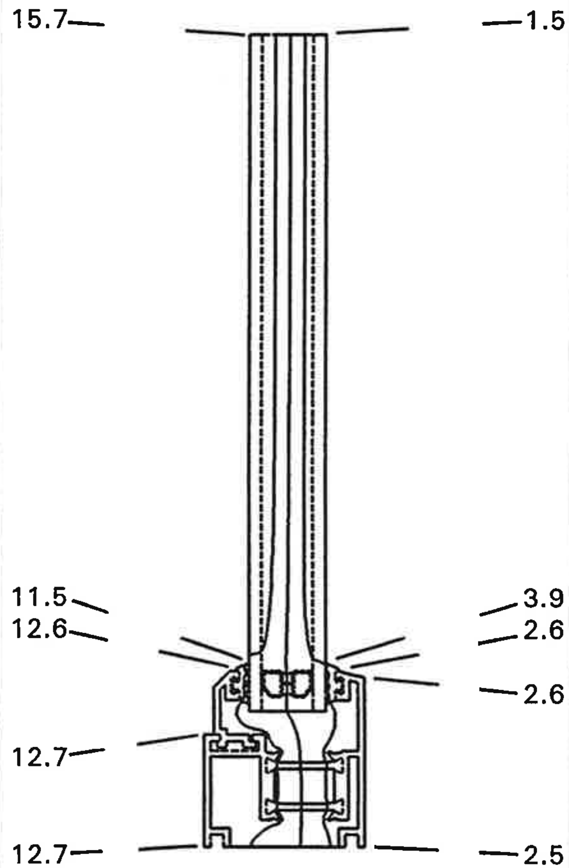
6.1 Dimensions



6.1 Ordinary 4/16/4 mm glazing



6.1 Low-e 4/16/4 mm glazing



6.2 Aluminium spacer with wide pour-and-de-bridge thermal break

This spacer is of the same type as the previous example, but with a wider de-bridging cut of 6 mm.

The U-value of the frame has been reduced by a further 10%. The minimum temperature on the warm side of the glazing has been increased by about 2°C from the original non-thermally-broken aluminium glazing spacer. This represents a significant improvement in performance.

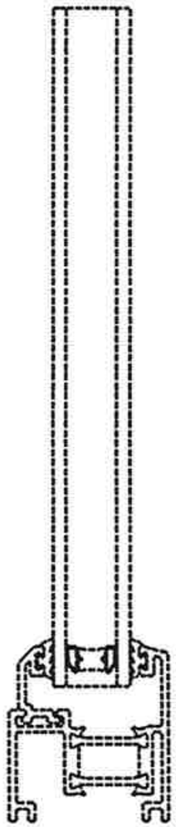
Performance

	Ordinary	Low-e	
Q_{total}	14.88	11.02	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.88	4.10	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.53	3.73	W/m²K

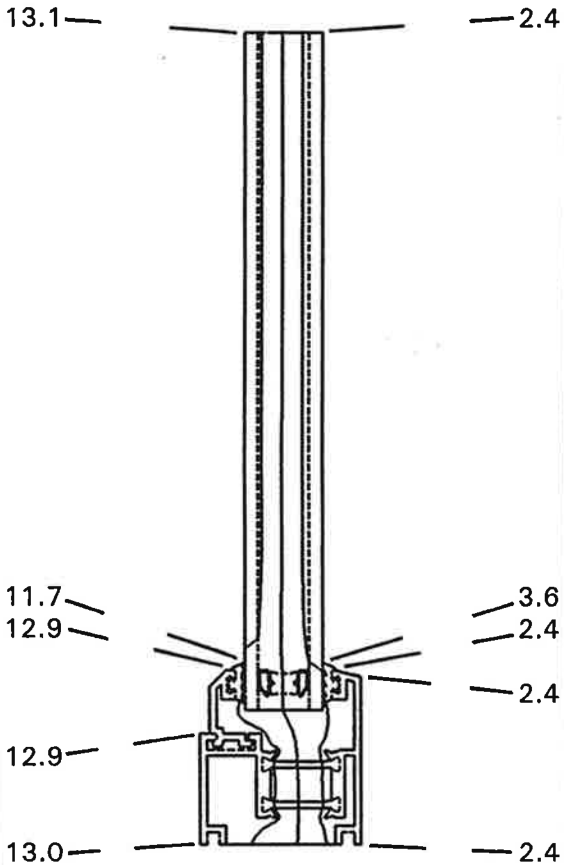
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.53	3.73	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.91	2.13	W/m²K

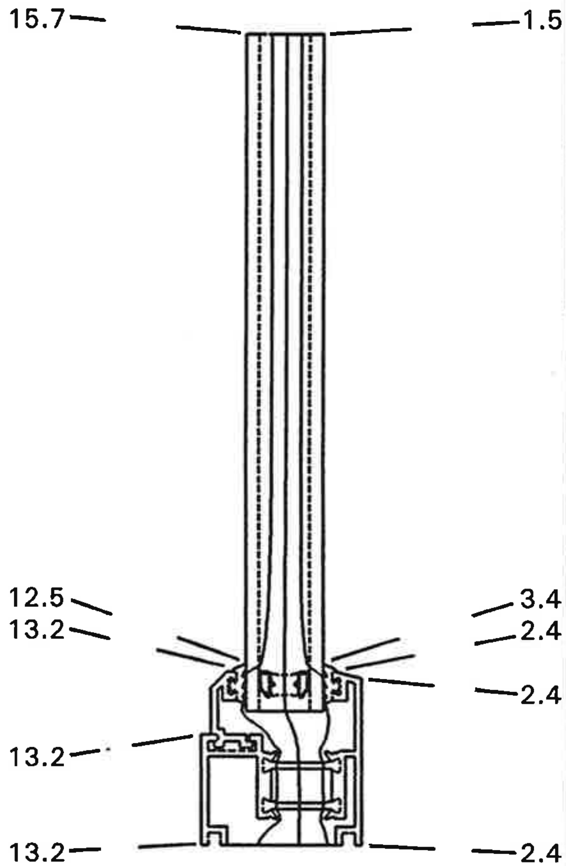
6.2 Dimensions



6.2 Ordinary 4/16/4 mm glazing



6.2 Low-e 4/16/4 mm glazing



6.3 Butyl spacer with aluminium reinforcement

This type of spacer is formed from a non-setting butyl sealant, with a desiccant blended into the butyl, and a corrugated aluminium strip used to reinforce the sealant. This type of spacer has the advantage that it does not require any additional sealants and is flexible, allowing acute corners to be negotiated.

The performance of this spacer is a little better than the first pour-and-de-bridge spacer. However, the aluminium strip still provides a cold-bridge through much of the spacer width, although the aluminium strip is only 0.2 mm thick, compared to a typical 0.35-0.5 mm for each side of a traditional aluminium spacer.

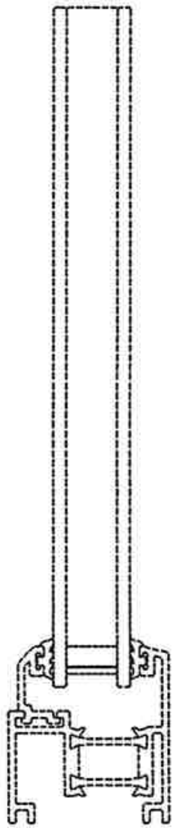
Performance

	Ordinary	Low-e	
Q_{total}	15.17	11.35	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.17	4.43	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.79	4.03	W/m²K

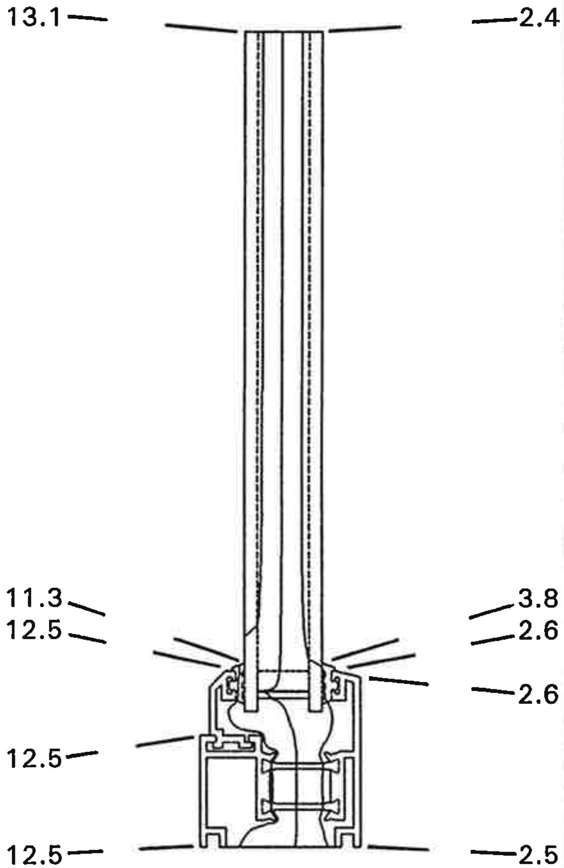
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.79	4.03	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.96	2.19	W/m²K

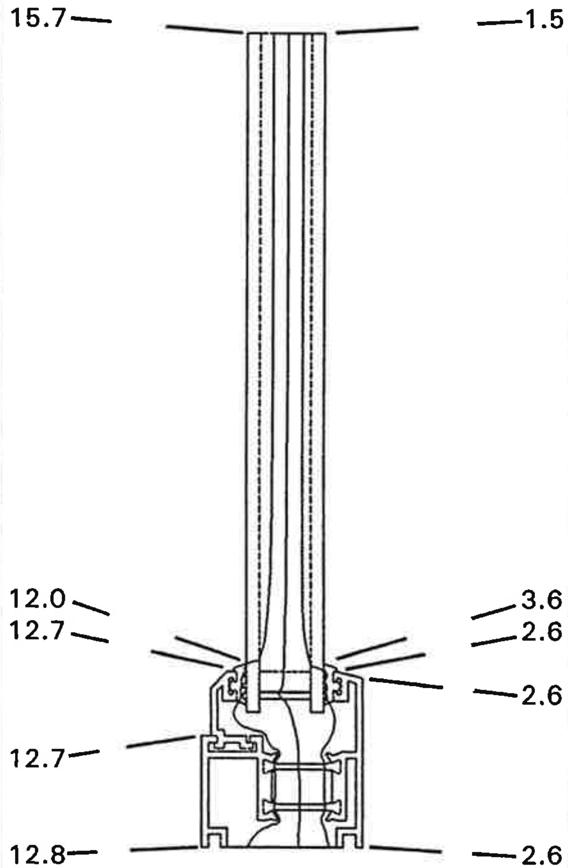
6.3 Dimensions



6.3 Ordinary 4/16/4 mm glazing



6.3 Low-e 4/16/4 mm glazing



6.4 Butyl spacer with stainless steel reinforcement

Some grades of stainless steel have a thermal conductivity less than one-tenth of that of aluminium. Furthermore the increased strength of stainless steel allows thinner strips to be used. This spacer is identical to that considered in example 6.4, except that the reinforcement is a 0.1 mm thick strip of corrugated stainless steel.

The U-value is some 20% less than that obtained using the traditional aluminium spacer. The warm-side surface temperatures are again 2°C higher, and the temperature difference across the warm side glazing gaskets is only 50% of that seen with the traditional aluminium spacer for the ordinary glazing, and 25% of that for the low-e glazing, representing a significant reduction in heat transfer through the edge of the glazing unit.

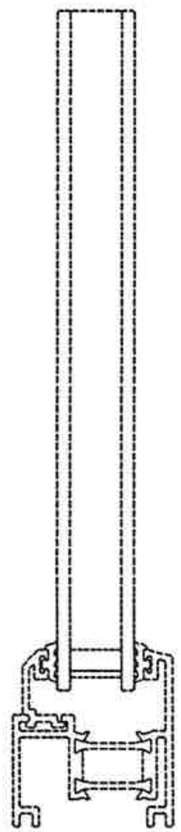
Performance

	Ordinary	Low-e	
Q_{total}	14.73	10.84	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.73	3.92	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.39	3.56	W/m²K

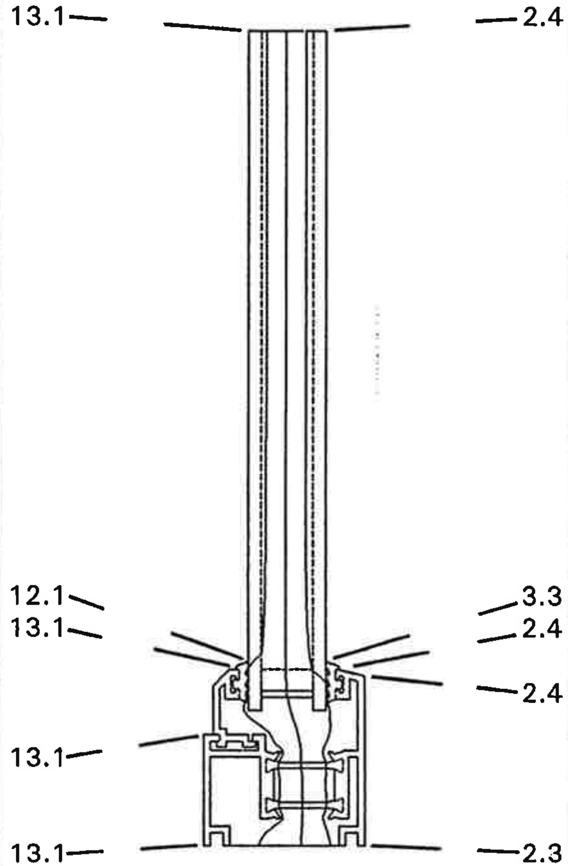
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.39	3.56	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.88	2.10	W/m²K

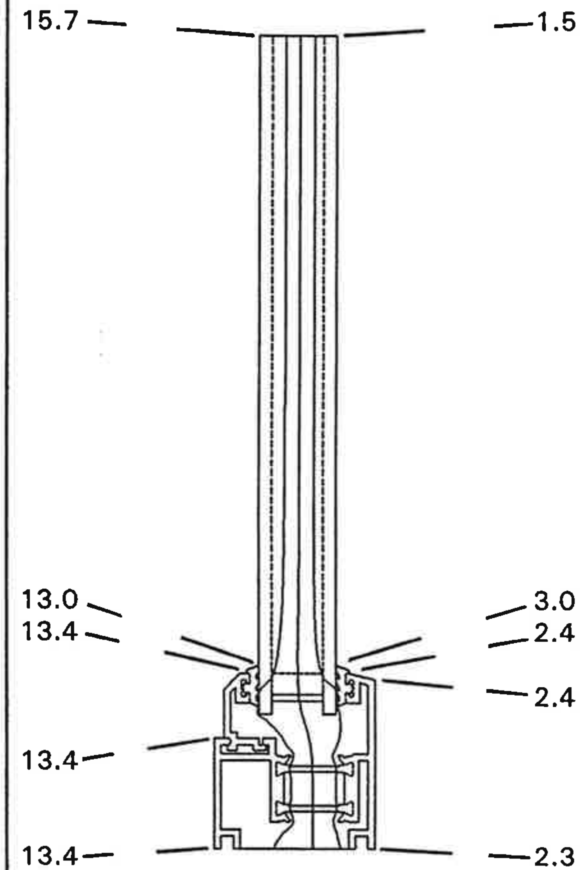
6.4 Dimensions



6.4 Ordinary 4/16/4 mm glazing



6.4 Low-e 4/16/4 mm glazing



6.5 Low density foam rubber spacer

Foam rubber spacers have the advantage that metal is completely eliminated from the spacer. However, it is known that the thermal conductivity of any polymer foam is dependent on its density, and so two alternatives are considered in this example and the next.

The spacer considered in this example has a thermal conductivity of 0.12 W/mK, which might be appropriate for a lower density foam. Note that this spacer is flexible, able to follow corners, and the desiccant is incorporated into the silicone foam.

This spacer clearly has excellent thermal properties, offering a reduction of 25% in the frame U-value. The warm-side glazing surface temperature is increased by 2.5°C, and with low-e glazing the temperature difference across the warm side glazing gasket is negligible.

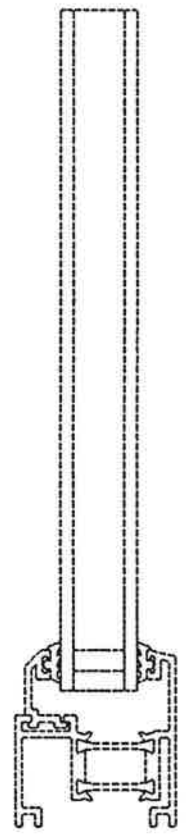
Performance

	Ordinary	Low-e	
Q_{total}	14.57	10.65	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.57	3.73	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.25	3.39	W/m²K

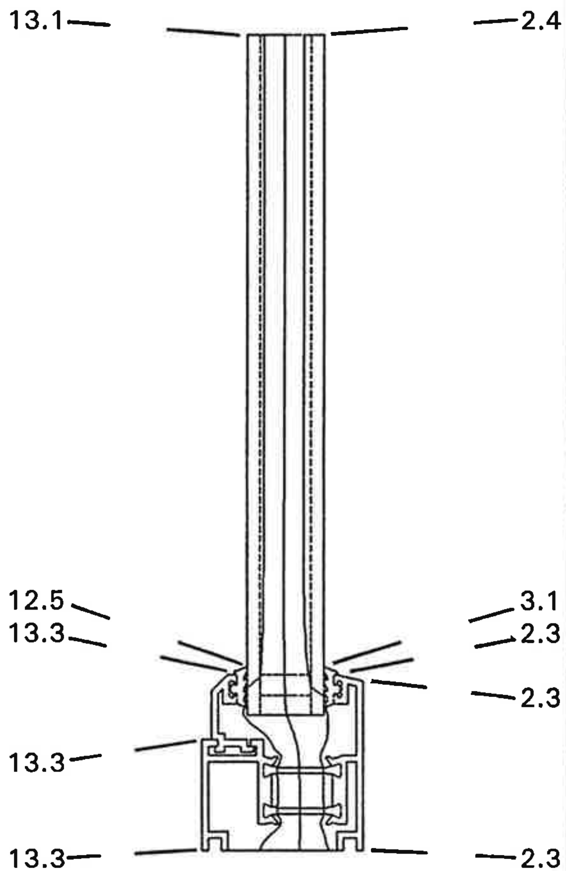
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.25	3.39	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.85	2.06	W/m²K

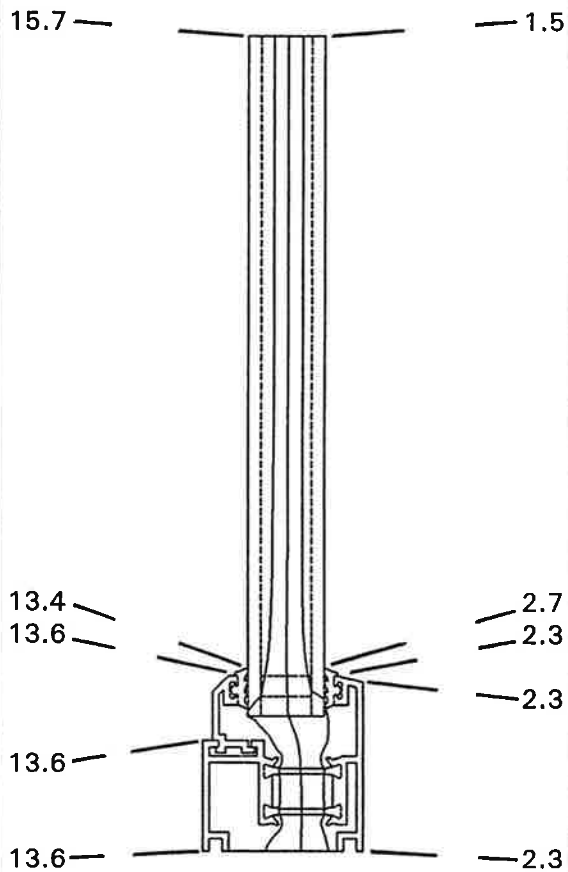
6.5 Dimensions



6.5 Ordinary 4/16/4 mm glazing



6.5 Low-e 4/16/4 mm glazing



6.6 High density foam rubber spacer

This foam rubber spacer has a higher thermal conductivity of 0.22 W/mK, consistent with a higher density. As expected this spacer is not as good as the foam spacer considered in the previous example, but it still offers very good performance, comparable with the spacers of the previous examples.

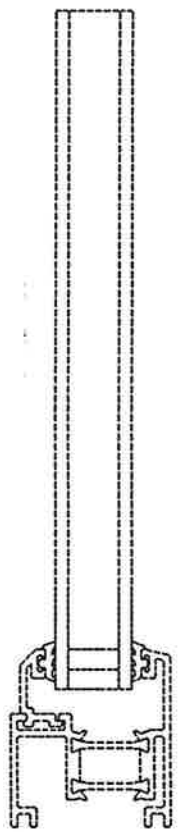
Performance

	Ordinary	Low-e	
Q_{total}	14.69	10.79	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.69	3.87	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.35	3.52	W/m²K

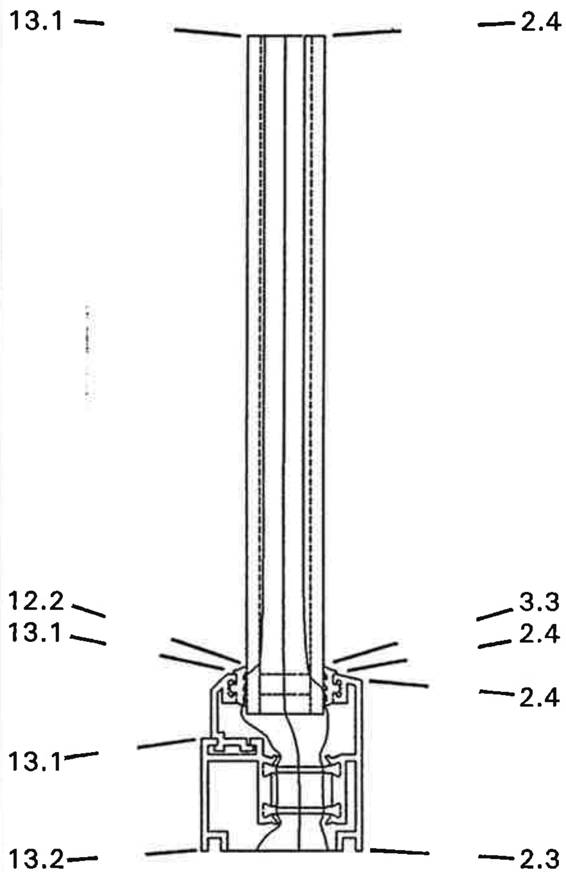
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.35	3.52	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.87	2.09	W/m²K

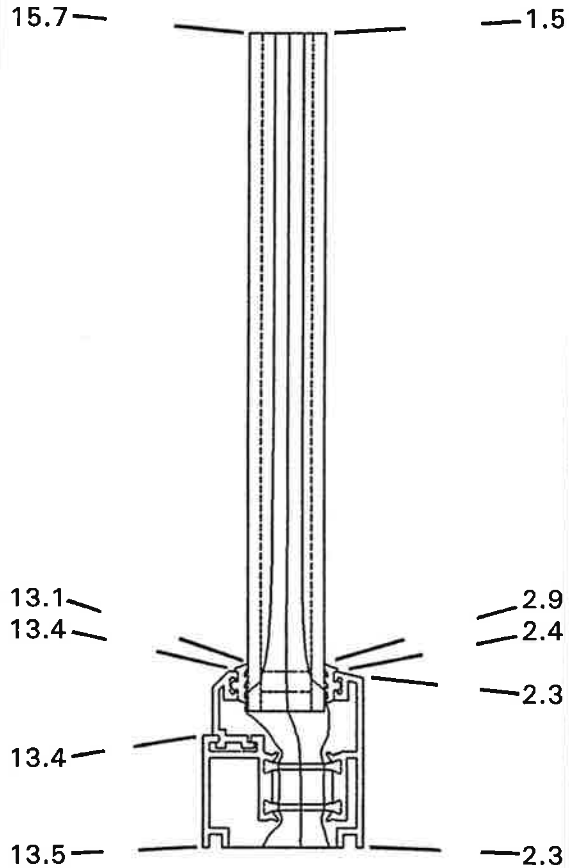
6.6 Dimensions



6.6 Ordinary 4/16/4 mm glazing



6.6 Low-e 4/16/4 mm glazing



6.7 Thin-walled stainless steel spacer

Stainless steel has much better thermal properties than aluminium. This spacer is made from thin corrugated stainless steel, with a wall thickness of just 0.1 mm.

The performance of this spacer is similar to those considered previously. A reduction of about 15% in the frame U-value is accompanied by a 1°C increase in the warm-side surface temperature of the glazing, and a clear reduction in the heat transfer through the warm-side glazing gasket.

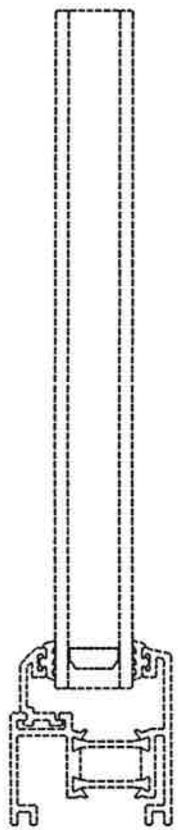
Performance

	Ordinary	Low-e	
Q_{total}	15.03	11.20	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.03	4.28	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.66	3.89	W/m²K

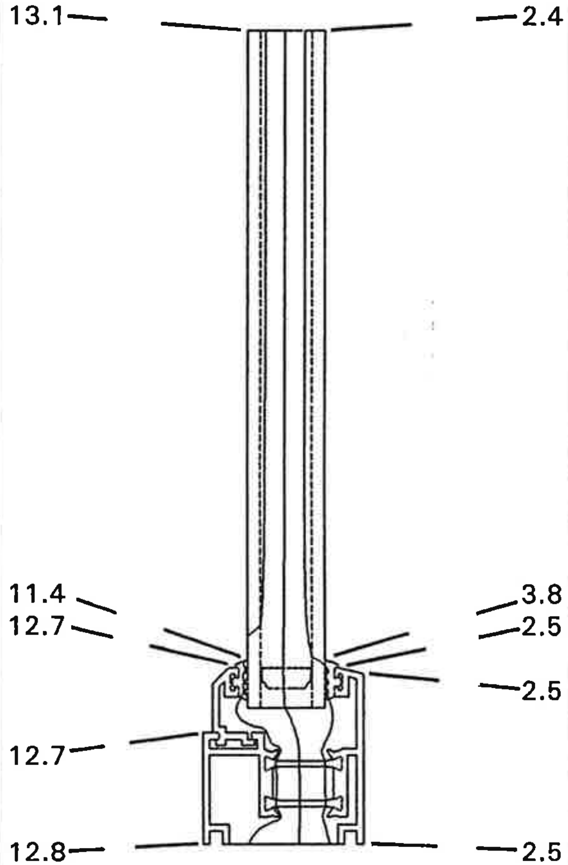
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.66	3.89	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.93	2.16	W/m²K

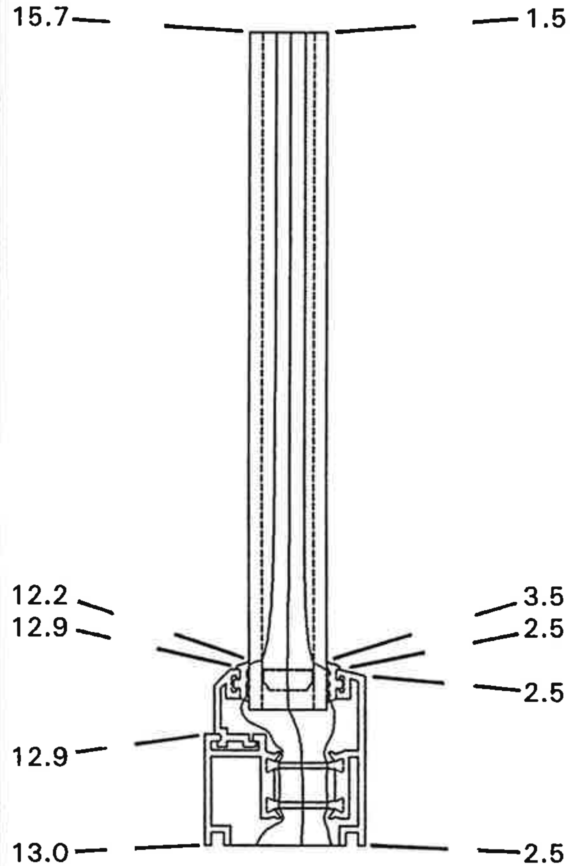
6.7 Dimensions



6.7 Ordinary 4/16/4 mm glazing



6.7 Low-e 4/16/4 mm glazing



6.8 Glass-filled polycarbonate spacer

The use of glass-filled polycarbonate is significantly different from the polymer-based spacers considered previously. This spacer has a traditional shape, but using a thermally improved polymer material.

The performance of this spacer is clearly excellent. The U-value of the frame is reduced by 25%, and the warm-side surface temperatures are increased by 3°C at the glazing edge. The warm-side of the frame is 1.7°C warmer than with the traditional aluminium spacer.

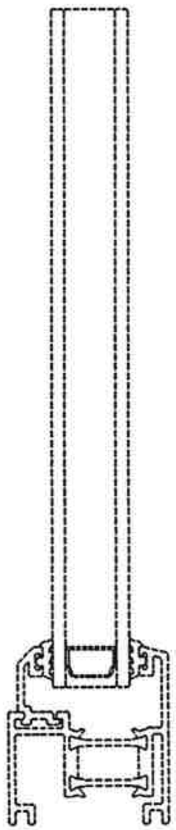
Performance

	Ordinary	Low-e	
Q_{total}	14.53	10.60	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.53	3.68	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.21	3.35	W/m²K

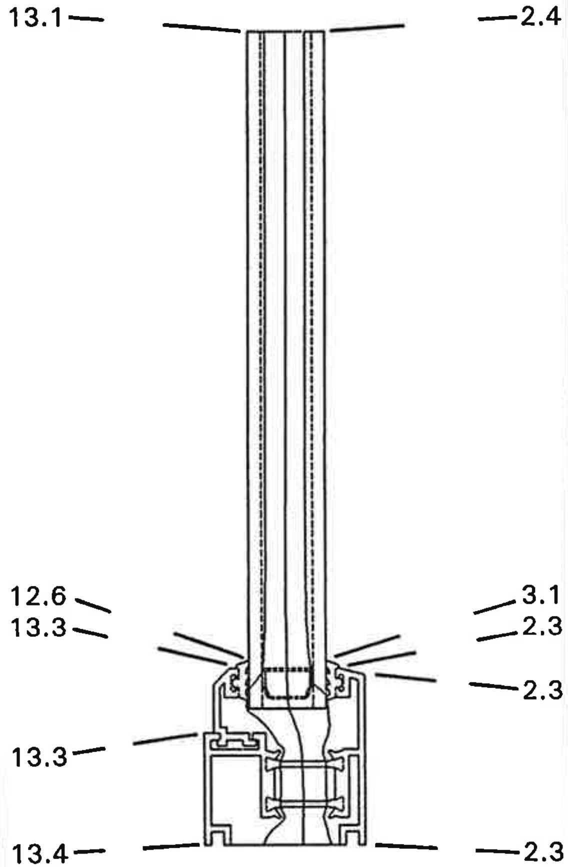
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.21	3.35	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.84	2.05	W/m²K

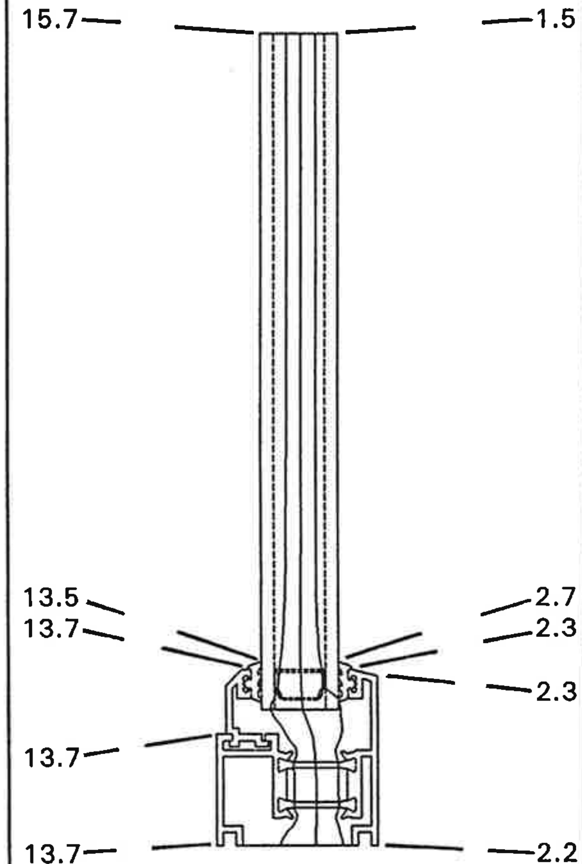
6.8 Dimensions



6.8 Ordinary 4/16/4 mm glazing



6.8 Low-e 4/16/4 mm glazing



6.9 Original aluminium spacer with PVC-U internal bead

This example considers another possibility - using a PVC-U bead to reduce heat loss from the frame through the glazing edge.

It is clear that this arrangement has far from good performance. The heat loss through the frame is reduced, but the effect of eliminating heat flow into the glazing edge, from the frame, is to reduce the glazing edge temperature. This arrangement reduces heat loss slightly and improves the condensation performance of the warm-side aluminium part of the frame but actually increases the risk of condensation on the glass.

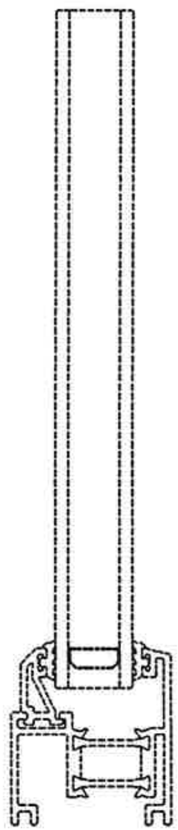
Performance

	Ordinary	Low-e	
Q_{total}	15.36	11.66	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.36	4.74	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.96	4.31	W/m²K

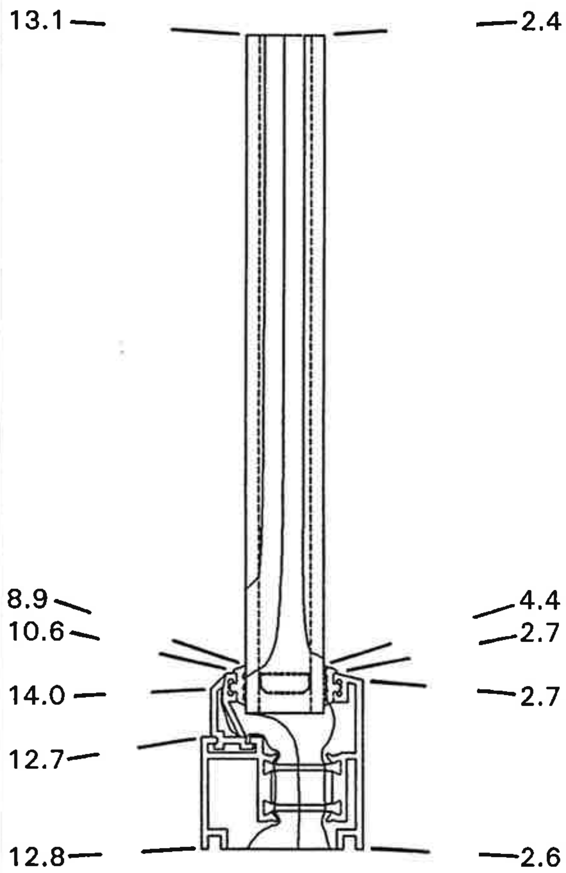
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.96	4.31	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.99	2.24	W/m²K

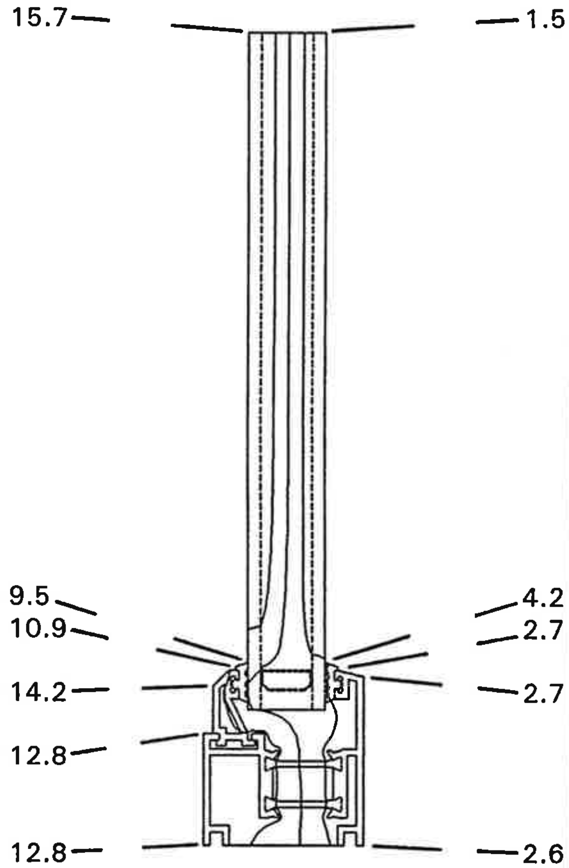
6.9 Dimensions



6.9 Ordinary 4/16/4 mm glazing



6.9 Low-e 4/16/4 mm glazing



6.10 Simple pour-and-de-bridge warm edge spacer with a basic timber frame

The use of the basic warm edge spacer of example 6.1 with this timber frame, previously considered in example 3.1, shows similar results to those obtained in the first example of this chapter - the frame U-value is reduced by 10% and the minimum glass temperature is increased by 1°C.

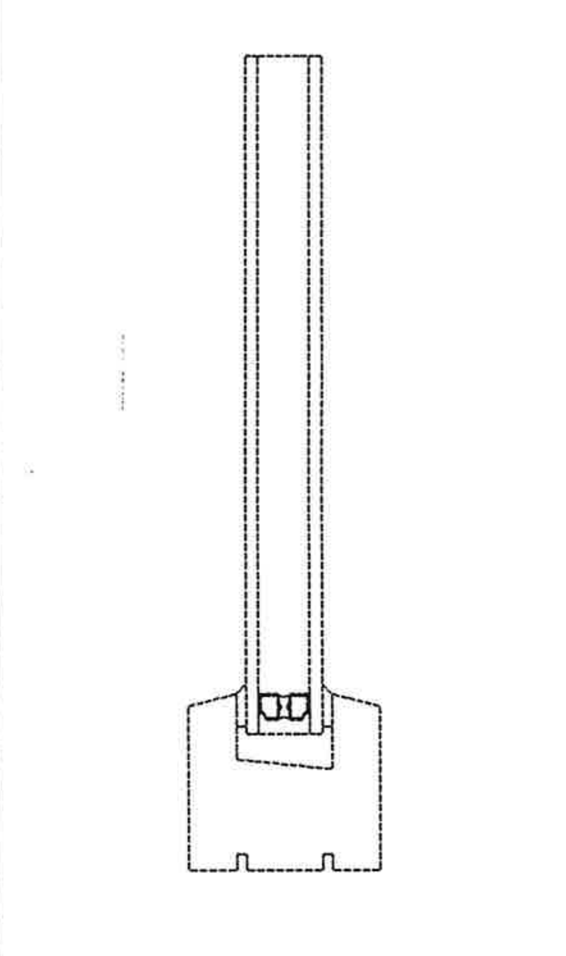
Performance

	Ordinary	Low-e	
Q_{total}	13.79	10.03	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	2.79	3.11	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.54	2.83	W/m^2K

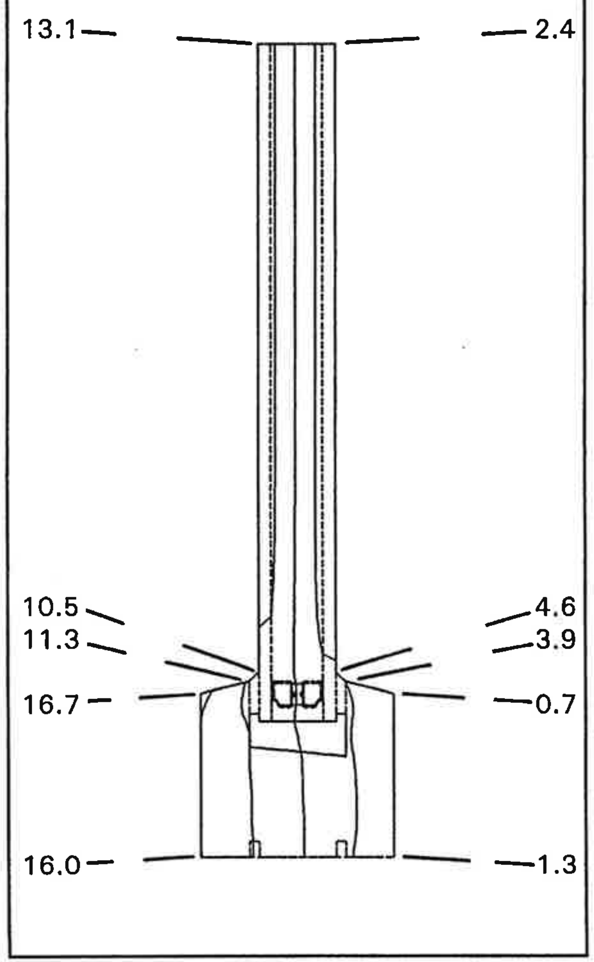
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	2.54	2.83	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	2.71	1.95	W/m^2K

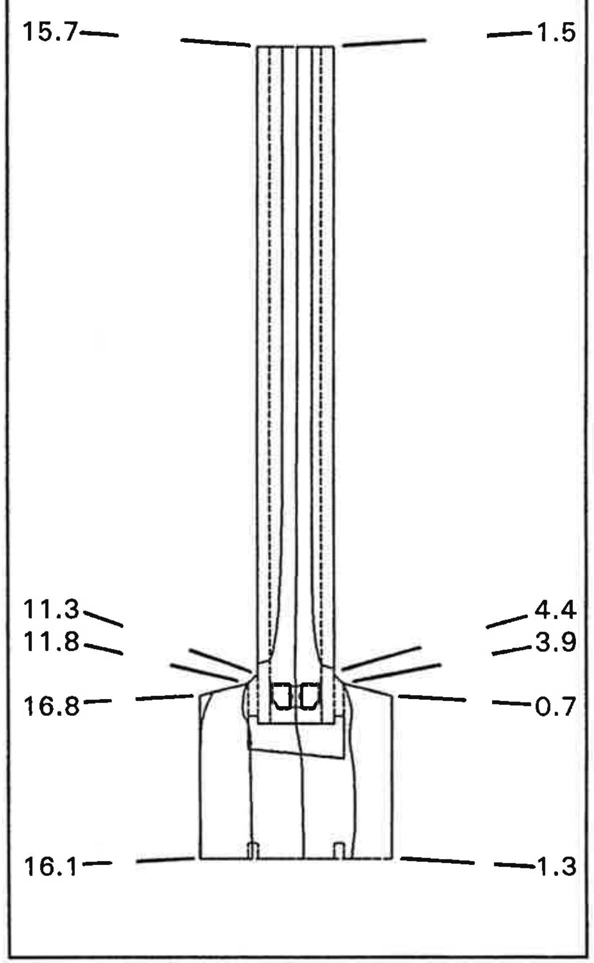
6.10 Dimensions



6.10 Ordinary 4/16/4 mm glazing



6.10 Low-e 4/16/4 mm glazing



6.11 Simple pour-and-de-bridge warm edge spacer with an aluminium-clad timber frame

This frame was previously considered in example 3.11. Again the frame U-value is reduced by 10% by using this basic warm edge spacer, and the minimum glass temperature is increased by 1.2°C.

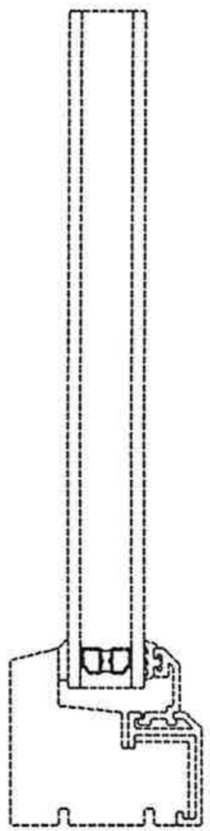
Performance

	Ordinary	Low-e	
Q_{total}	14.28	10.53	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.28	3.61	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.98	3.28	W/m²K

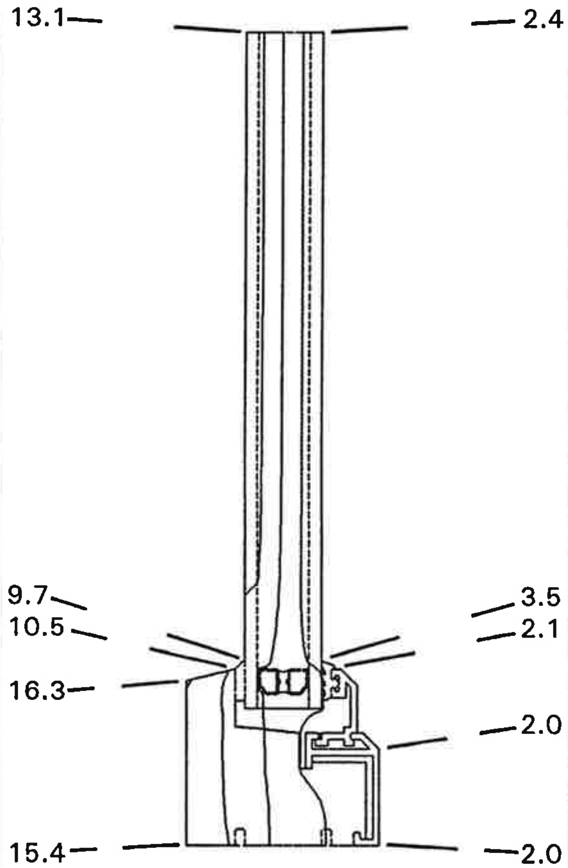
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	2.98	3.28	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.80	2.04	W/m²K

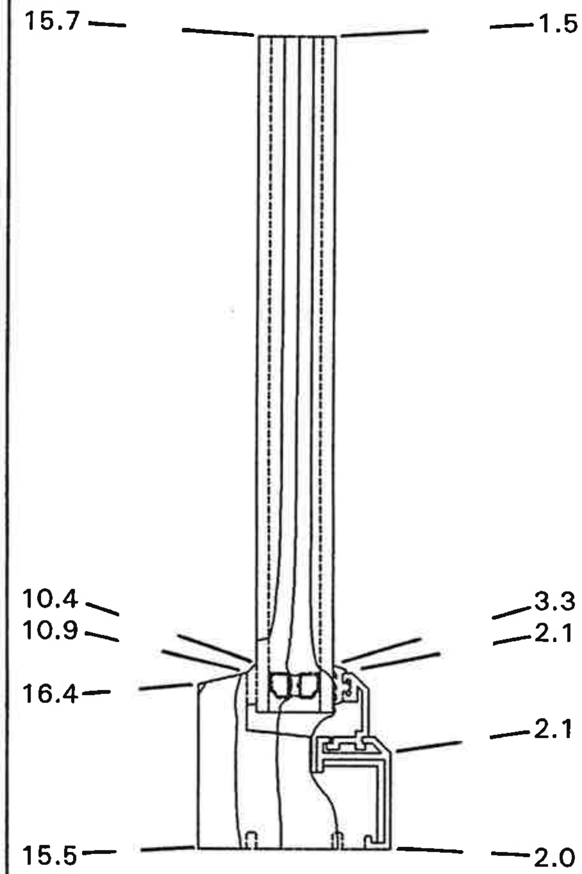
6.11 Dimensions



6.11 Ordinary 4/16/4 mm glazing



6.11 Low-e 4/16/4 mm glazing



6.12 Simple pour-and-de-bridge warm edge spacer with a reinforced PVC-U frame

The basic frame is that considered in example 4.3. The effect of the warm edge spacer on the PVC-U frame is slightly less than seen in the previous examples for other frame materials. However, there is still an increase in the warm side glass surface temperature of 1°C, and the frame U-value is reduced by 8%.

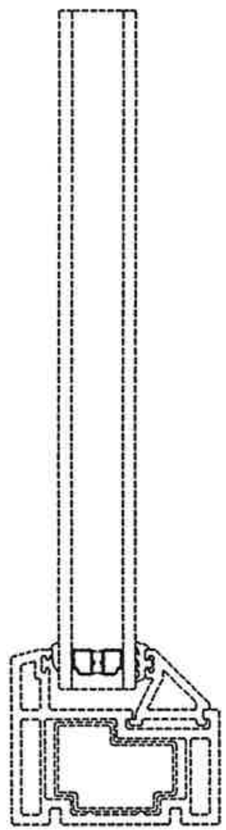
Performance

	Ordinary	Low-e	
Q_{total}	13.87	10.11	W
U_{glass}	2.75	1.73	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	2.87	3.19	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	2.61	2.90	W/m^2K

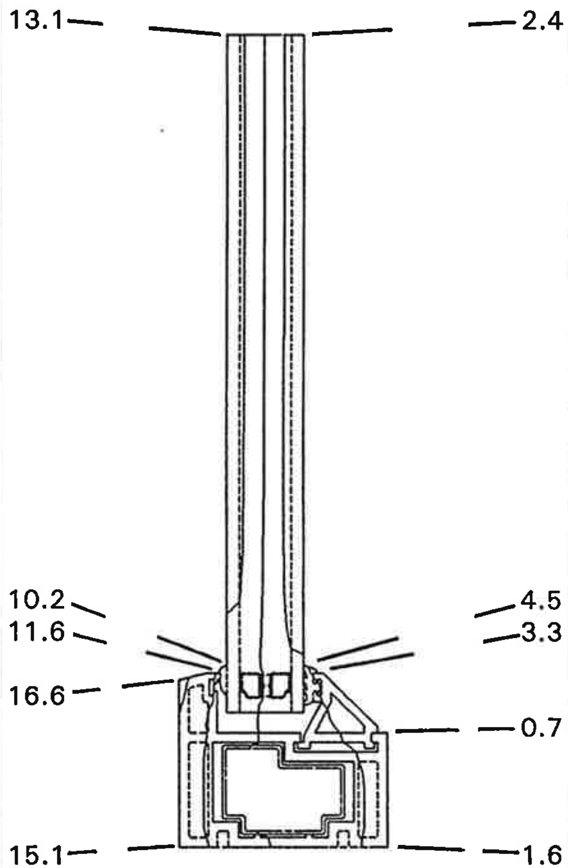
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m^2K
A_{glass}	0.9006	0.9006	m^2
U_{frame}	2.61	2.90	W/m^2K
A_{frame}	0.2244	0.2244	m^2
A_{total}	1.1250	1.1250	m^2
U_{window}	2.72	1.96	W/m^2K

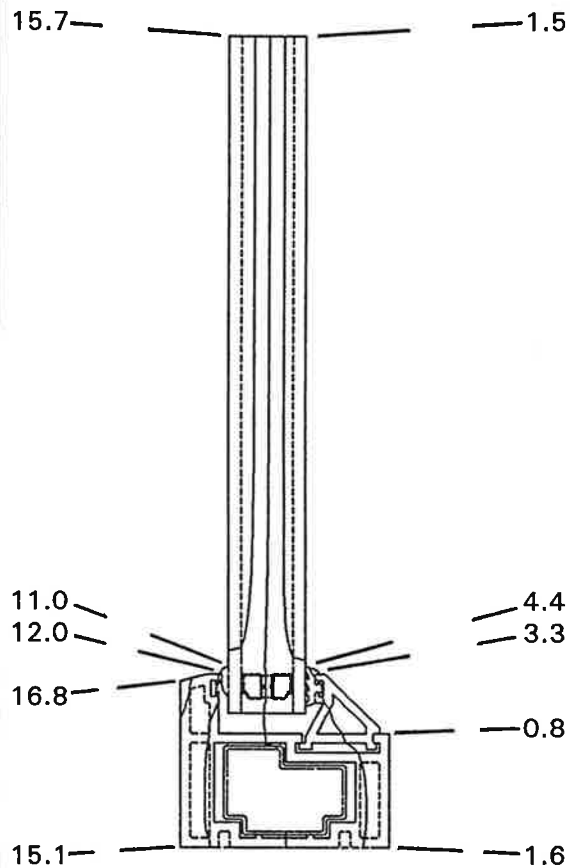
6.12 Dimensions



6.12 Ordinary 4/16/4 mm glazing



6.12 Low-e 4/16/4 mm glazing



6.13 Simple pour-and-de-bridge warm edge spacer with a PVC-U/aluminium composite frame

This frame was considered previously in example 4.7. Again the use of the basic warm edge spacer reduces the U-value of the frame by about 9%. The warm-side glazing temperature is increased by 1.2°C.

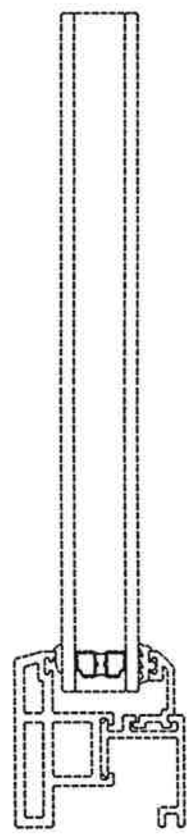
Performance

	Ordinary	Low-e	
Q_{total}	14.32	10.58	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	3.32	3.66	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	3.02	3.33	W/m²K

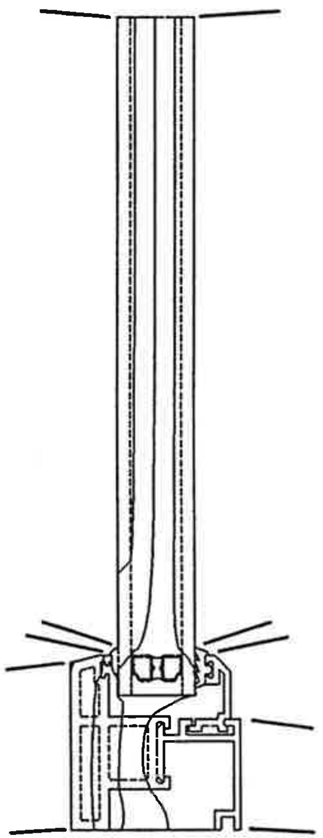
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	3.02	3.33	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	2.80	2.05	W/m²K

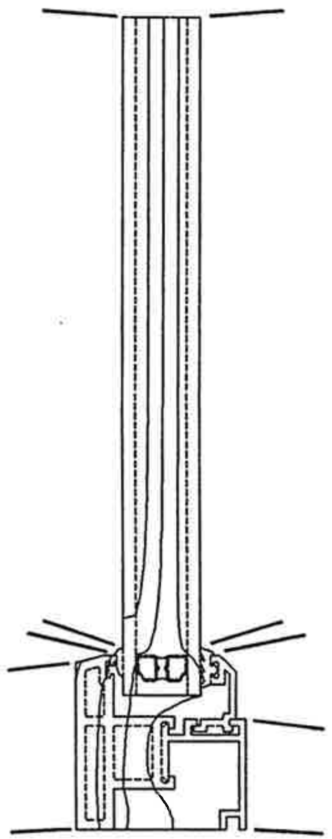
6.13 Dimensions



6.13 Ordinary 4/16/4 mm glazing



6.13 Low-e 4/16/4 mm glazing



6.14 Simple pour-and-de-bridge warm edge spacer with a thermally-broken steel frame

This frame was considered in example 5.3. The U-value of the frame is again reduced by 10% with the introduction of the simple warm edge spacer. The minimum glass surface temperature shows the now expected 1.2°C increase.

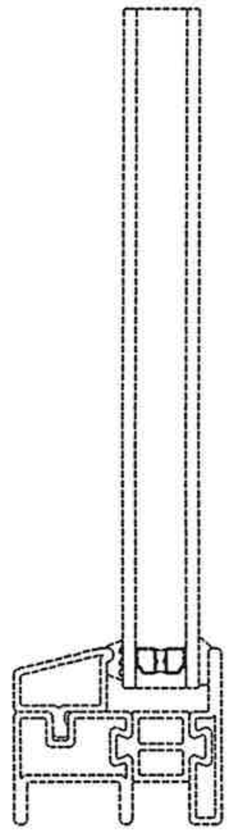
Performance

	Ordinary	Low-e	
Q_{total}	15.49	11.68	W
U_{glass}	2.75	1.73	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.00	6.92	W
Q_{frame}	4.49	4.76	W
P_{frame}	0.055	0.055	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	4.08	4.33	W/m²K

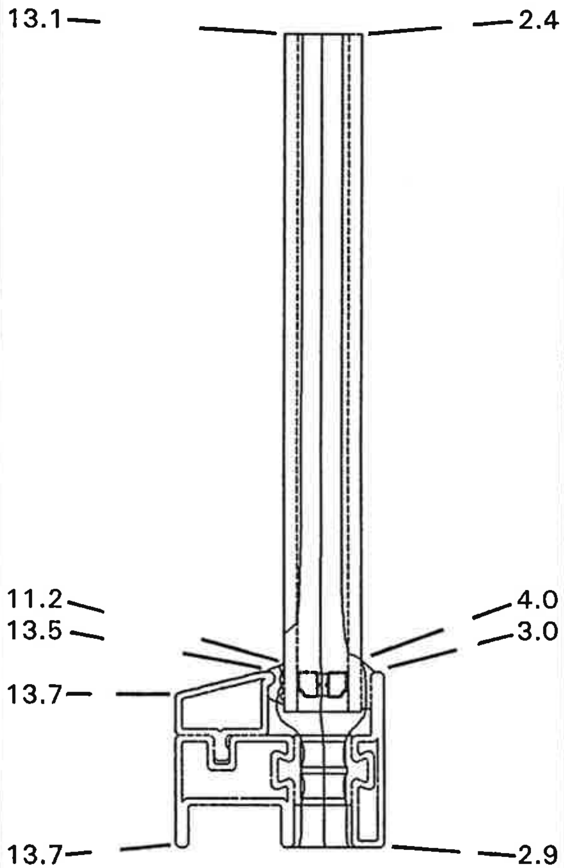
Typical window, 900 mm wide × 1250 mm high

U_{glass}	2.75	1.73	W/m²K
A_{glass}	0.9006	0.9006	m²
U_{frame}	4.08	4.33	W/m²K
A_{frame}	0.2244	0.2244	m²
A_{total}	1.1250	1.1250	m²
U_{window}	3.02	2.25	W/m²K

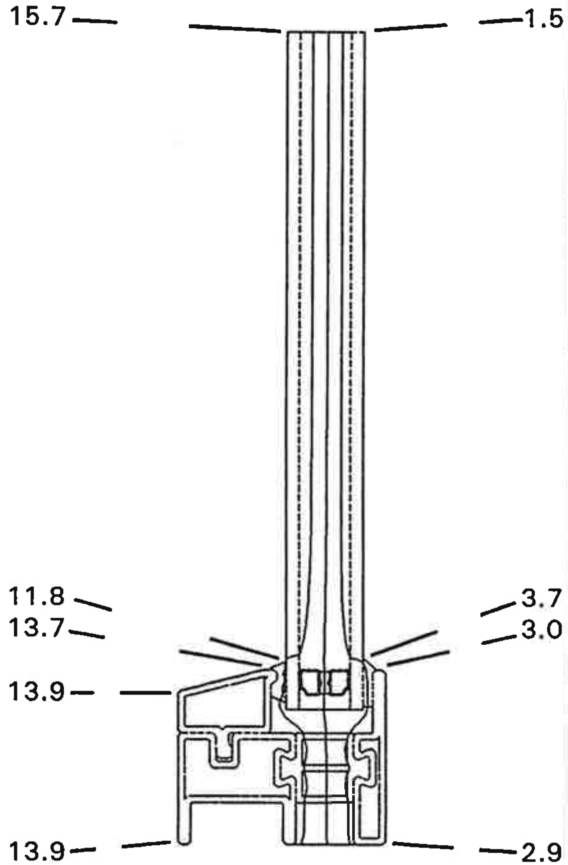
6.14 Dimensions



6.14 Ordinary 4/16/4 mm glazing



6.14 Low-e 4/16/4 mm glazing



6.15 Summary

The use of even a simple warm edge glazing spacer will both reduce the U-value of a frame and increase the minimum glazing temperature on the warm-side surface. However, it is still not possible to reach a level of performance of the edge detail that is comparable to the centre-glazing performance - few solid materials have a thermal conductivity as low as the equivalent thermal conductivity of the air-space in the low-e glazing unit.

The effect of the first-considered warm edge spacer has been shown to be near-identical for all frame types. If spacer performance is ranked in terms of the likely percentage reduction in frame U-value for some standard frame type then this could be used as a method for rating glazing spacers. However, the standard aluminium spacer is available in a range of shapes, and some examples may exhibit better performance than the basic aluminium spacer used for this study.

7 Curtain walling

Curtain walling frames, as used in stick system curtain walling, are primarily aluminium, and the basic dimensions of the frame are governed by structural strength requirements. Design modifications to improve U-values are therefore limited to details such as thermal break design and gasket shape. This chapter examines some of the basic designs found in practice.

Each simulation reported in this chapter is for one-half of a mullion, using the rule of symmetry to simplify the analysis. The reported heat transfer Q_{total} is for the half-mullion with a single 200 mm strip of glazing. The projected width of the half-mullion is 30 mm, and the U-value is based on this width. It should be noted that with the full-width mullion there would be double the heat transfer, twice the glazing heat transfer, and so twice the frame heat transfer. With the full projected width of 60 mm the frame would therefore have exactly the same U-value as calculated for the half-mullion.

The standard glazing type for the simulations in this chapter has been changed to a typical 6/12/6 mm unit. The centre-glazing U-values are then 2.84 W/m^2K and 1.93 W/m^2K, all other parameters being unchanged.

The glazing gaskets comprise a 5 mm thick foam EPDM gasket on the warm-side and a 4 mm thick solid EPDM gasket on the cold-side. The glazing edge spacer is a narrower version of that used in the previous chapters.

Frame/glazing interactions

Experience has shown that measured U-values for curtain walling frames may be up to 20% lower than simulated values. In part this is due to radiated heat exchange between the glazing and the sides of the frames, and in part is due to poor thermal contact between the various parts of the frame, which is typically a sandwich construction with intermittent fixing screws. However, the simulations contained in this chapter should give a reasonable indication of the range of performance that can be expected, and show the relative advantages of different designs.

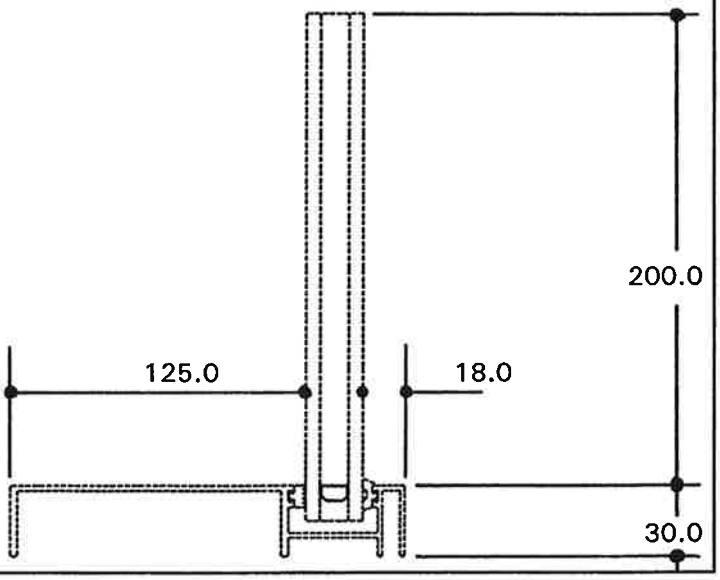
7.1 Non-thermally-broken mullion

This is a basic non-thermally-broken aluminium curtain wall frame. The U-value is very high, due to the large exposed warm-side surface. The warm-side surface temperatures are considerably higher than for the non-thermally-broken aluminium window frame of example 2.1 however, demonstrating the advantages of a greater exposed surface area.

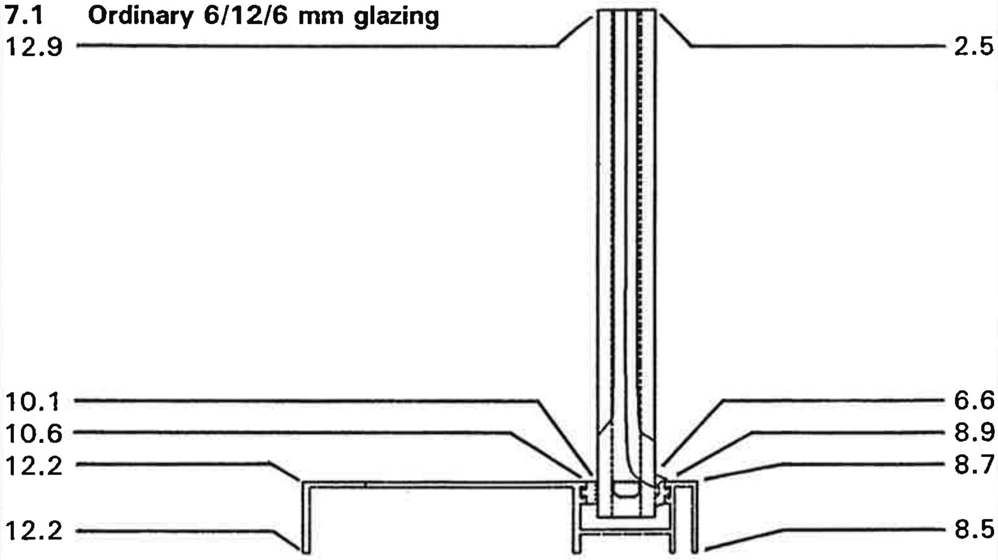
Performance

	Ordinary	Low-e	
Q_{total}	22.14	18.87	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	10.78	11.15	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	17.97	18.58	W/m²K

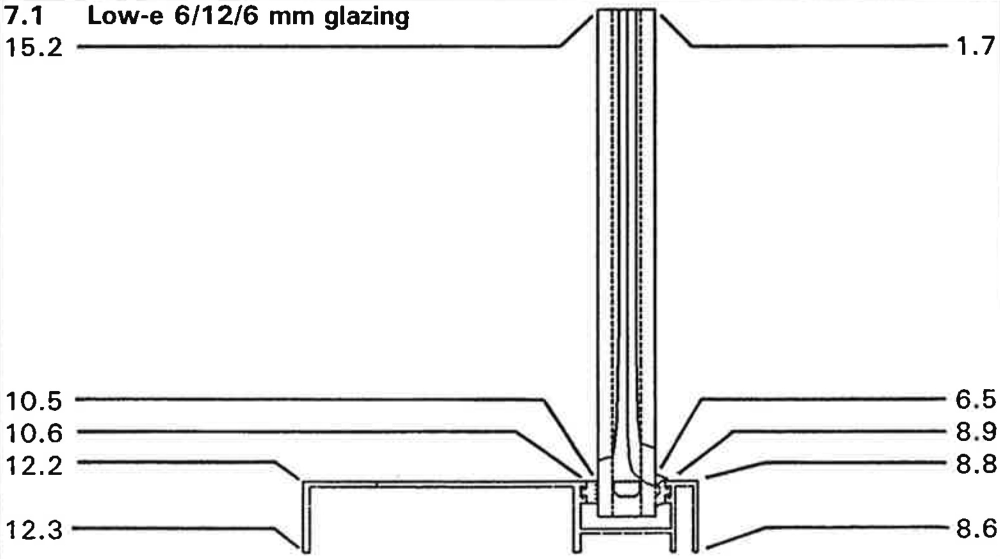
7.1 Dimensions



7.1 Ordinary 6/12/6 mm glazing



7.1 Low-e 6/12/6 mm glazing



7.2 Mullion with short PVC-U thermal break

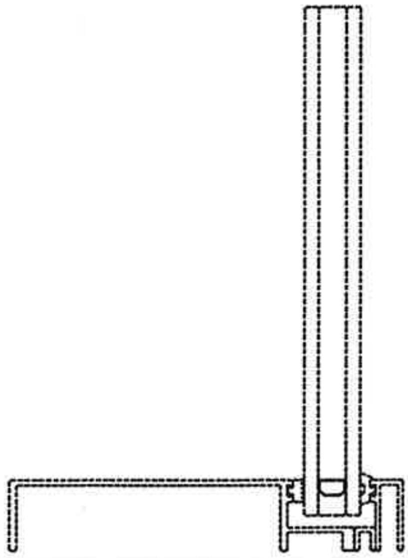
This is the basic aluminium mullion with an extruded PVC-U thermal break, overall length 9 mm.

The addition of even a simple thermal break reduces the mullion U-value by one-half. The mullion warm-side surface temperature is increased sufficiently that the risk of condensation on the frame is virtually eliminated.

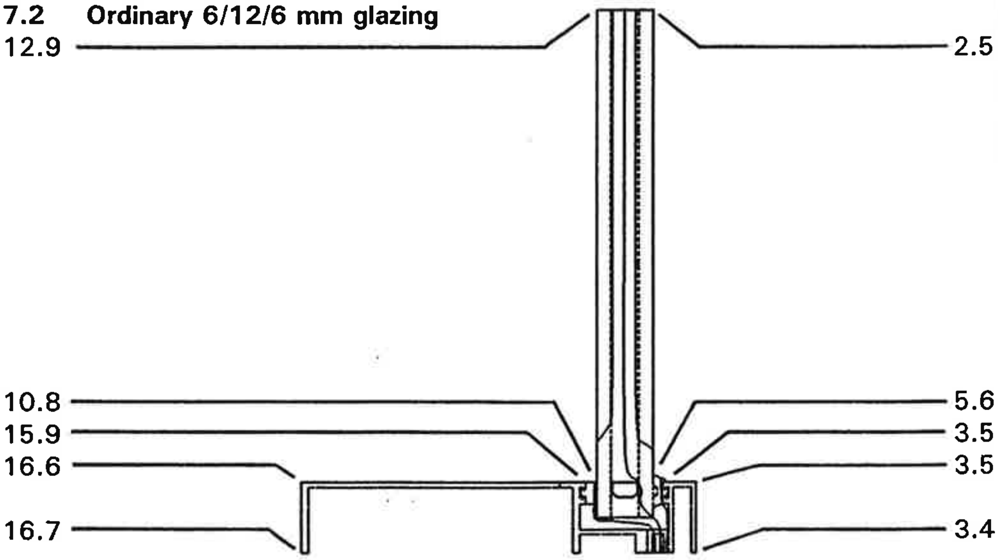
Performance

	Ordinary	Low-e	
Q_{total}	16.26	12.95	W
U_{glass}	2.84	1.93	W/m^{2}K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.90	5.23	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	8.17	8.72	W/m^{2}K

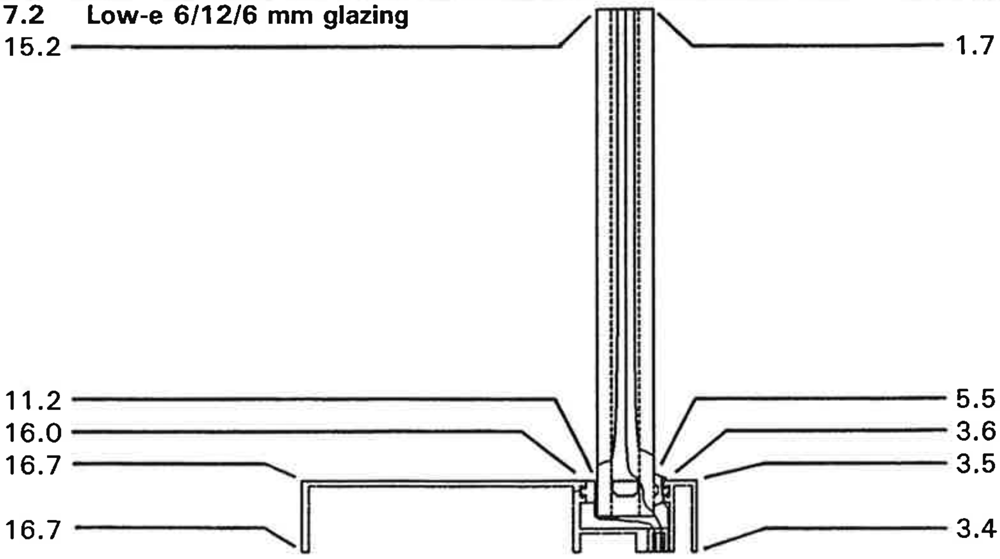
7.2 Dimensions



7.2 Ordinary 6/12/6 mm glazing



7.2 Low-e 6/12/6 mm glazing



7.3 Mullion with long PVC-U thermal break

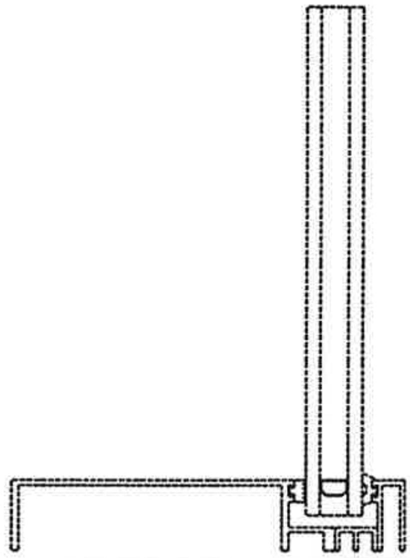
This is the basic aluminium mullion with a longer extruded PVC-U thermal break.

The thermal break is twice as long (18 mm) as that used in the previous example. The U-value of the mullion has reduced by a further 14%. This again clearly demonstrates that where a material of low thermal conductivity is used it should be longer in the direction of heat transfer to obtain better performance. However, doubling the resistance of the thermal break has a smaller effect on the overall thermal resistance.

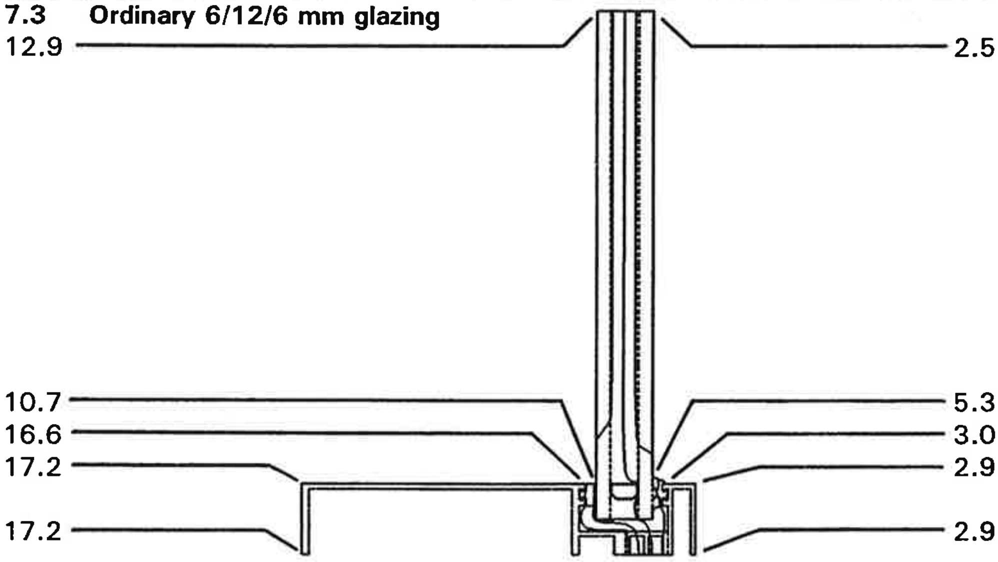
Performance

	Ordinary	Low-e	
Q_{total}	15.58	12.26	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.22	4.54	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.03	7.57	W/m²K

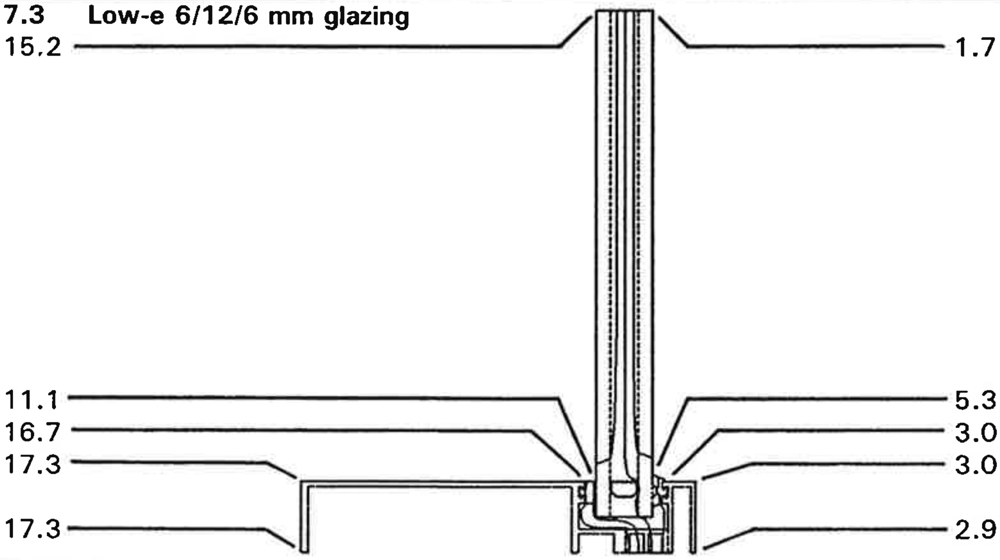
7.3 Dimensions



7.3 Ordinary 6/12/6 mm glazing



7.3 Low-e 6/12/6 mm glazing



7.4 Mullion with short polyamide thermal break

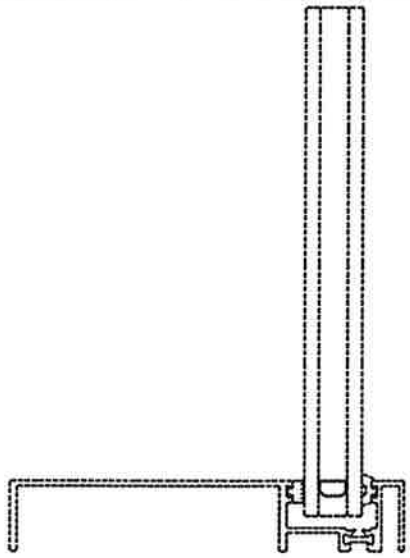
This is the basic mullion with a short extruded polyamide thermal break. The clearance between the aluminium sections is 7.2 mm. Note that there are a pair of polyamide strips, but only one appears in this half of the mullion.

The U-value is clearly not as low as with the short 9 mm PVC-U thermal break. The PVC-U thermal break is both longer and has a lower thermal conductivity.

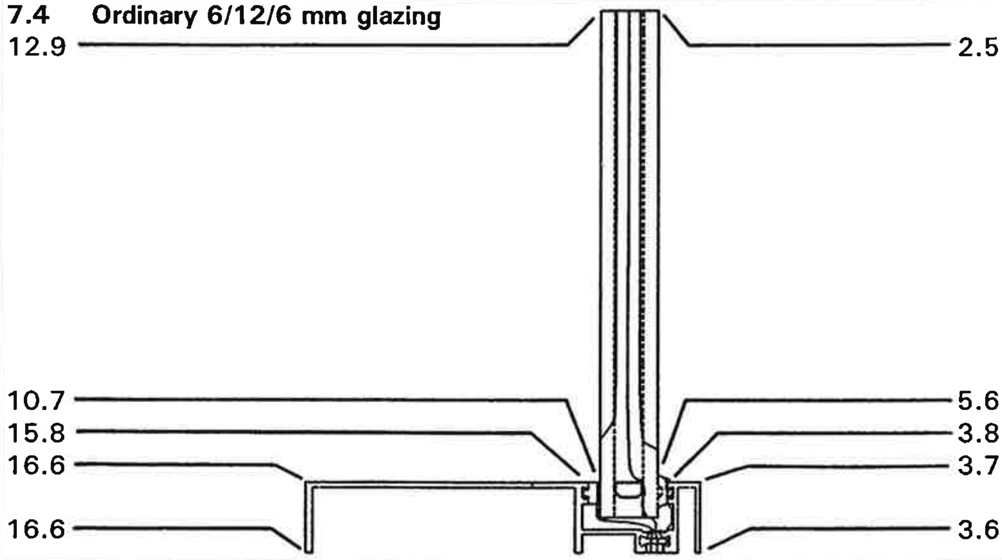
Performance

	Ordinary	Low-e	
Q_{total}	16.42	13.11	W
U_{glass}	2.84	1.93	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	5.06	5.39	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	8.43	8.98	W/m^2K

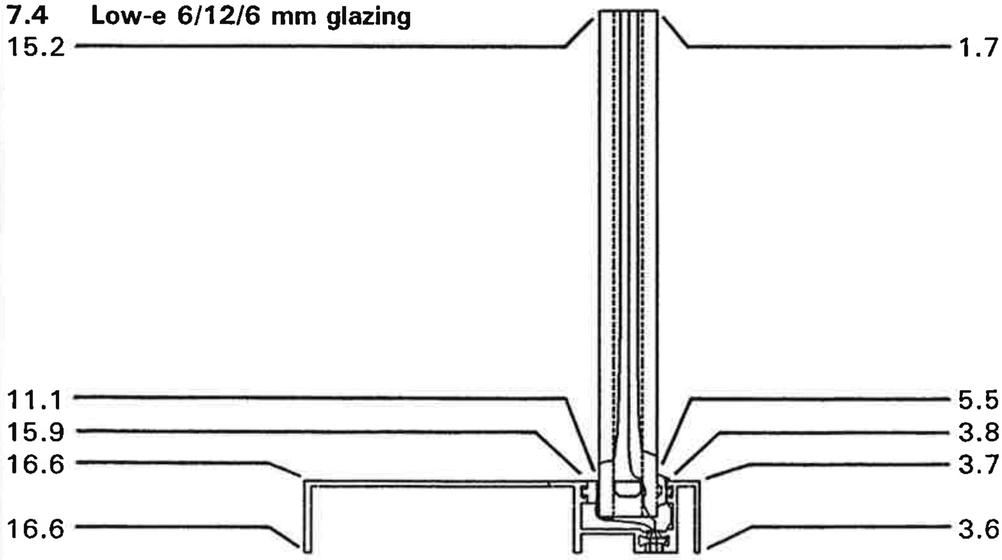
7.4 Dimensions



7.4 Ordinary 6/12/6 mm glazing



7.4 Low-e 6/12/6 mm glazing



7.5 Mullion with long polyamide thermal break

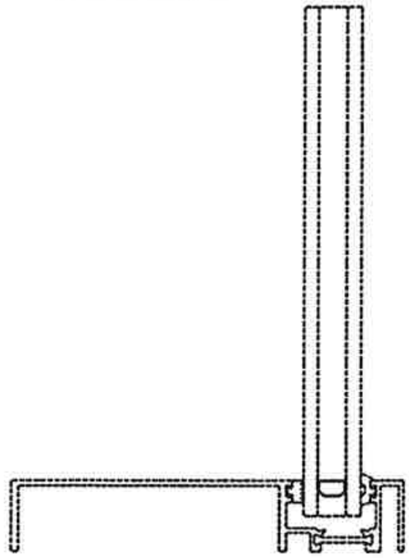
This mullion uses the longer extruded polyamide thermal break, which gives a gap of 18.8 mm between the aluminium sections. The U-value is now comparable to that obtained with the longer PVC-U thermal break.

Examples 7.2 to 7.5 clearly demonstrate the range of performance available with readily available thermal breaks. The following examples show some of the typical variations on the designs considered so far.

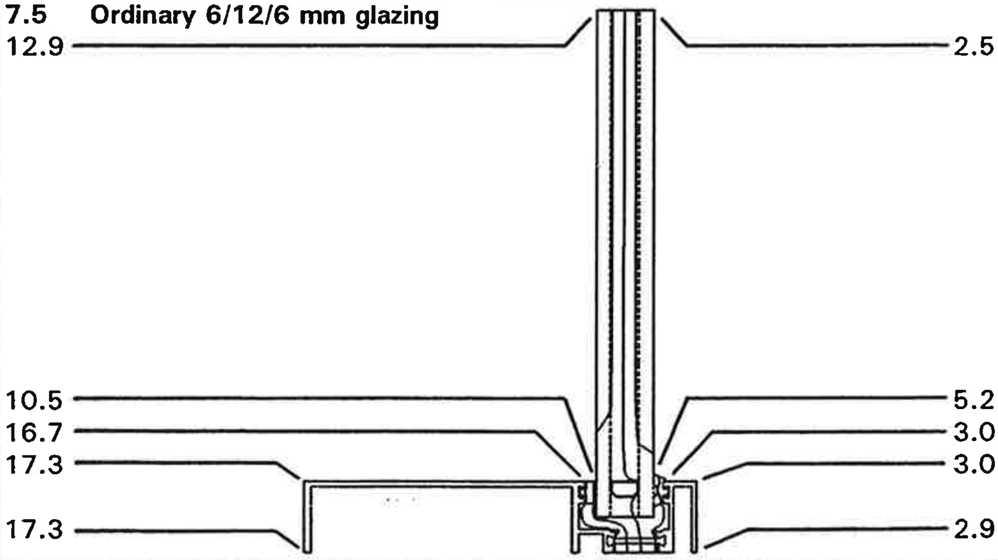
Performance

	Ordinary	Low-e	
Q_{total}	15.52	12.21	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.16	4.49	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	6.93	7.48	W/m²K

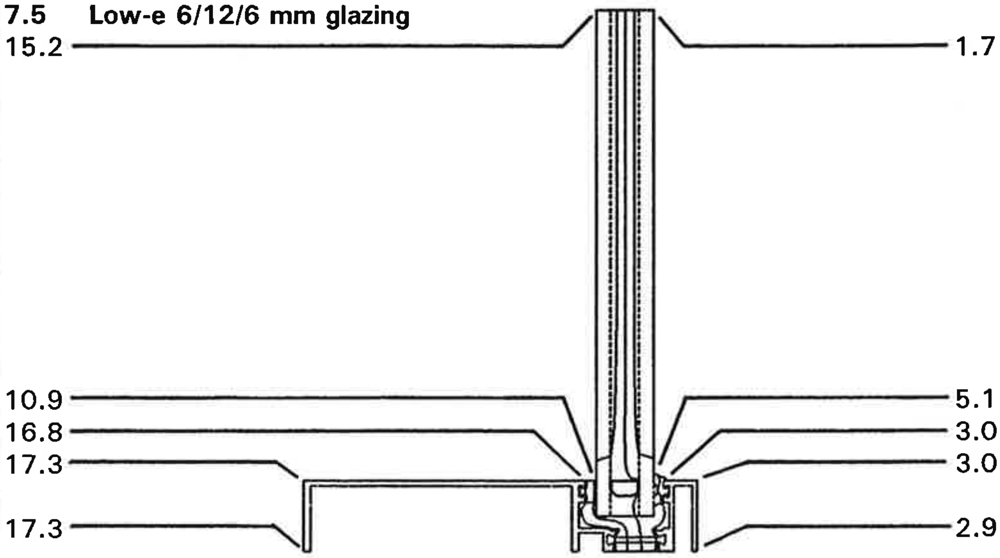
7.5 Dimensions



7.5 Ordinary 6/12/6 mm glazing



7.5 Low-e 6/12/6 mm glazing



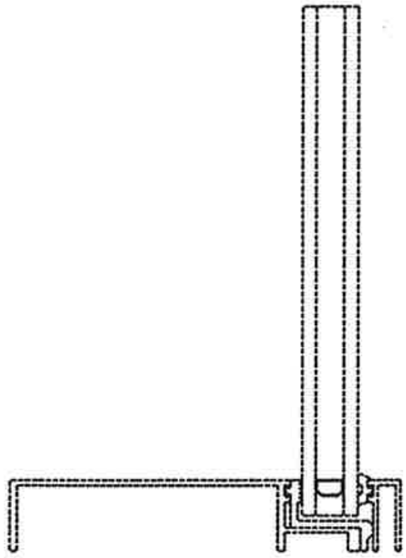
7.6 Mullion with full-width warm-side gasket

This mullion uses a warm-side gasket which is extended across the full-width of the mullion to form a thermal break. However, although the gasket material (foam EPDM) has a lower thermal conductivity than either PVC-U or polyamide the heat transfer path is somewhat shorter (5.5 mm) than previously considered, and so the U-value is higher and the warm-side surface temperatures are lower.

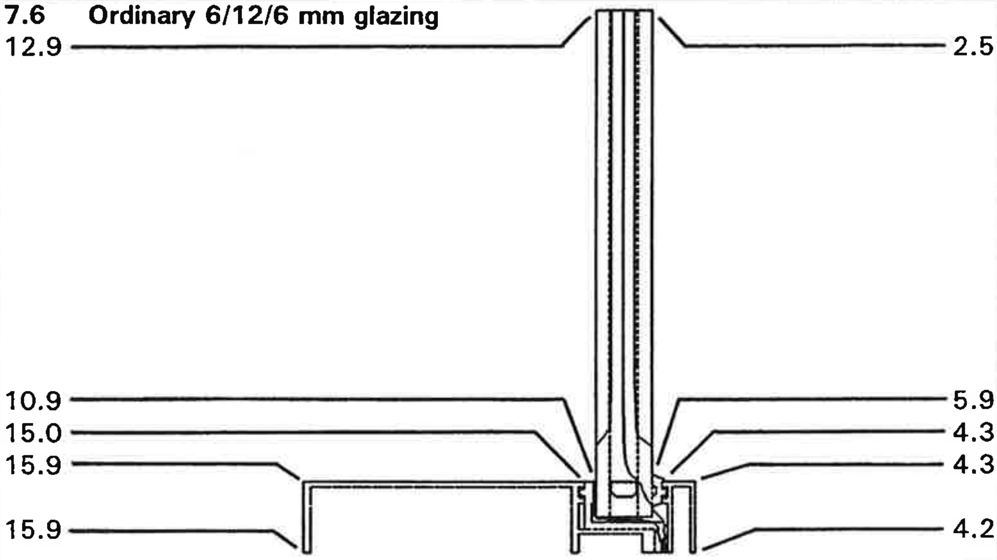
Performance

	Ordinary	Low-e	
Q_{total}	17.23	13.92	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	5.87	6.20	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	9.78	10.33	W/m²K

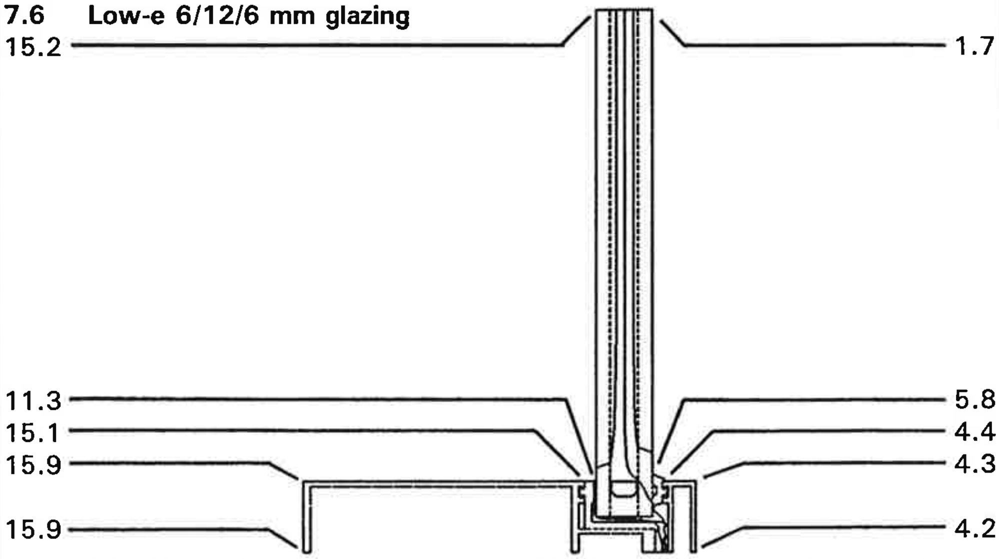
7.6 Dimensions



7.6 Ordinary 6/12/6 mm glazing



7.6 Low-e 6/12/6 mm glazing



7.7 Mullion with full-width warm-side gasket and short PVC-U thermal break

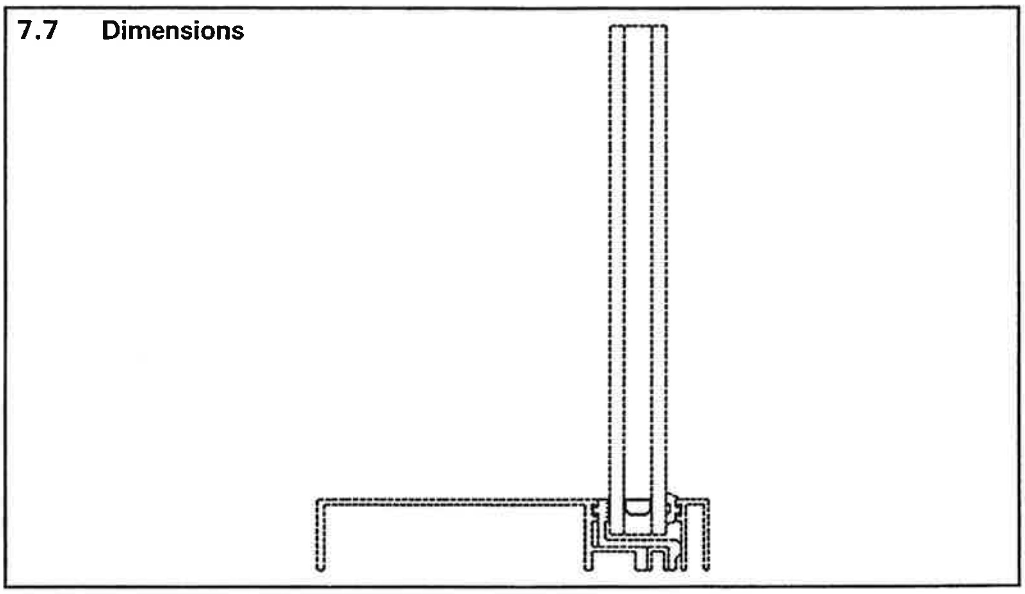
This mullion combines a full-width gasket with a short PVC-U thermal break. Clearly the U-value is lower than that obtained with just the PVC-U thermal break, but the additional effect of the gasket is small.

This simulation and example 7.6 demonstrate how a simple strip of insulating material can improve the U-value of a mullion, but that the gain in adding a strip of rubber to a PVC-U thermal break is somewhat less than the gain in adding the same strip of rubber to a non-thermally-broken mullion. This example provides another demonstration of the complexity of the relationship between the thermal resistance of one component of the frame and the overall U-value.

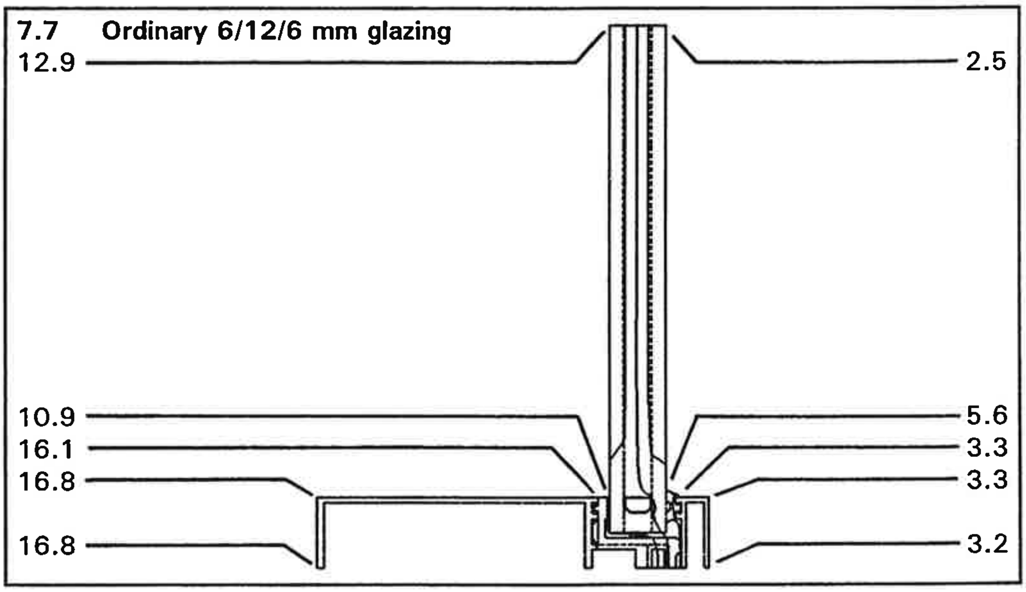
Performance

	Ordinary	Low-e	
Q_{total}	16.06	12.74	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.70	5.02	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.83	8.37	W/m²K

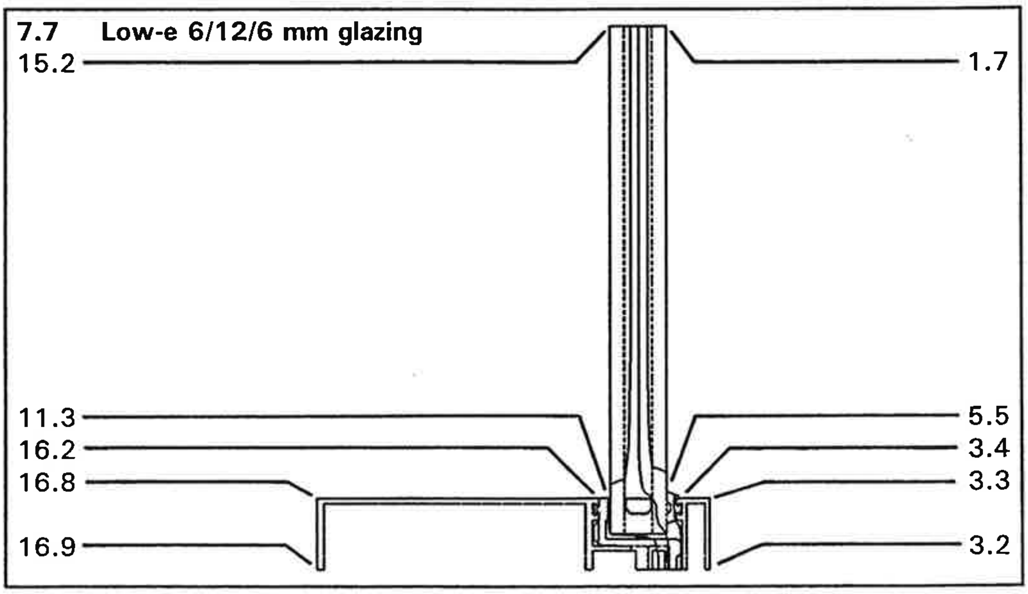
7.7 Dimensions



7.7 Ordinary 6/12/6 mm glazing



7.7 Low-e 6/12/6 mm glazing



7.8 Mullion with full-width cold-side gasket

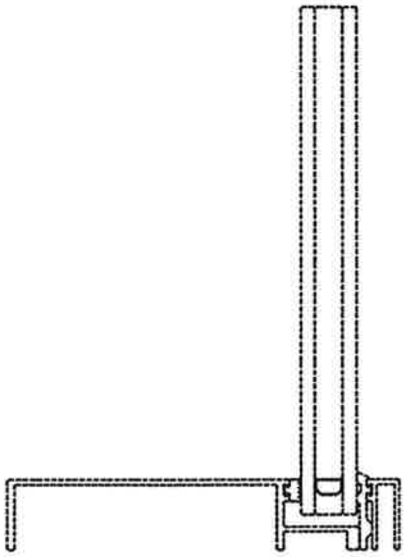
This mullion differs from example 7.6 in that it is the cold-side gasket that is extended to form a thermal break.

The U-value is higher than in example 7.6, because although the strip of rubber is the same thickness across the thermal break it is made from solid EPDM, which has a higher thermal conductivity (0.29 W/mK, compared to 0.15 W/mK) than the foam EPDM of example 7.6.

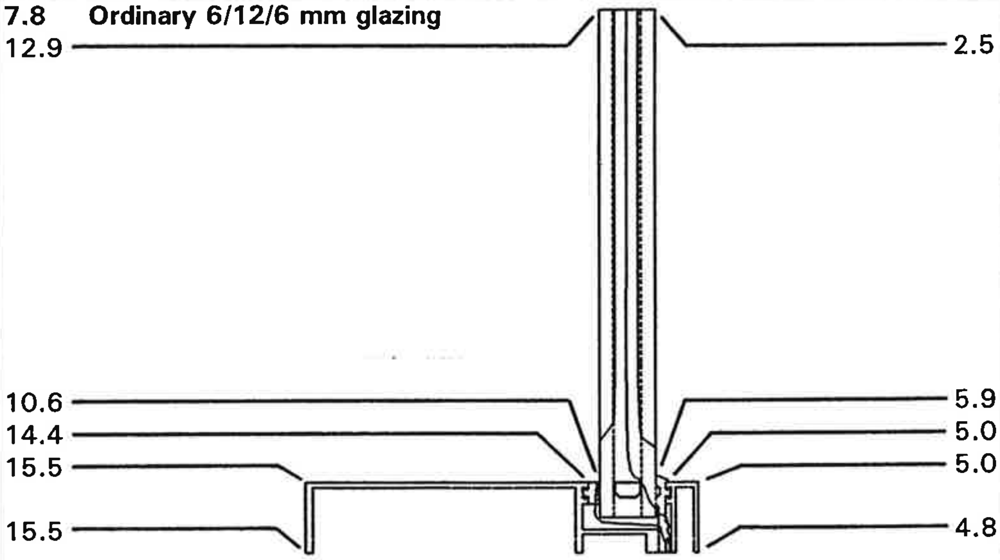
Performance

	Ordinary	Low-e	
Q_{total}	17.89	14.58	W
U_{glass}	2.84	1.93	W/m^2K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	6.53	6.86	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	10.88	11.43	W/m^2K

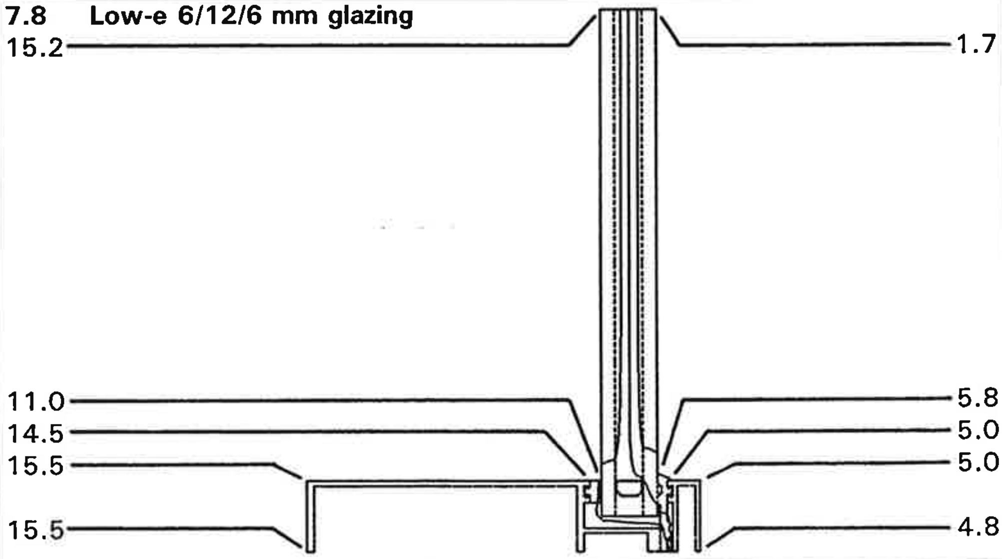
7.8 Dimensions



7.8 Ordinary 6/12/6 mm glazing



7.8 Low-e 6/12/6 mm glazing



7.9 Mullion with full-width cold-side gasket and short PVC-U thermal break

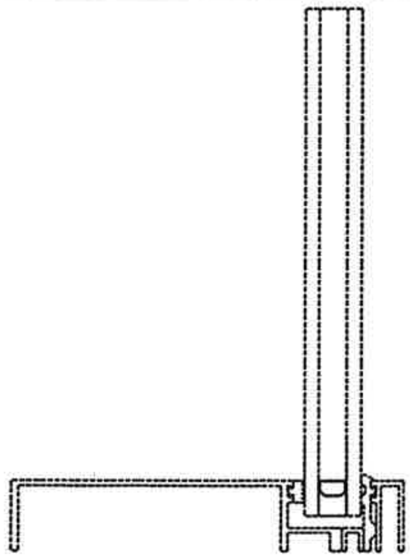
The addition of the short PVC-U thermal break has the unexpected effect of reducing the U-value to below that of example 7.7. Introducing the PVC-U extrusion eliminates the overlap between the 'nose' of the mullion and the cold-side glass. It is probable that significant radiation heat transfer occurs between these components. The effect would be less pronounced in example 7.7 because of the gasket shrouding the nose of the mullion.

Heat transfer through cavities is complex, and depends on the shortest distance between the warmest and coldest surfaces around the cavity. A significant amount of heat transfer can occur by radiation across cavities, and it is clear from the temperature contours within the cavity that the direction of heat transfer is from the side of the mullion nose to the edge of the glazing unit.

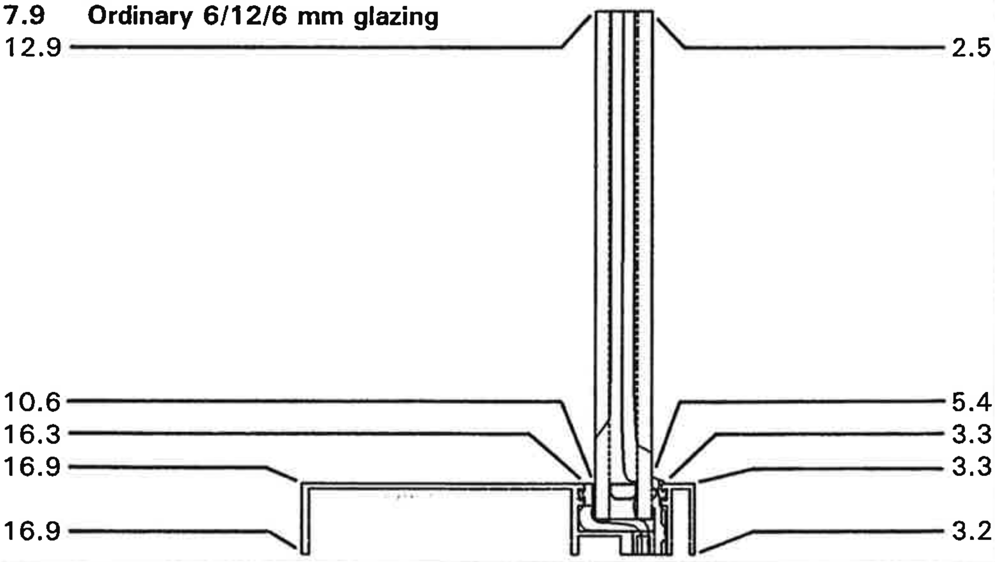
Performance

	Ordinary	Low-e	
Q_{total}	15.94	12.62	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.58	4.90	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.63	8.17	W/m²K

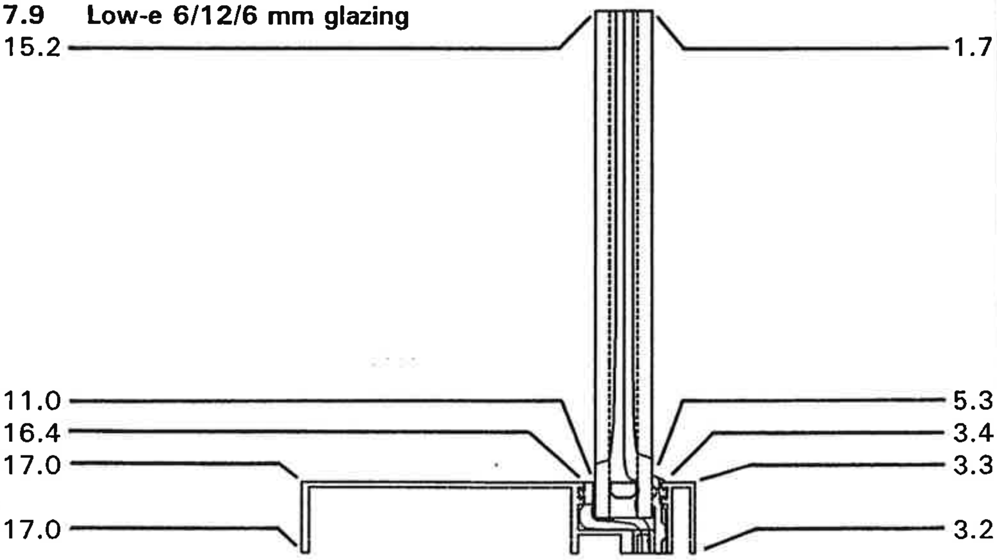
7.9 Dimensions



7.9 Ordinary 6/12/6 mm glazing



7.9 Low-e 6/12/6 mm glazing



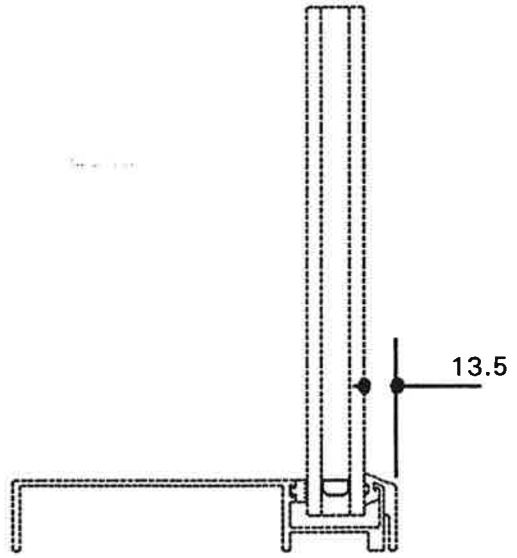
7.10 Mullion with cold-side shrouding gasket

In this mullion the cold-side gasket has been wrapped around the outside of the cold-side mullion surface. The U-value is somewhat higher than previously encountered, because the mullion is extended within the cold-side gasket to provide support. The mullion is now providing an excessive warm finger, encouraging heat loss. At its thinnest point the shrouding gasket is only 2.2 mm thick.

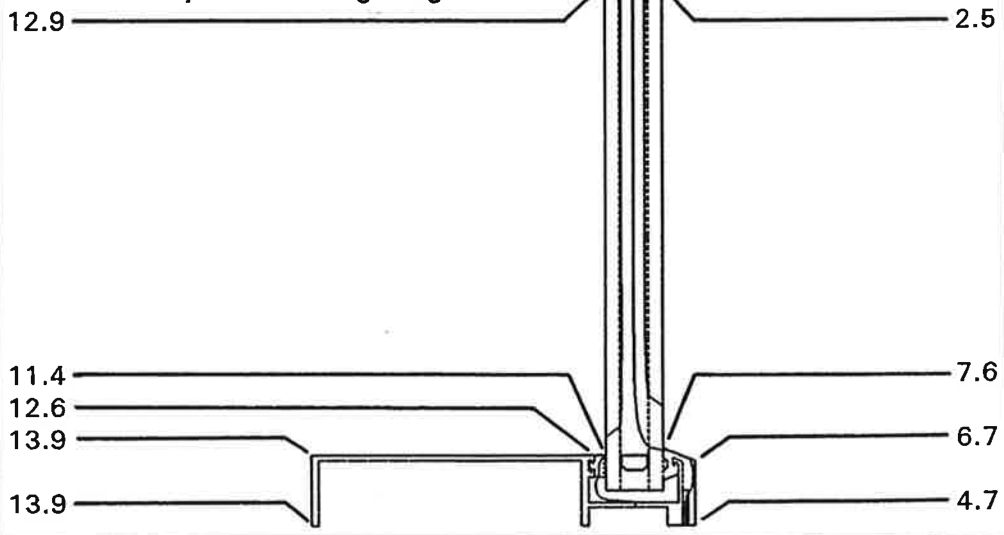
Performance

	Ordinary	Low-e	
Q_{total}	19.66	16.37	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	8.30	8.65	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	13.83	14.42	W/m²K

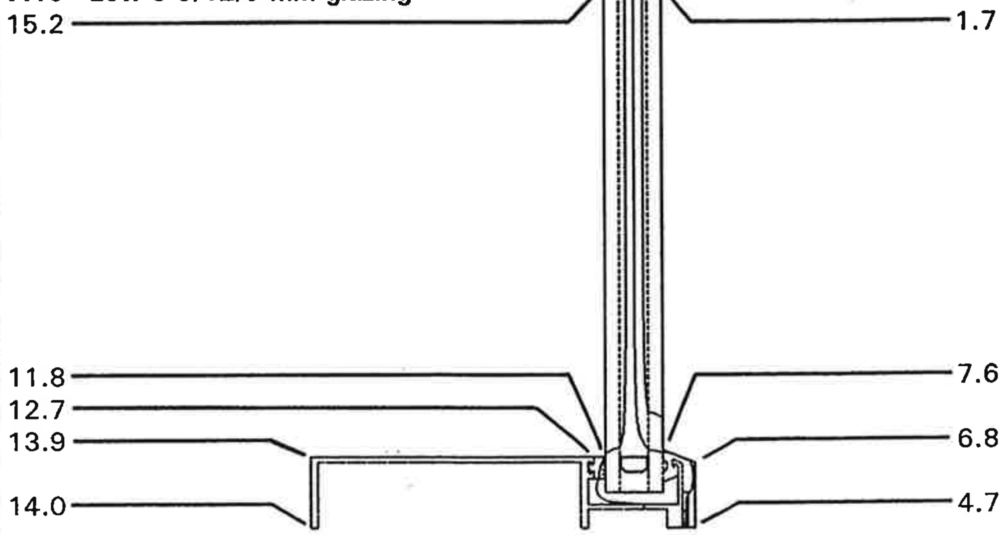
7.10 Dimensions



7.10 Ordinary 6/12/6 mm glazing



7.10 Low-e 6/12/6 mm glazing



7.11 Mullion with cold-side shrouding gasket and short PVC-U thermal break

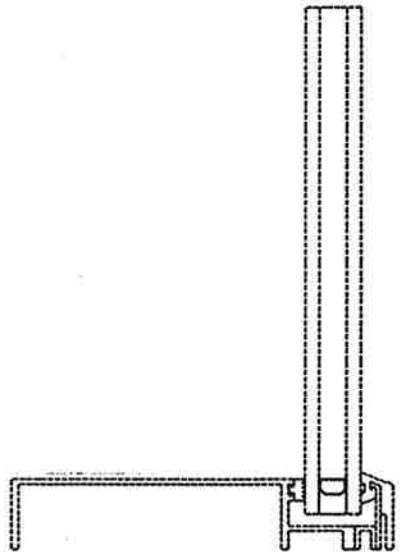
The inclusion of a simple extruded PVC-U thermal break significantly improves the performance of this mullion. The U-value is now somewhat better than with just the PVC-U thermal break, and the value of covering the cold-side surface of the mullion with an insulating material is significant. A better thermal break will clearly give a superior level of performance.

These examples have shown that thicker insulating materials, with a lower thermal conductivity, will give best performance. However, there is still one significant option to consider.

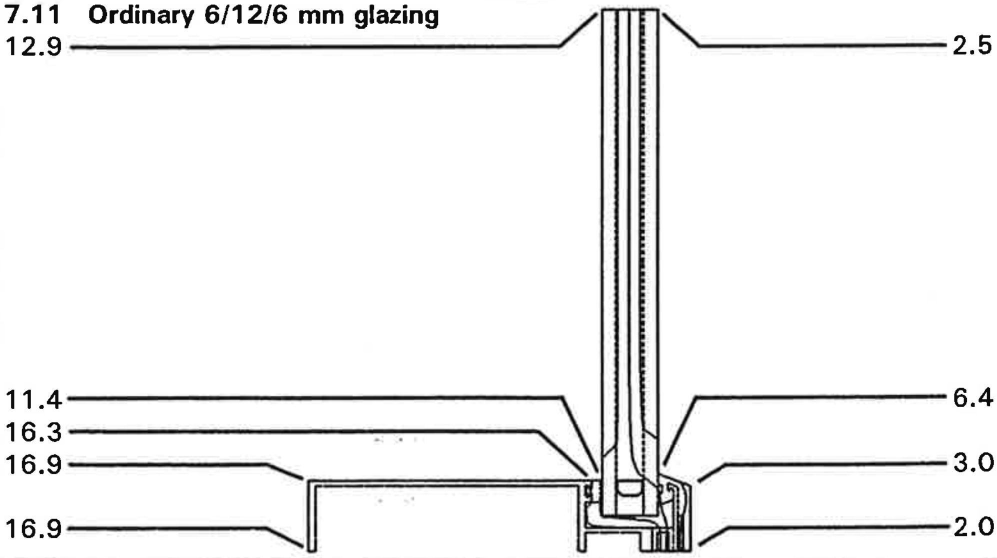
Performance

	Ordinary	Low-e	
Q_{total}	15.74	12.42	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.38	4.70	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.30	7.83	W/m²K

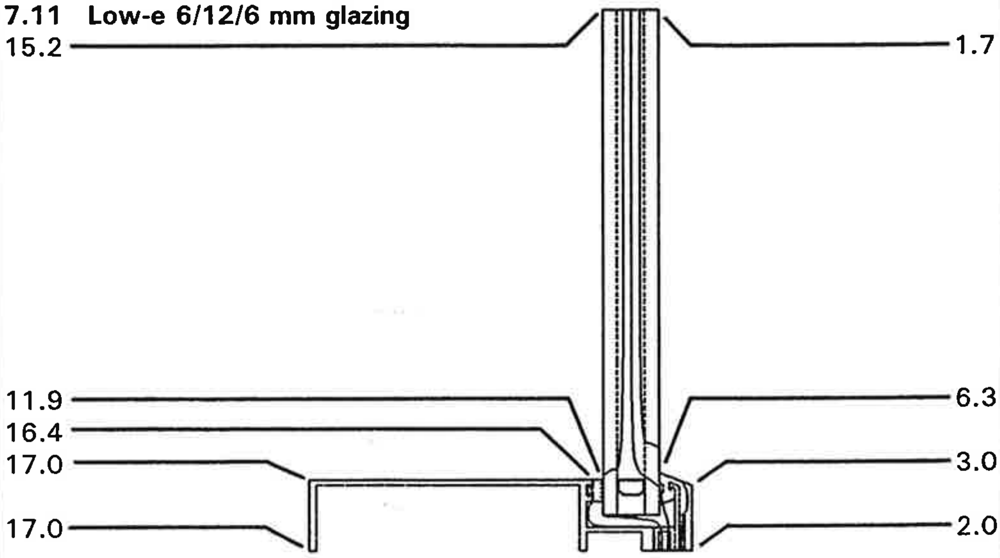
7.11 Dimensions



7.11 Ordinary 6/12/6 mm glazing



7.11 Low-e 6/12/6 mm glazing



7.12 Mullion with omitted thermal break

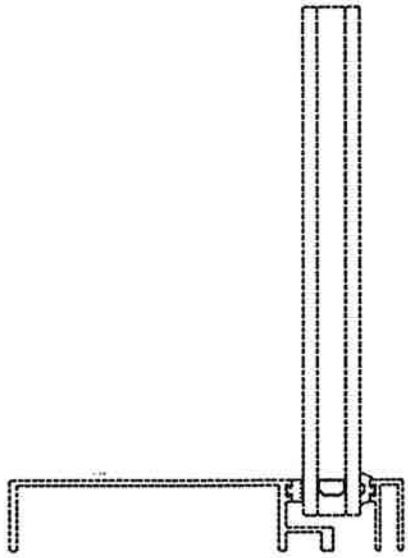
This mullion is identical to that considered in example 7.3, but with the thermal break completely omitted.

The effect of removing the thermal break altogether is surprisingly small. the radiation and conduction heat transfer across the resulting air-space are similar in magnitude to the conduction heat transfer through the PVC-U thermal break!

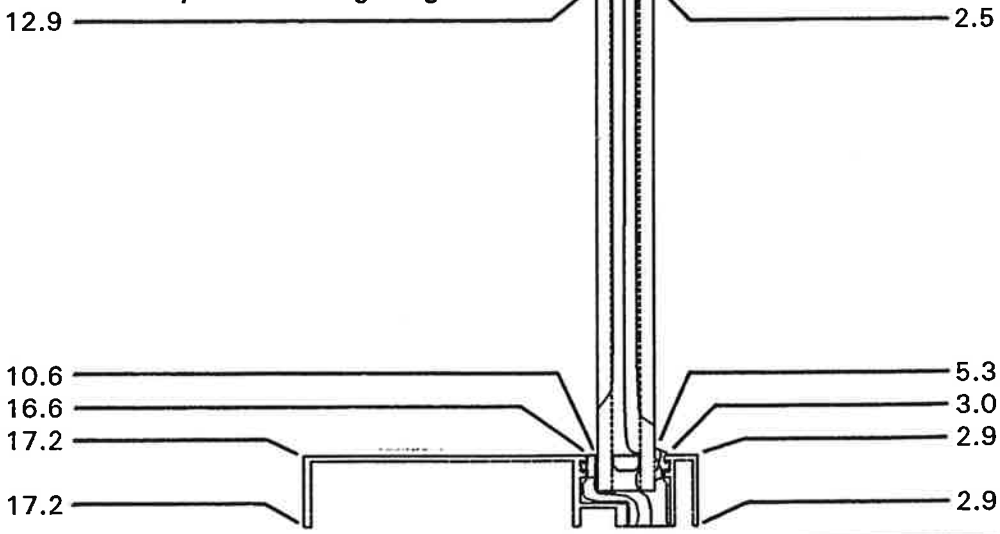
Performance

	Ordinary	Low-e	
Q_{total}	15.56	12.25	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.20	4.53	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.00	7.55	W/m²K

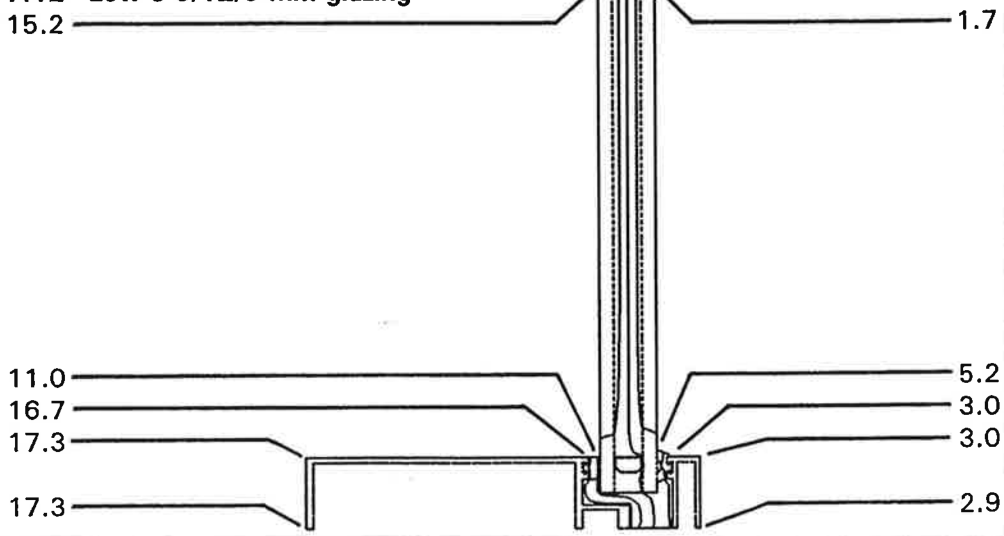
7.12 Dimensions



7.12 Ordinary 6/12/6 mm glazing



7.12 Low-e 6/12/6 mm glazing



7.13 Short mullion with long PVC-U thermal break

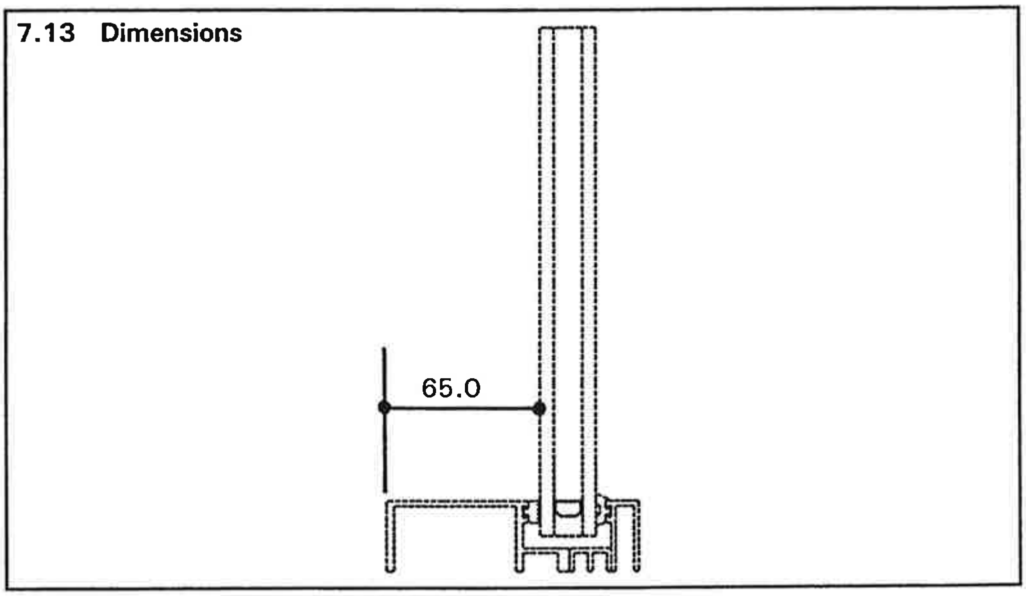
This mullion is identical to that of example 7.3, but with a shorter warm-side box.

The shorter box only reduces the U-value by about 7%, but the warm-side surface temperatures have reduced by 1.5°C. This is expected from the results of previous simulations.

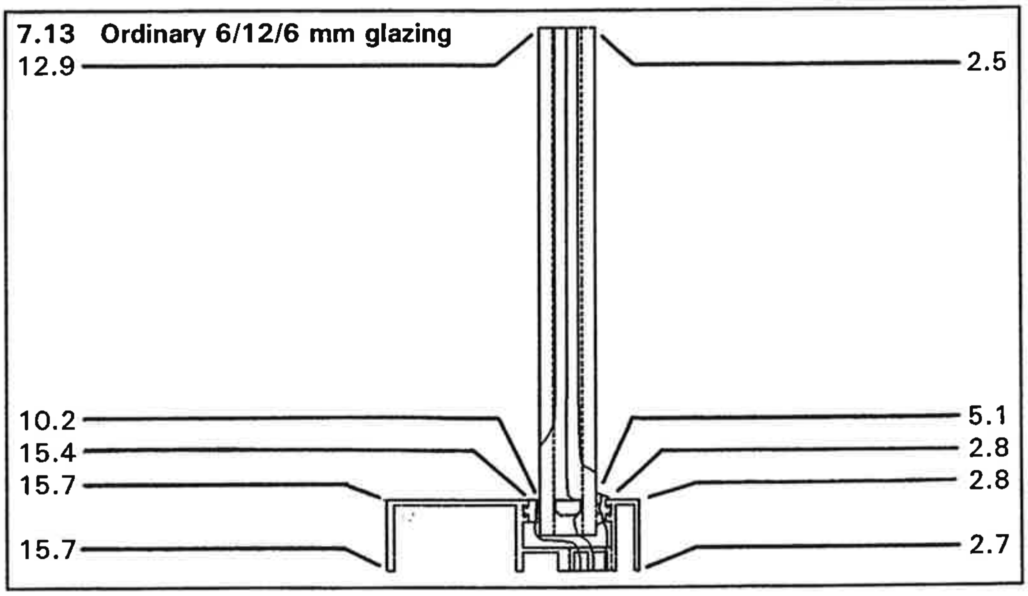
Performance

	Ordinary	Low-e	
Q_{total}	15.28	11.98	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	3.92	4.26	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	6.53	7.10	W/m²K

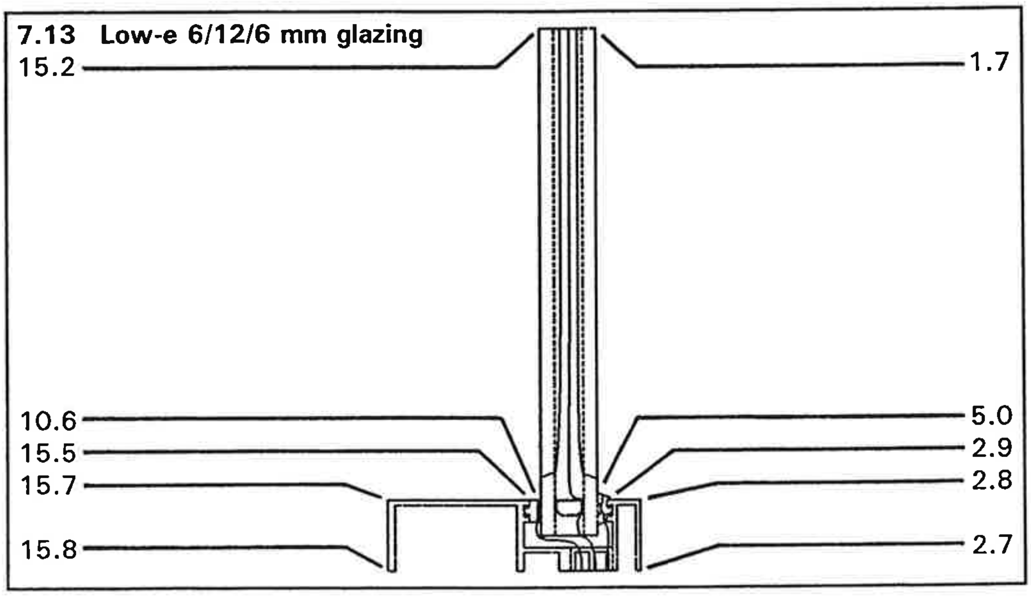
7.13 Dimensions



7.13 Ordinary 6/12/6 mm glazing



7.13 Low-e 6/12/6 mm glazing



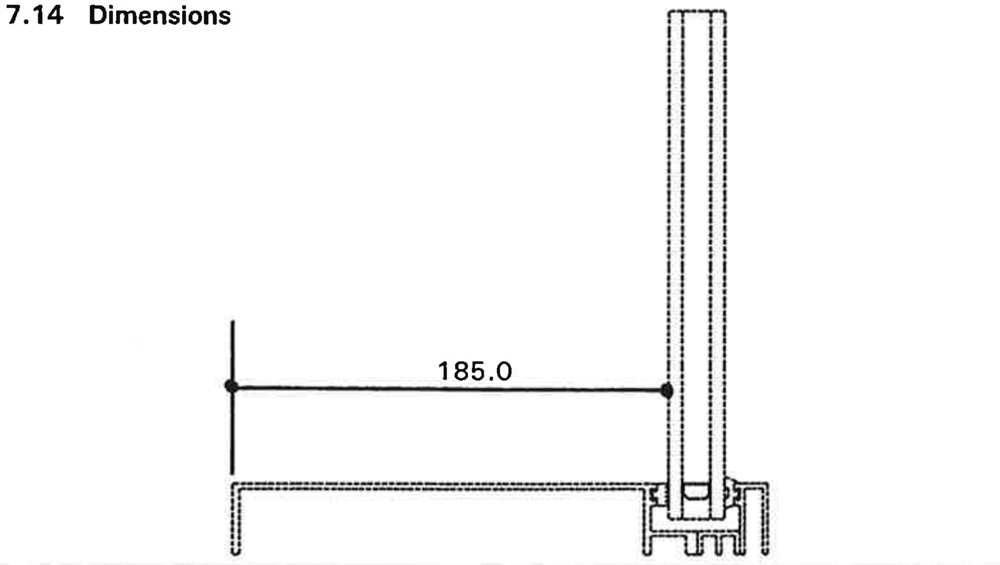
7.14 Long mullion with long PVC-U thermal break

In this mullion the warm-side box is increased in length. As expected the U-value and the warm-side surface temperatures are higher.

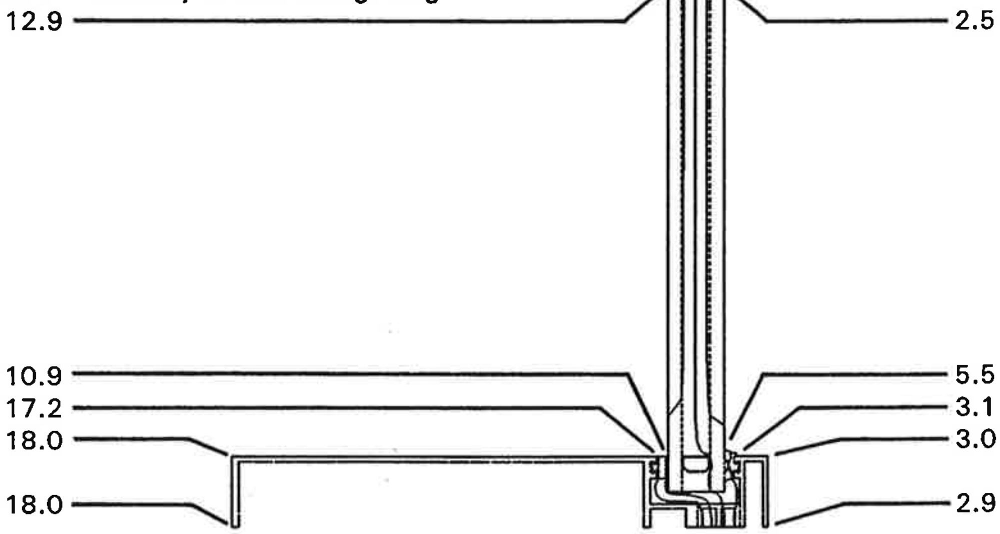
Performance

	Ordinary	Low-e	
Q_{total}	15.71	12.38	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.35	4.66	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.25	7.77	W/m²K

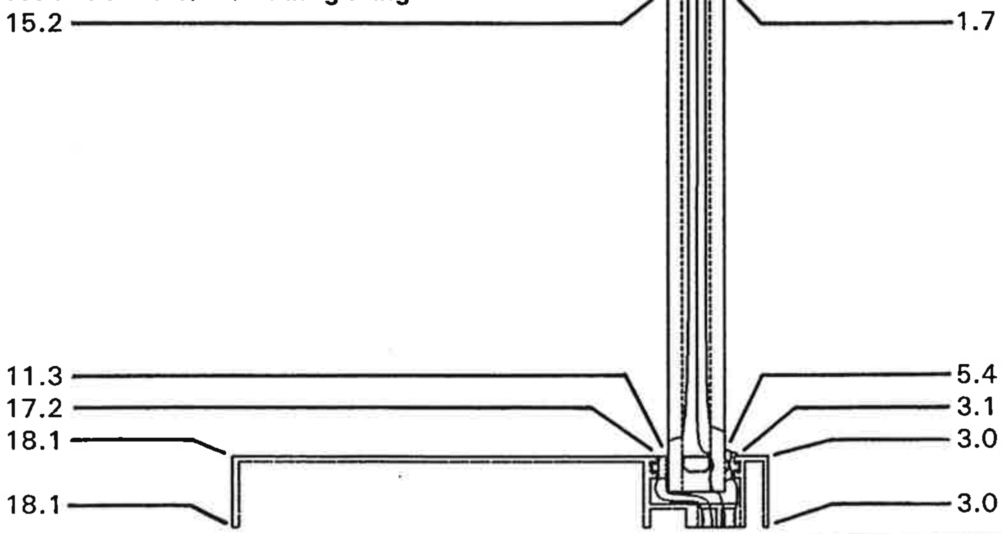
7.14 Dimensions



7.14 Ordinary 6/12/6 mm glazing



7.14 Low-e 6/12/6 mm glazing



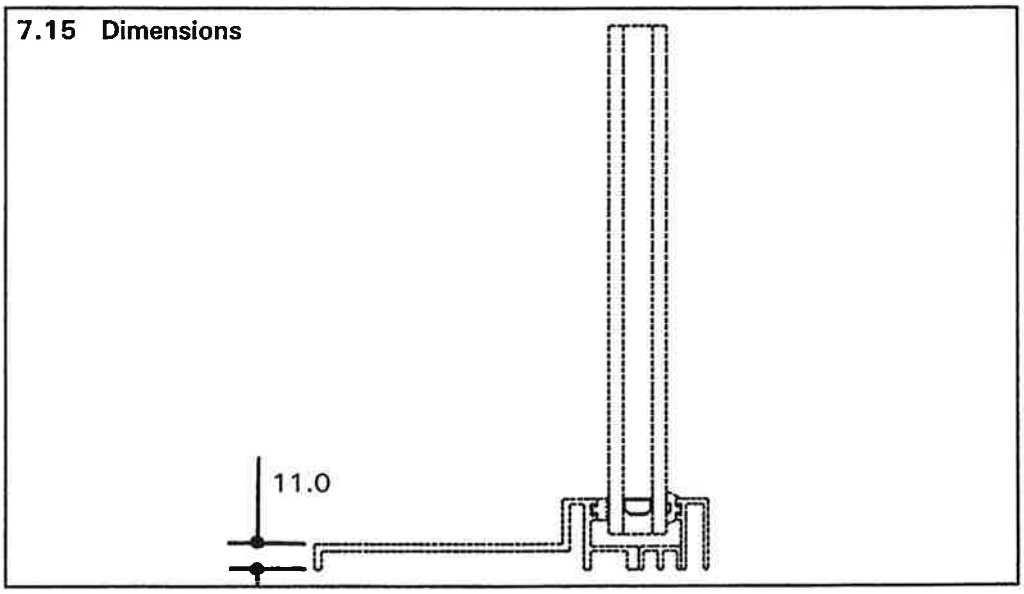
7.15 Mullion with narrower box

A typical variation on the design of the mullion is to use a narrower box. However, this modification has neither changed the length of any heat transfer path nor the amount of exposed surface area. The U-value and surface temperatures are therefore identical to those obtained in example 7.3.

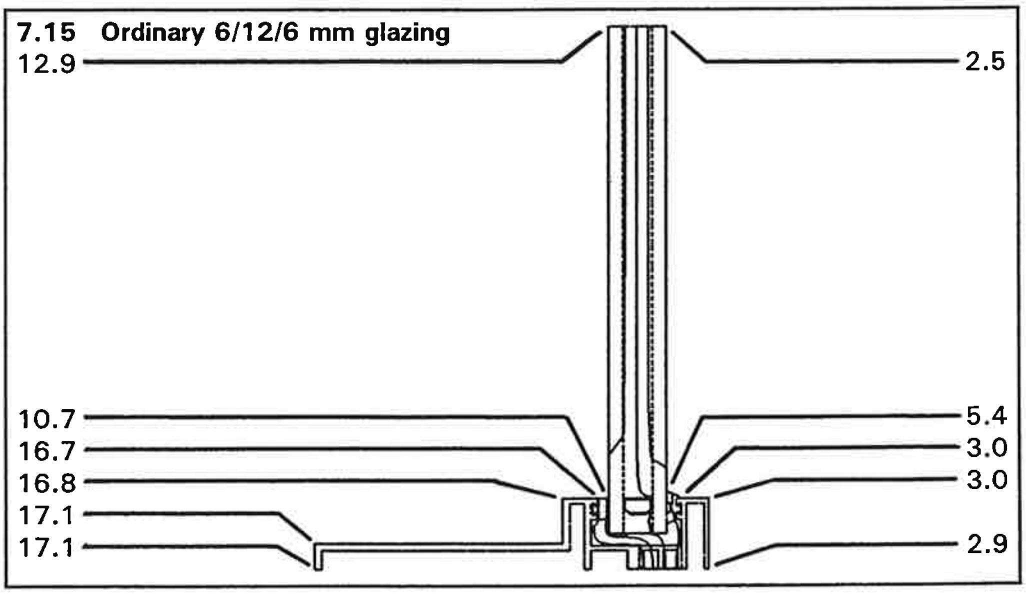
Performance

	Ordinary	Low-e	
Q_{total}	15.61	12.30	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	4.25	4.58	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	7.08	7.63	W/m²K

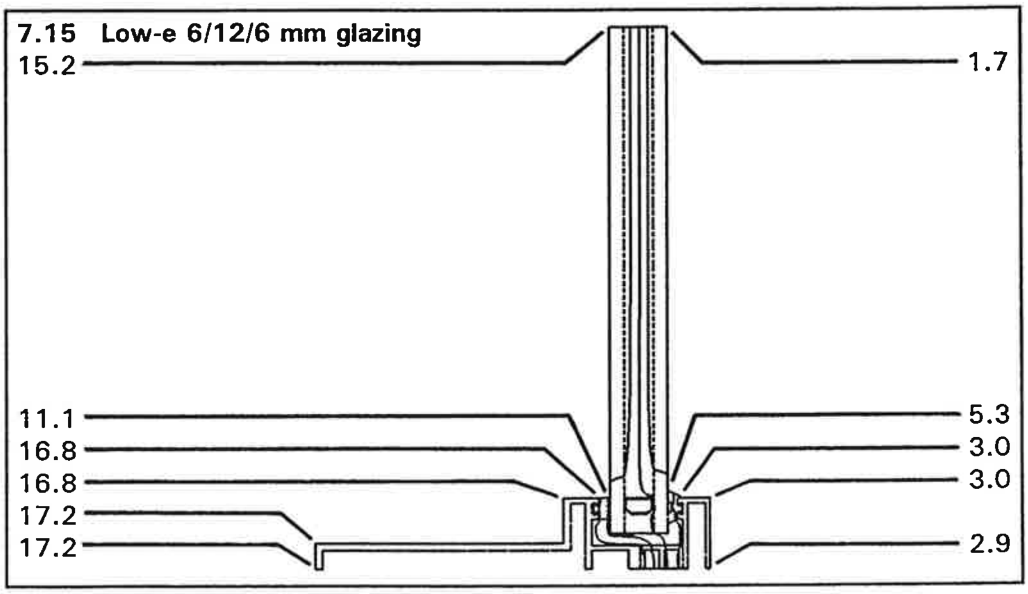
7.15 Dimensions



7.15 Ordinary 6/12/6 mm glazing



7.15 Low-e 6/12/6 mm glazing



7.16 Mullion with long PVC-U thermal break and warm edge technology glazing spacer

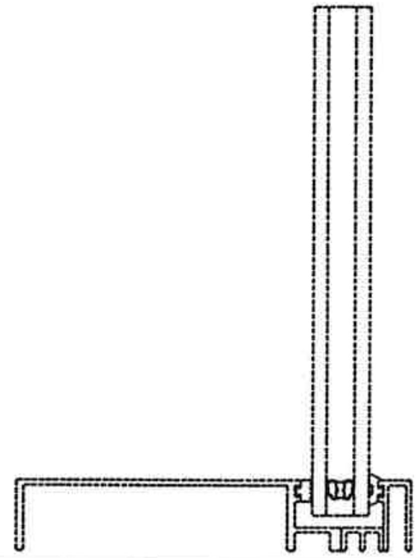
This example uses the mullion of example 7.3 with the warm edge technology glazing spacer of examples 6.1 and 6.10-6.14.

As with previous examples this warm edge spacer reduces the U-value of the mullion by 11%, and increases the temperature at the edge of the glass by 1.2°C. Warm edge technology therefore offers the same potential benefits to the thermal performance of curtain walling systems as to windows.

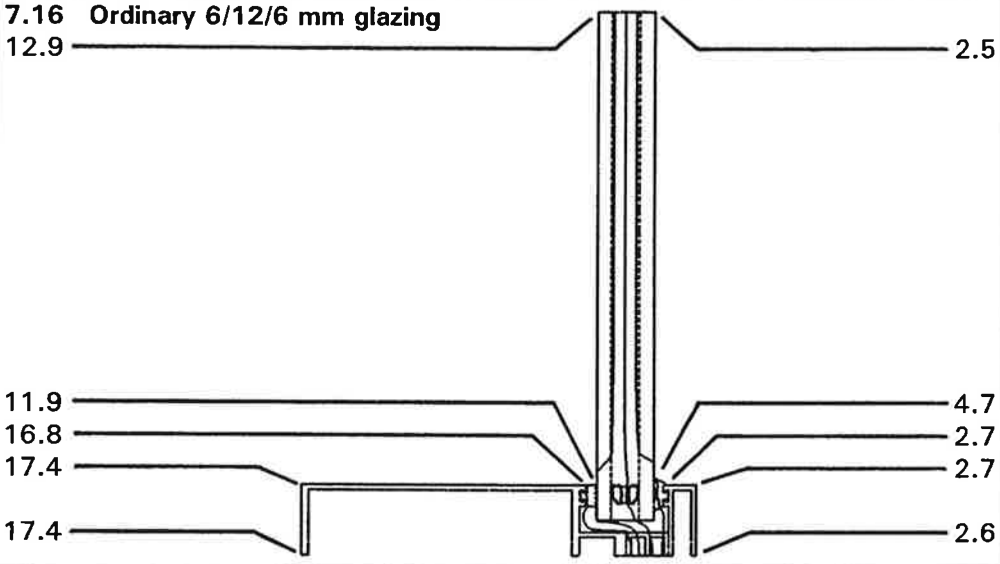
Performance

	Ordinary	Low-e	
Q_{total}	15.09	11.68	W
U_{glass}	2.84	1.93	W/m²K
P_{glass}	0.200	0.200	m
ΔT_{glass}	20.0	20.0	°C
Q_{glass}	11.36	7.72	W
Q_{frame}	3.73	3.96	W
P_{frame}	0.030	0.030	m
ΔT_{frame}	20.0	20.0	°C
U_{frame}	6.22	6.60	W/m²K

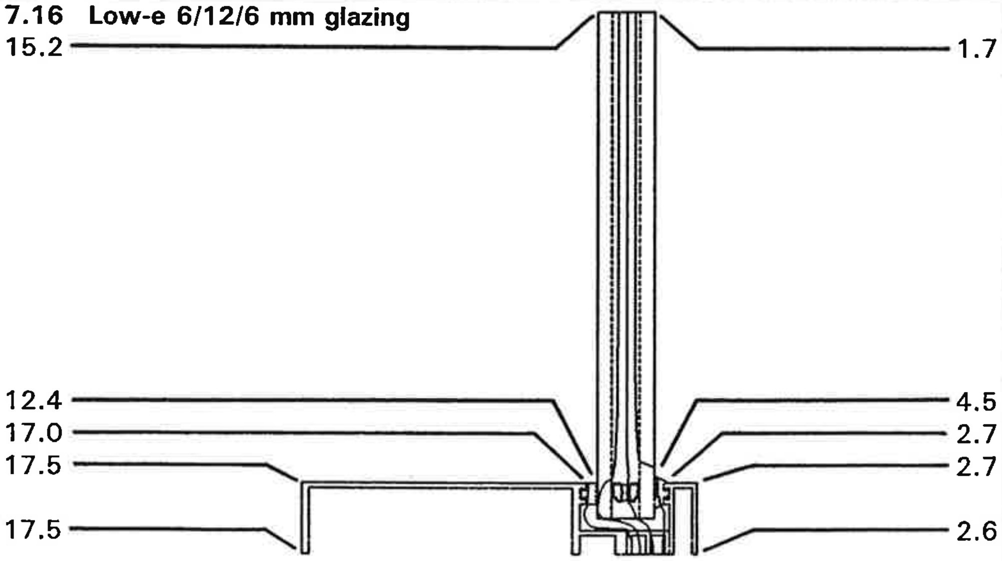
7.16 Dimensions



7.16 Ordinary 6/12/6 mm glazing



7.16 Low-e 6/12/6 mm glazing



7.17 Summary

Aluminium stick system curtain walling frames show a greater variation in performance than aluminium window frames, with regard to heat transfer. This chapter has demonstrated the great range of design options available for just one part of the frame.

For reasons of economy some types of framing system have not been considered in this chapter, most noticeably structural sealant glazing systems. It is intended that future additions to this study will examine such systems, and also examine the insulated panels which are essential to the stick system curtain wall.

8 A model for heat transfer through glazing frames

It is always difficult to estimate the effect of a modification to a particular part of a glazing frame on the overall heat transfer through the frame, because the heat transfer is, at very best, a two-dimensional process which does not obey linear rules. It is only through the use of tools such as computer-based finite element analysis simulation that the design process can be used to give a reasonable estimate of the significance of various parts of a design, and even then there are many simplifications which must be made in order to keep the analysis to a manageable size. However, it is possible to draw up a simple schematic for the principal heat transfer paths through a frame, and this is demonstrated here.

8.1 Basic rules of thermal resistance

Although two-dimensional heat transfer is difficult to describe it is possible, if the heat transfer paths are visualised as a network of one-dimensional heat flows, to show how modifying one heat transfer path will affect the thermal performance of the glazing frame.

The basic formula for one-dimensional conduction heat transfer is

$$Q = \lambda A \frac{\Delta T}{L}$$

This relationship assumes that the material is in a block of uniform thickness L, with a uniform cross-sectional area A and a uniform temperature difference ΔT, with the heat transfer occurring from hot to cold.

The thermal resistance of the block is defined as the temperature drop across the block per unit heat flow, or

$$\Re = \frac{\Delta T}{Q} = \frac{L}{\lambda A}$$

A similar relationship can be derived for combined convection and radiation heat transfer at a surface, where the surface is a plane of area A, with a uniform temperature difference between the surface and the environment, such that the surface thermal resistance is

$$\Re = \frac{1}{hA}$$

In this formula h is an overall heat transfer coefficient, combining convection and radiation heat transfer.

Note that some authors use the term 'surface resistance' when they mean 1/h; this idea originated with layered structures (the area A is the same for each layer in the structure and so cancels out). For the examples given below the term 'surface thermal resistance' is used to mean the expression in the equation above.

For any possible conduction heat transfer path through a structure it follows that the thermal resistance will be greatest for longer and narrower paths through materials of lower thermal conductivity. For heat transfer from surfaces the thermal resistance is greatest for surfaces of small area and lower heat transfer coefficients (sheltered surfaces with natural convection heat transfer).

8.1.1 Basic examples of heat transfer through resistances

Figure 8.1 shows some simple resistance networks, where various paths for heat transfer exist between a warm internal environment denoted by point 'i' and a cool external environment denoted by point 'e'. Assume that the temperatures of points 'i' and 'e' remain fixed, and are the same for each of the following examples.

8.1.2 Two resistances in series

In Figure 8.1(a) there are two resistances, RI and RE. The intermediate point 'p' is at some temperature which depends on the relative magnitudes of RI and RE. If RI and RE are equal then 'p' is at a temperature midway between 'i' and 'e'. The general formula for the temperature at point 'p' is

$$T_p = \frac{RE}{RI+RE} \times (T_i - T_e) + T_e$$

If RE is then increased by some design modification then less heat can flow through RE for given temperatures at 'p' and 'e'. If the temperature at 'p' remained unchanged then more heat would be flowing into 'p' than is flowing out. The temperature at point 'p' must therefore be higher than before, so that the heat transfer through RI is reduced, and the heat transfer through RE is increased, until the heat transfers are equal. In this simple case the temperature drop across each resistance is proportional to the resistance, because the heat flow through a resistance is directly proportional to the temperature difference across the resistance. With two resistances in series the heat flow must be the same through each under steady conditions.

8.1.3 One resistance in series with two resistances in parallel

In Figure 8.1(b) the resistance RE has been split into two resistances in parallel, RE1 and RE2, whilst the resistance RI is unchanged. If the heat flows through RE1 and RE2 are Q_1 and Q_2 respectively then the total heat flow Q is

$$Q = Q_1 + Q_2 = \frac{T_p - T_e}{RE1} + \frac{T_p - T_e}{RE2}$$

The single resistance RE which gives the same heat flow Q for the same temperature difference must satisfy

$$Q = \frac{T_p - T_e}{RE}$$

and so

$$\frac{1}{RE} = \frac{1}{RE1} + \frac{1}{RE2}$$

Thus if RE1 = RE2 it follows that RE1 and RE2 must each be twice the value of RE from the previous example to give the same temperature at point 'p'.

For this network the temperature at point 'p' is given by

$$T_p = \frac{1}{\left(1 + \frac{RI}{RE1} + \frac{RI}{RE2}\right)} \times (T_i - T_e) + T_e$$

Increasing the resistance RE1 now has an interesting result. If RE1 is doubled then the heat transfer through RE1 out of point 'p' should reduce, requiring the temperature at 'p' to increase and balance the heat flows. However, as well as reducing the heat transfer through RI an increase in temperature 'p' also increases the heat transfer through RE2. The temperature at 'p' cannot increase by as much as if the single resistance RE was doubled in the previous example. Where there are two parallel heat transfer paths increasing the resistance of one will not have as significant an effect as the case where both are increased. Therefore increasing the resistance of the thermal break in an aluminium window will not have a significant effect if the glazing edge detail is not improved.

Increasing the resistance RI has the effect that the temperature at 'p' must decrease, so that there is less heat transfer through RI, RE1 and RE2. This generally increases the condensation risk at point 'p', suggesting that the best way to improve the condensation risk of a structure is to increase resistances on the cold-side of the structure, which will also reduce the total heat loss through the structure, or to reduce resistances on the cold-side of the structure, which will increase the heat loss through the structure. The former case is demonstrated by putting a PVC-U cladding on the exterior surface of the hot-rolled steel frame, whilst the latter case is demonstrated by increasing the warm-side surface area of the thermally broken aluminium window and curtain walling frames.

8.1.4 Two parallel pairs of series resistances, with a bridging resistance

In a real component the type of resistance network shown in Figure 8.1(c) is more likely. There are now two paths between the warm environment 'i' and the cool environment 'e', but they are linked by a cross-resistance, $R\alpha$.

The temperature at point 'p1' is now given by the formula

$$T_{p1} = \frac{\frac{1}{RI1} + \frac{1}{RI2} + \frac{R\alpha}{RI1}\left(\frac{1}{RI2} + \frac{1}{RE2}\right)}{\left[\left(\frac{1}{RI1} + \frac{1}{RE1}\right) + \left(\frac{1}{RI2} + \frac{1}{RE2}\right) + R\alpha\left(\frac{1}{RI1} + \frac{1}{RE1}\right)\left(\frac{1}{RI2} + \frac{1}{RE2}\right)\right]} \times (T_i - T_e) + T_e$$

It is apparent that even with just five thermal resistances the prediction of temperature at a point is complex. The prediction of overall heat flow is equally difficult, even if the resistance paths through a system can be identified as straightforwardly as above.

Now, increasing the resistance RE1 will increase the temperature at 'p1', which then causes an increase in the temperature at 'p2'. Note that it does not matter if the normal direction of heat transfer is from 'p1' to 'p2' or vice versa! If the normal direction of heat transfer is from 'p1' to 'p2' then the extra heat transfer through $R\alpha$ (caused by an increase in the temperature at 'p1') must pass through RE2 or require a drop in the heat transfer through RI2, both of which require 'p2' to increase in temperature. If the normal direction of heat transfer is from 'p2' to 'p1' the heat transfer through Rα would be reduced by an increase in the temperature at 'p1', which would require less heat transfer through RI2 or more through RE2, and so the temperature at 'p2' must increase. It is important to observe that increasing RE1 will always result in more heat transfer through RE2, but there will be less heat transfer overall.

It is a general feature of resistance networks that increasing the resistance of one part of the network will reduce the overall heat transfer, but in a proportion which is less as the network becomes more complex. The following examples consider some resistance networks for a glazing frame.

8.2 A simplified thermal resistance diagram for glazing frames

Figure 8.2 shows a typical double-glazed window frame, in outline, overlaid with a number of thermal resistances. A minimum number of resistances has been drawn to illustrate the general paths for heat transfer through the frame.

The thermal resistance of the frame has been represented as 16 discrete resistances. These resistances are:

GI between the warm-side environment and the warm-side glass

G between the warm-side glass and the cold-side glass

GE between the cold-side glass and the cold-side environment

Gα between the centre of the warm-side glass and the edge of the warm-side glass

Gβ between the centre of the cold-side glass and the edge of the cold-side glass

GS through the glazing unit edge spacer

Fα linking the warm-side of the glazing edge and the warm-side of the frame

Fβ linking the cold-side of the glazing edge and the cold-side of the frame

FI between the warm-side environment and the warm-side frame surface

F through the frame

FE between the cold-side frame surface and the cold-side environment

The magnitude of each resistance would depend on the various materials used in the frame and glazing. Generally however the cold-side surface resistances (GE and FE) are lower than the warm-side surface thermal resistances (GI and FI) because the cold-side overall heat transfer coefficient is 2-3 times higher. The glazing unit edge resistance (GS) is negligible if a traditional aluminium glazing spacer is used.

More specific examples of resistance networks for different types of glazing frame are given below.

8.3 Non-thermally-broken metal window frames

In a non-thermally-broken metal frame (aluminium or steel) the resistances Fα, Fβ and F are negligible (the resistances Fα and Fβ are due only to the glazing seals) and the resistance network is as shown in Figure 8.3.

The temperature of the frame is dominated by the frame surface thermal resistances FI and FE, which will depend on the exposed surface areas. It is possible for the frame temperature ('f1'/'f2') to be somewhere between the glass edge temperatures 'e1' and 'e2', in which case heat transfer from 'e1' to 'e2' will occur both through the edge resistance GS and through the frame, which also offers little resistance (Fα+F+Fβ). Improving the value of GS, by using a warm edge technology glazing spacer, will have little effect, as the majority of the heat transfer is already likely to be occurring through the frame.

8.4 Thermally-broken metal window frames

In a thermally-broken metal frame (aluminium or steel) the resistances Fα and Fβ are still negligible, but the resistance F is now significant, as shown in Figure 8.4. If the resistance F is significant then the temperature at point 'f1' will be higher than the temperature at 'e1'. The heat transfer into the frame warm-side surface, through resistance FI, will now be distributed between two paths through the frame: the thermal break (resistance F) or the glazing edge (resistance GS). Improving one of these resistances will cause the temperature at 'f1' to increase, and so force more heat through the other resistance. Note that the temperature of point 'e1' will also rise, and the condensation risk will be generally reduced.

8.5 PVC-U or timber window frames

In PVC-U or timber frames all of the frame resistances are significant, as originally shown in Figure 8.2. Increasing any resistance will both reduce the heat flow through the resistance and increase the point temperatures on the warm-side of the resistance.

8.6 PVC-U or timber window frames with aluminium cladding on the cold-side

With an aluminium profile as part of the frame the metal surface of the frame behaves as a fin. Figure 8.5 shows the case of an insulating frame material with an aluminium section forming the cold-side of the frame.

The resistance F is strongly dependent upon the proportion of the insulating material used in the frame. Clearly if F is increased then the temperature 'f1' will increase and more heat is pushed into the glazing edge. This will increase the temperature 'e1'. Note that the resistance Fβ is negligible so that the temperature at 'e2' is likely to be low, as is the temperature at 'e1'. However, the point 'f1' is somewhat isolated from points 'e1' and 'f2' by the resistances Fα and F, and so the temperature at 'f1' should be significantly higher.

8.7 PVC-U or timber window frames with aluminium cladding on the warm-side

Reversing the frame of the previous example gives rise to the resistance network of Figure 8.6. The resistance Fα is now negligible and the resistance Fβ is now significant. The temperature at point 'e2' should be higher than in the previous example, with a corresponding increase in the temperature at 'e1', but the temperature at 'f1' should now be closer to the temperature at 'e1' and should be lower than in the previous example.

8.8 Window frames with sills

For a window frame with a sill there are a number of additional resistances, as shown in Figure 8.7:

Sα linking the warm-side of the frame and the warm-side of the sill

Sβ linking the cold-side of the frame and the cold-side of the sill

SI between the warm-side environment and the warm-side sill surface

S through the sill

SE between the cold-side sill surface and the cold-side environment

The heat transfer paths within the sill are of most significance if the sill is a non-thermally-broken metal sill, such that the resistance S is zero and the resistances Sα and Sβ are low. Clearly in such a circumstance the temperature at 's1' will be low, and this may compromise the performance of the window frame.

8.9 Curtain walling frames

A symmetrical curtain walling frame with identical glazing either side is shown overlaid with a resistance network in Figure 8.8. It is important to note that the resistance network is also symmetrical, and the same issues apply as for the thermally-broken metal window frame.

8.10 Other modifications

There are three modifications which may be made to the glazing unit, the effects of which are considered below. Figure 8.2 is used for reference. It should be noted that the temperatures of points 'g1' and 'g2' are fixed by the centre glazing performance, and that the temperatures 'e1' and 'e2' are usually somewhere between 'g1' and 'g2' in magnitude because the edge spacer is not as good thermally (yet!) as the gas-space.

8.10.1 Thicker glass

Thicker glass will reduce the resistance of the heat transfer path from the centre to the edge of the glass. Thus resistances Gα or Gβ will decrease, as the glass thickness is increased.

If resistance Gα decreases there will be more heat transfer into the edge of the glazing unit on the warm-side, and the temperature at 'e1' must increase (although probably only slightly). This will cause an increase in the temperature at 'f1' and so more heat transfer will occur through F. Generally then the heat transfer through the framing system will increase.

If resistance Gβ decreases there will be more heat transfer from 'e2' to 'g2', such that 'e2' will decrease in temperature, as will 'e1' and 'f1'. If all of the temperatures on the warm-side of the frame decrease then there must again be more heat transfer through the system because the heat flow through FI is increased (remembering that the temperature at 'g1' is fixed).

8.10.2 Improved centre-glazing performance

If the centre-glazing resistance G is increased, for example by using a less-conductive gas or a low-emissivity coating, then point 'g1' will become warmer and 'g2' will become cooler. The result is more heat transfer from 'g1' to 'e1' (which becomes warmer) and more heat transfer from 'e2' to 'g2' ('e2' becomes cooler). If the temperatures on the warm-side of the system are increasing then there must be less overall heat transfer through the resistances GI and FI, but there is a greater interaction between the glazing and the frame.

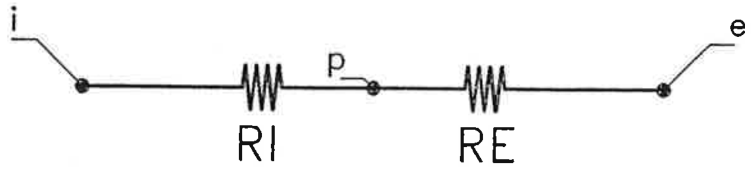
8.10.3 Warm edge technology

With a warm edge technology glazing spacer the resistance GS is increased. Clearly this will cause in increase in the temperatures 'e1' and 'f1', and so must reduce the heat transfer into the frame warm-side surface. Similarly the heat transfer through the resistance Gα must be reduced, and so the overall heat transfer through the system reduces.

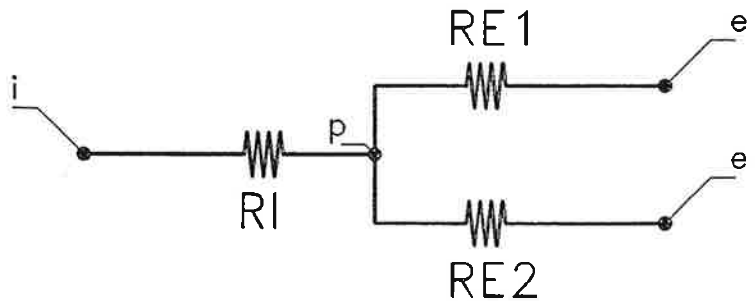
8.11 Summary

With the aid of a simple schematic such as that shown in Figure 8.2 it is possible to visualise heat transfer through a glazing frame and predict the general effect of simple design modifications. It is a common result that reducing any thermal resistance results in more heat transfer through the system, whereas increasing a thermal resistance results in less heat transfer! However, there may be a local reduction in heat transfer, even if the overall heat loss is increased, and the temperature at a point is a complex function of the various resistances. Condensation risk may be reduced at some points by increasing the heat transfer through a glazing frame.

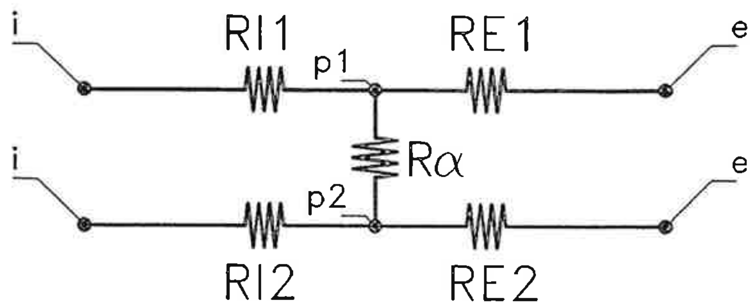
Figure 8.1 **Simple resistance networks**



a) **Two resistances in series**



b) **One resistance in series with two resistances in parallel**



c) **Two parallel pairs of series resistances, with a bridging resistance**

Figure 8.2 **A simple resistance network for a glazing frame**

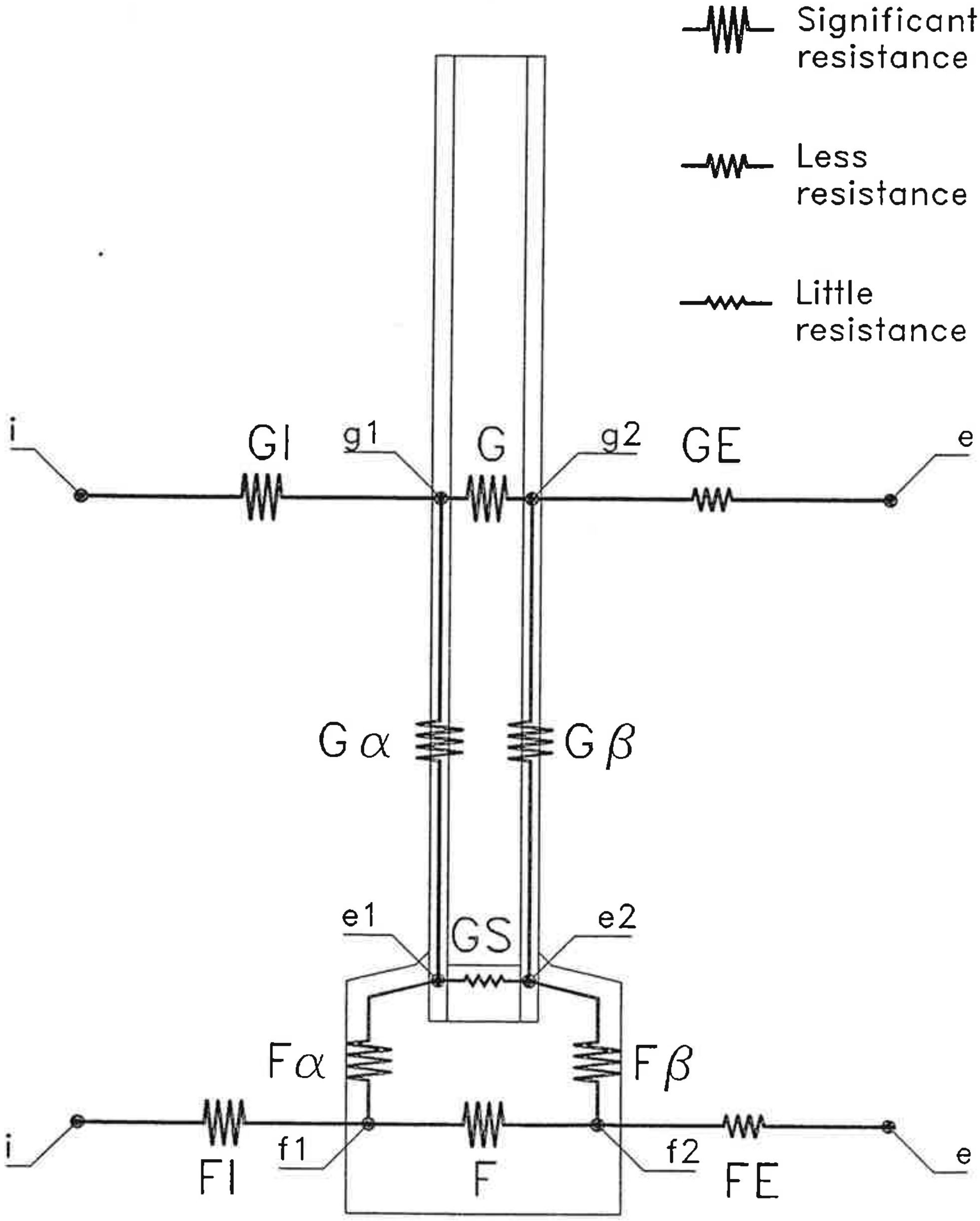


Figure 8.3 **Non-thermally-broken metal window frames**

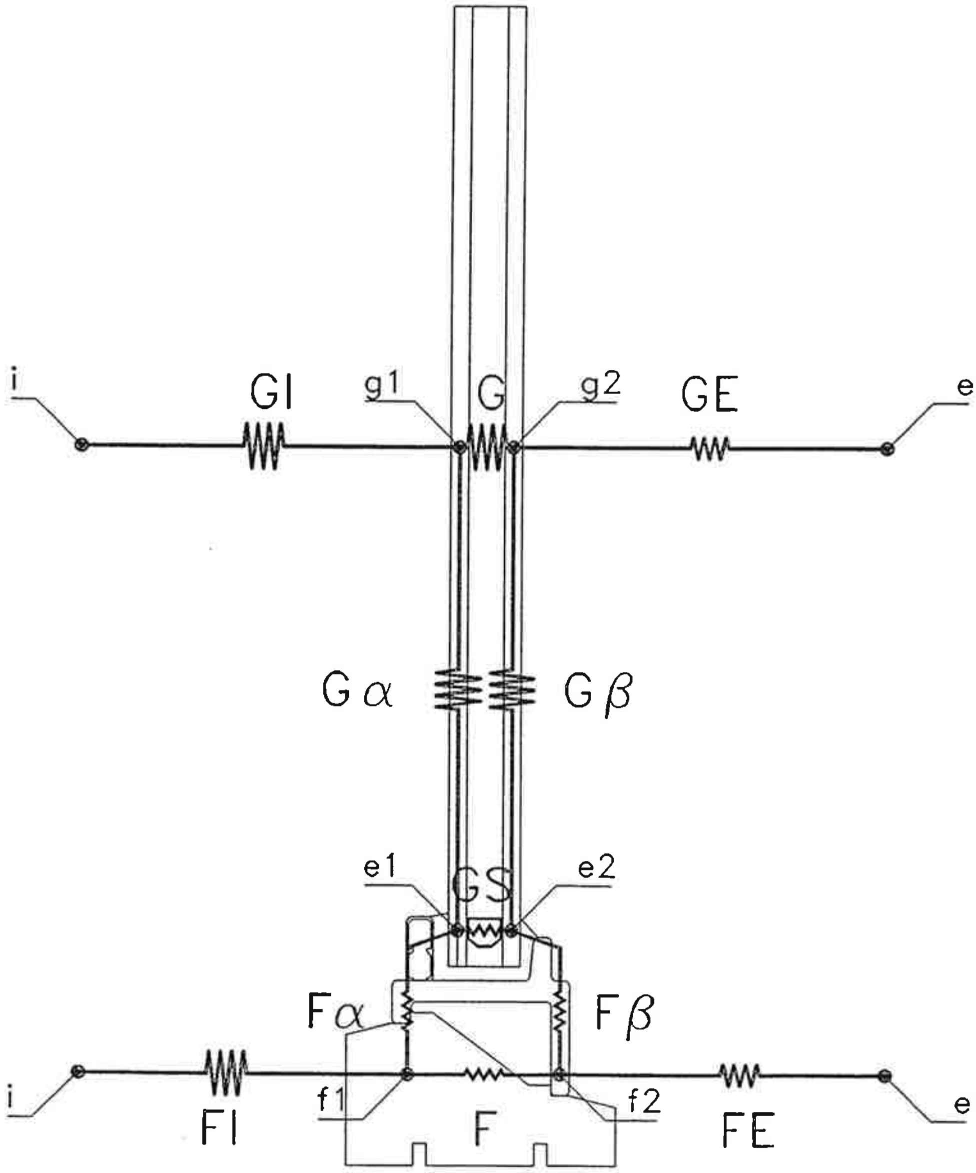


Figure 8.4 **Thermally-broken metal window frames**

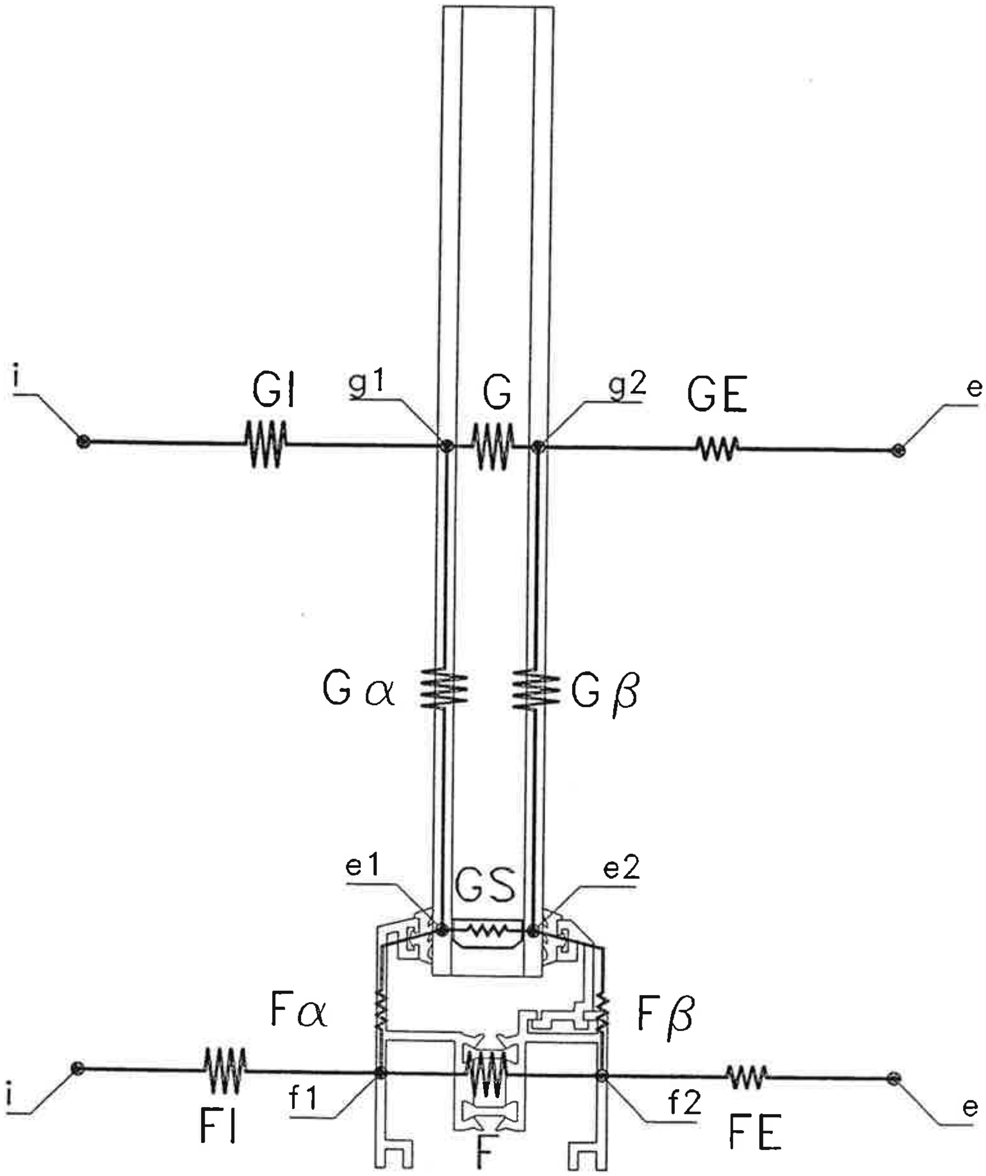


Figure 8.5 **PVC-U or timber window frames with aluminium cladding on the cold-side**

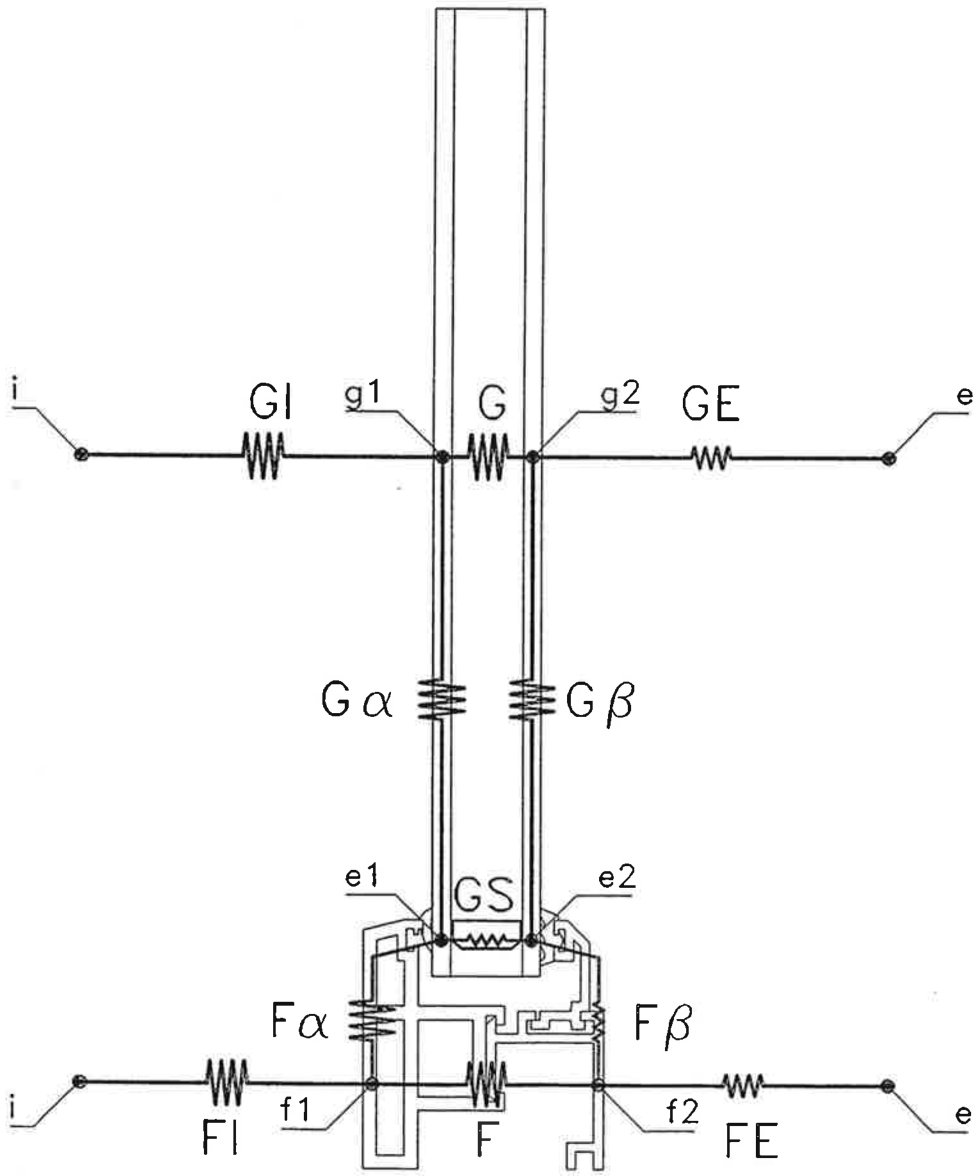


Figure 8.6 **PVC-U or timber window frames with aluminium cladding on the warm-side**

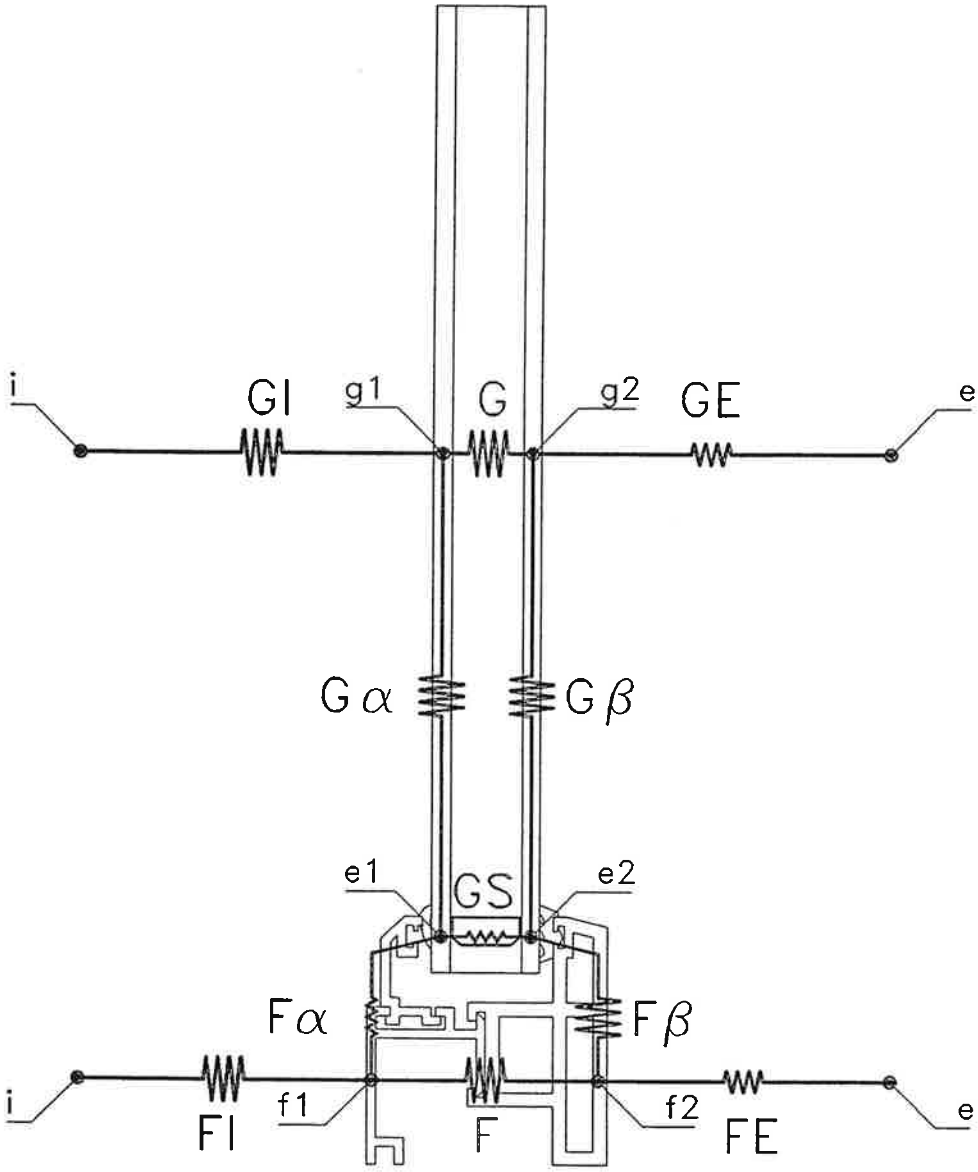


Figure 8.7 **Window frames with sills**

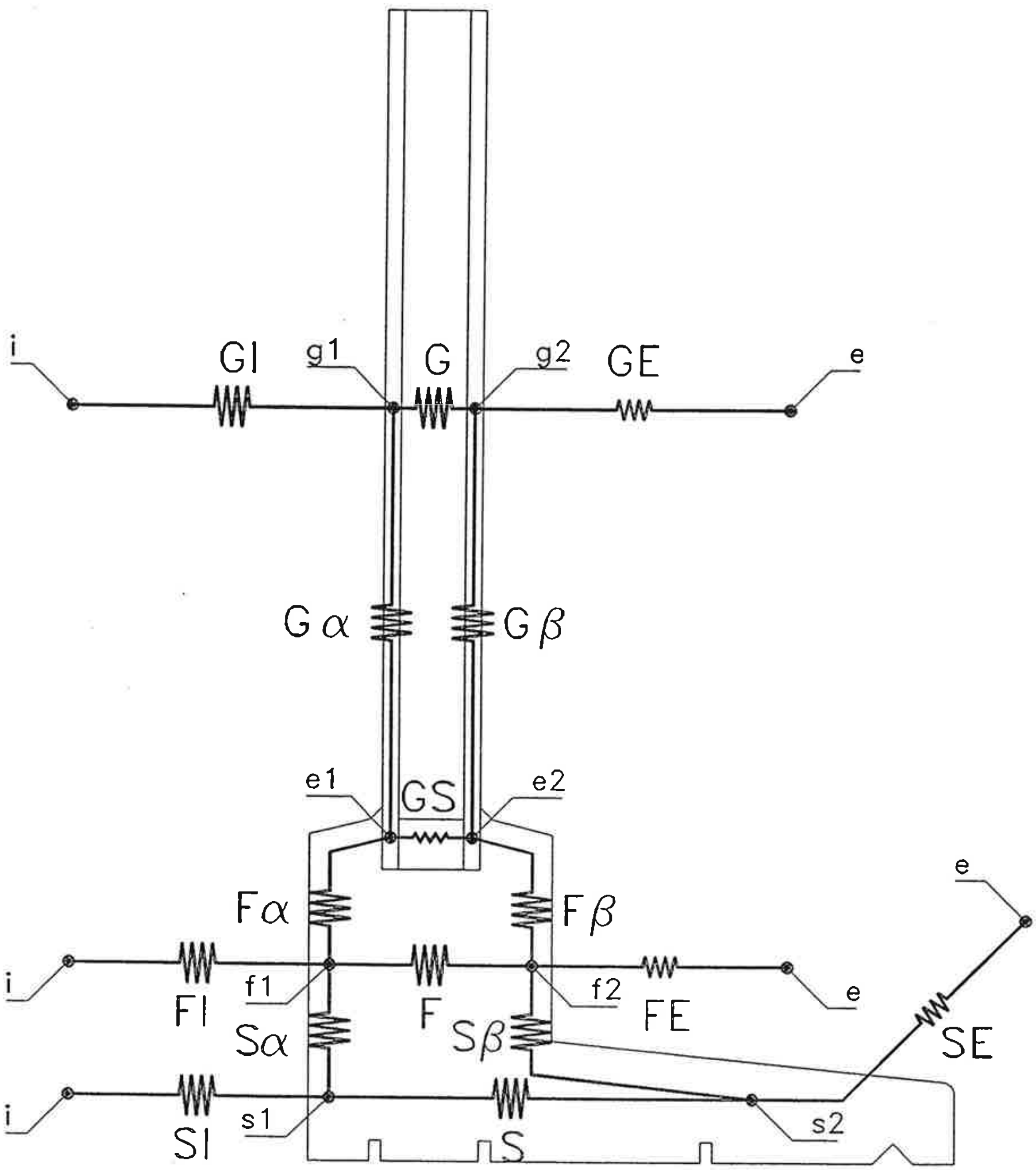
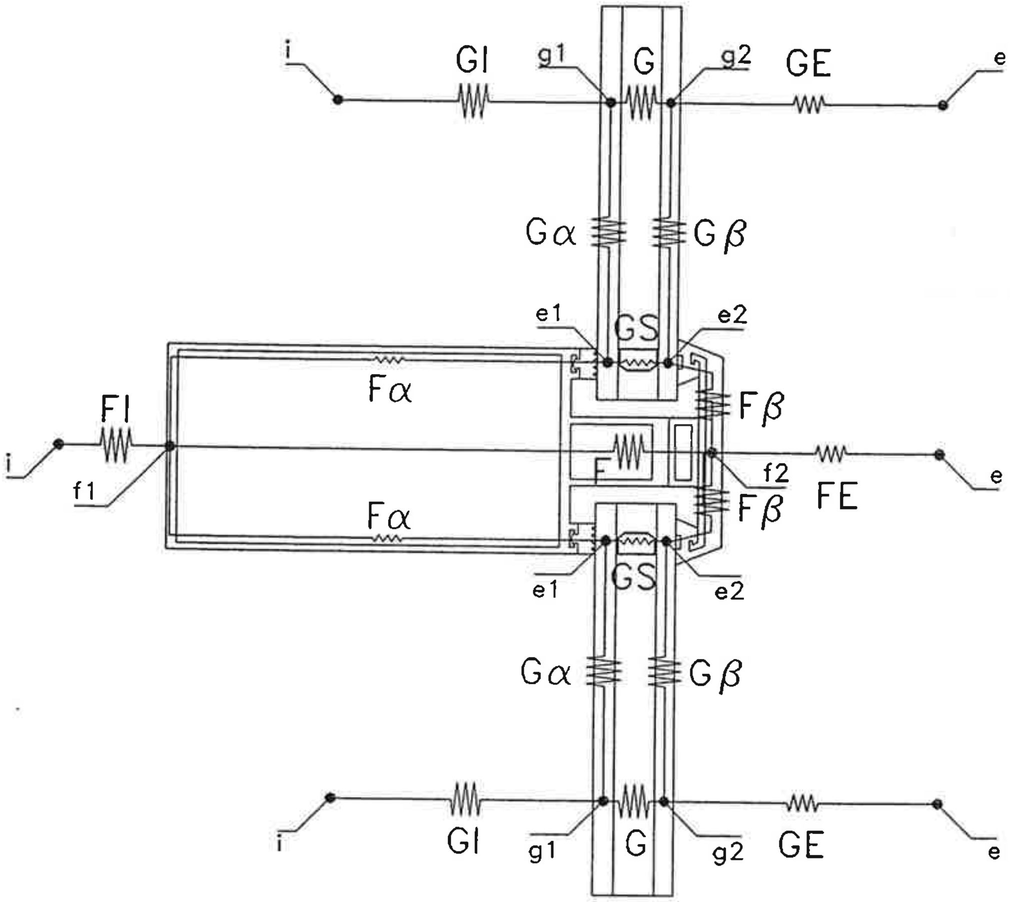


Figure 8.8 **Curtain walling frames**



Appendix A The method of analysis

A.1 Introduction

Measurement and hand-calculation are both limited as methods of understanding the heat transfer through typical glazing frames.

A measurement study would require a large set of samples, each differing from the others in only one or two details, and would require a considerable period of time for the study. The study would have to be constrained to one particular measuring device, as the basic apparatus for measuring heat transfer through complex system is not manufactured to a fixed design, instead being tailored to suit a particular laboratory and relying on standardised calibration procedures to achieve an acceptable level of repeatability.

Hand-calculations (calculations relying on a calculator rather than a computer) are limited in that the only readily applicable mathematical formulae are based on one-dimensional heat flow and are not particularly accurate when used to approximate two- or three-dimensional heat flow through a complex structure.

The only alternative is to use a method of analysis which can replicate two- or three-dimensional heat flows and which does not require a physical sample of the glazing frame. Such methods of analysis are computer-based, and are generally termed 'simulation' methods.

A.2 Finite element analysis

Simulation methods work by sub-dividing the structure into a number of small elements and then applying heat transfer relationships between adjacent elements. The type of simulation analysis used for this study is called 'finite element analysis' (FEA), and is performed using a commercially available software package called ANSYS®. FEA was chosen because it allows curved and diagonal lines to be represented exactly, unlike some other simulation methods. ANSYS® was selected because it allows the exact solution of radiation heat transfer problems within cavities in the glazing frame. As a major piece of commercially available and fully-supported software ANSYS® also offers a degree of confidence in the results obtained that could not be obtained for other pieces of unsupported software.

The level of detail to which a finite element analysis can be performed is limited by the computer hardware available. For a typical personal computer, as used for this study, the only constraint was that three-dimensional heat transfer could not be modelled. The glazing frames are therefore modelled in cross-section, which only requires a two-dimensional analysis, and the properties of the frame are assumed to be equal at any point along its length.

It is important to realise however that some heat transfer phenomena are not modelled, generally because there is a lack of understanding of the significance of those phenomena, and consequently a lack of parametric data that would be required for simulations. However, these neglected phenomena usually have the effect of reducing the heat transfer through the real structure, and so the predicted heat transfer through the structure is therefore higher than that which would be observed in the real system. A factor of safety is thereby introduced into the assessment.

The analyses reported in this study typically used 2-3000 elements per frame, the maximum side of any element being limited to 3 mm generally, and to 2 mm in the region of the glazing edge spacer.

A.3 Basic heat transfer processes

There are three basic heat transfer processes - conduction, convection and radiation.

A.3.1 Conduction

Conduction heat transfer occurs through solids and small volumes of fluids (such as the air in small cavities). However, in larger bodies of fluid a transition into convection heat transfer occurs if the fluid begins to move under the influence of temperature-gradient-induced buoyancy forces.

Conduction across a boundary between two solids may be limited if the solids are not in good thermal contact. This 'thermal contact resistance' is difficult to assess however, as it depends on the pressure of contact between the surfaces, as well as the relative hardness of the surfaces. The heat transfer through a real component will always be reduced by the effects of thermal contact resistance.

A.3.2 Convection

Convection heat transfer may occur between a surface and a volume of fluid. If the fluid moves over the surface (either due to natural temperature-gradient-induced buoyancy forces or as a result of forced air movement) then a greater rate of heat transfer occurs than that possible by conduction alone. If a body of fluid is trapped between two surfaces then a double-transfer occurs which appears to be from surface to surface. The occurrence of natural (buoyancy-induced) convection in closed cavities depends on there being a sufficient temperature difference and a large enough volume of fluid (compared to the minimum dimension of the cavity) to allow the buoyancy forces to overcome surface friction. In small cavities, or where the temperature gradient is too small, then conduction may occur but convection cannot. Convection may also be limited where two surfaces meet to form a corner, and fluid motion is limited. Convection heat transfer will be reduced wherever a corner or recess occurs, and the convection heat transfer associated with a real component is likely to be less than assumed for the analyses here.

A.3.3 Radiation

Radiation heat transfer is due to the emission of heat from surfaces in the infra-red part of the electromagnetic spectrum. Radiation heat transfer occurs between any two surfaces which are in direct line of sight, and separated by a medium which is transparent to infra-red. Thus a window may receive radiated heat from all of the surfaces within a room which are in direct line of sight of the window. However, some of the radiated heat which falls on a surface will be reflected, and the effect of multiple reflections cannot be calculated without first identifying all of the surfaces within the room. To simplify this problem it can be assumed that all of the surfaces within the room are at the same temperature. Radiation heat transfer between the glazing frame and the glazing surface will reduce the heat transfer through a real glazing frame.

A.4 Setting-up the analysis

Before setting up an analysis of heat transfer through a glazing frame it is necessary to consider how each of the different types of heat transfer is to be modelled.

A.4.1 Two-dimensional heat transfer

For reasons of simplicity and economy a simulation almost always considers a two-dimensional cross-section through a component. However, there are always interactions where frames meet, and the heat transfer at a corner or some other frame joint will be increased slightly by these 'end effects'.

A.4.2 Wall interactions

The interaction between a frame and the wall into which it is mounted is not considered. Generally there are a large number of wall constructions, and the position of the frame in the wall is variable. All current standard methods of assessment isolate the frame from the wall.

A.4.3 Solids

Solid parts of the frames are modelled as conduction elements. This requires only that the thermal conductivity of the material is known. For some materials the thermal conductivity can be found from tables of typical values. Such tables are usually published alongside standards or guidelines relating to thermal performance assessment. However, the best source of thermal conductivity data is usually the producer of the material, who may have values measured to one of several compatible standards available world-wide. For some widely used materials, for which there is a known composition, such as many metal alloys, values may be quoted in various literature sources.

For some materials, where formulation is a guarded commercial secret, suitable thermal conductivity data may be hard to obtain. It is particularly difficult to obtain reliable data for the thermal conductivity of many synthetic rubbers because various additives and fillers are incorporated in the final product. The raw polymer thermal conductivity may differ significantly from the thermal conductivity of the final blend. Seemingly identical rubbers of different hardnesses can be expected to have different thermal conductivities. It is not unusual for quoted values of thermal conductivity of synthetic rubbers to vary in a ratio of 4 to 1.

Foamed materials present an additional problem in that the thermal conductivity of a foam depends on the proportion of gas within the foam. An un-compressed foam will therefore have a lower thermal conductivity than the same foam when compressed into place. Although a value may be quoted for the thermal conductivity of a particular foam it is always sensible to determine both the un-compressed density of the foam (which helps to define the initial amount of gas in the product) and the degree of compression for which the value was measured.

Appendix B lists the values of thermal conductivity taken for each of the solid materials considered in this study.

A.4.4 Gas-filled cavities

A cavity in a frame is usually air-filled. If the cavity is small then conduction and radiation heat transfers occur - friction effects prevent the formation of a convection current. The size of the cavity is important both in the direction of heat transfer, and perpendicular to this direction. Although much work has been directed at the problem of convection heat transfer in the large cavities found in multiple glazing units and cavity walls, very little work has been performed on the smaller cavities found within window and curtain walling frames.

For cavities defined by a continuous aluminium boundary analysis shows that the maximum temperature difference across the cavity is too small to allow any significant heat transfer through the air. Heat transfer through these cavities is therefore not modelled.

For most other cavities it has been assumed that only conduction and radiation heat transfer occur, with the single exception of the glazing air-space, which is discussed further below. Whilst an assumption of conduction only (no convection) in the various cavities may generate small errors, they are unlikely to be greater than the errors generated by assumptions that would be required to determine convection heat transfer coefficients. Most experimental data on convection heat transfer is based on flat surfaces and rectangular enclosures, whereas the majority of frame cavities are irregular in shape.

Radiation within cavities is modelled in one of two ways. For irregular cavities the radiation heat transfer is modelled exactly, using one of the advanced features of ANSYS® which allows radiation view factors to be calculated automatically for any combination of surfaces. This procedure automatically accounts for multiple reflections from surfaces. The only limitation of the procedure is that each surface is assumed to have a constant radiation emissivity for all radiation wavelengths, and regardless of the direction in which the radiation leaves the surface.

The procedure laid out in BS 6993 Part 1 is used to estimate the effect of radiation in rectangular cavities and to determine the magnitude of the convection heat transfer in the glazing cavities. Where BS 6993 Part 1 has been applied the emissivity of the various surfaces has been taken as 0.845 for plain glass, 0.2 for the low-e coating and 0.85 for all other surfaces. Although this value of 0.85 is lower than might normally be used it should be noted that the method used in BS 6993 Part 1 to determine radiation heat transfer coefficients assumes the surfaces to be infinite and parallel - this overestimates the amount of heat transferred between the two surfaces and the lower emissivity therefore compensates for this. For those surfaces modelled using ANSYS® capability for determining view factors the surface emissivities have been taken as 0.95.

The net effect of radiation heat transfer in parallel with either conduction or convection is then converted to an equivalent thermal conductivity for the cavity.

A.4.5 Exposed surfaces

Exposed surfaces will generally be open to a sufficiently large body of air that convection heat transfer will occur, in parallel with radiation heat transfer. For a surface exposed to an outside environment then forced convection heat transfer will occur.

The exposed surfaces have been modelled using an overall heat transfer coefficient and a temperature. The temperature represents the temperature of the environment to which the surface is exposed, and the overall heat transfer coefficient combines both convection and radiation effects in a single parameter. Radiation between adjacent surfaces has not been allowed for, and the limiting effect of local geometry (corners and grooves) on convection currents has not been considered. The reason for this is practical - it would be unnecessarily time-consuming to consider radiation and convection effects separately, particularly since the radiation heat transfer would depend on all of the room and external surfaces to which the frame surfaces are exposed.

The temperatures used in this study have been taken as 20.0°C internally and 0.0°C externally. It is the nature of the finite element analyses performed in this study, in which all material properties are assumed to be constant and independent of temperature, that the point temperatures can be readily converted to the equivalent values for any other combination of internal and external temperatures using the simple formula described in section 1.6.1.

Suitable overall heat transfer coefficients are usually defined in national standards. However, there has been a move towards the use of 'surface resistances' in place of overall heat transfer coefficients. This should not be expected to cause a problem, as the surface resistance is simply the reciprocal of the overall heat transfer coefficient. However, when this change in philosophy occurred it was decided that although overall heat transfer coefficients had been quoted to three significant figures, surface resistances should be quoted to two decimal places. If the surface resistance is then converted back to an overall heat transfer coefficient (many simulation packages require the surface conditions to be defined as a temperature and an overall heat transfer coefficient) then the original value is not recovered.

The current European values for the surface resistances are 0.04 m^2K/W externally and 0.13 m^2K/W internally. These values originated from German standards which used surface heat transfer coefficients of 8.00 W/m^2K, and 23.0 W/m^2K respectively. The reciprocal of 8.00 W/m^2K is 0.125 m^2K/W, which rounds to 0.13 m^2K/W in two decimal places. This then converts back to 7.69 W/m^2K. Similarly a heat transfer coefficient of 23.0 W/m^2K becomes a value of 25.0 W/m^2K. Rather than perpetuate these errors the values of the overall heat transfer coefficients used here have been taken as 8.00 W/m^2K for all internal surfaces, and 23.0 W/m^2K for all external surfaces.

Note that the use of surface resistances was derived from measurement standards - when the U-value of a piece of glazing is measured then calibration procedures are applied to ensure that the total surface resistance is 0.17 m^2K/W. There is no requirement for either the internal or external surface resistances to be as defined above!

A.5 Summary

The selected method of performing the analyses in this study has been based on assumptions that over-predict heat transfer through the system.

Although values have been used for most parameters that are in line with those that will shortly become standard for Europe, the reader should be careful in comparing data in this report with frame U-values from other sources, which may not fully account for the interaction of the frame with the glazing. Overall glazing system U-values are usually the safest method of comparison.

A.6 Acknowledgement

The author gratefully acknowledges the support of ANSYS, Inc in allowing this work to be published. ANSYS® is a registered trademark of SAS IP.

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201 Johnson Road
Houston, PA 15342-1300
USA

Appendix B Material thermal conductivities

The following is a discussion of the sources of thermal conductivity (λ) data used for this simulation study. The principal source of such information in the UK is the CIBSE Guide part A3 (1986). It should be noted that in many cases a small alteration in the material thermal conductivity will not have a significant effect on overall performance.

B.1 Frame and structural materials

Aluminium alloy, $\lambda = 201$ W/mK

Aluminium frames and glazing spacers are made from a range of aluminium alloys, most typically 6063 T6. "Aluminium extrusions - a technical design guide" (1989) gives this value above for 6063 T6 alloy, although experience has shown that aluminium is such a good conductor of heat that using any value from 150 to 250 W/mK would give identical results.

Timber, $\lambda = 0.13$ W/mK

Timber has two thermal conductivities - a low thermal conductivity across the grain, and a higher thermal conductivity along the grain. However, window frames are cut so that heat transfer must occur across the grain, and the thermal conductivity is taken here as the value presented in the CIBSE Guide part A3 (1986) as a generic value for hardwood.

PVC-U, $\lambda = 0.16$ W/mK

There is a small difference between plasticized and un-plasticized PVC. This value is given in the CIBSE Guide part A3 for rigid PVC, although some authorities quote a value of 0.17 W/mK. Either value will give near identical results.

Mild steel, $\lambda = 55$ W/mK

This is a typical value for the thermal conductivity of mild carbon steel as used in frames and reinforcement. Galvanizing does not affect this value.

B.2 Thermal breaks and gaskets

Pour-and-de-bridge thermal break resin, $\lambda = 0.11$ W/mK
Pour-and-de-bridge warm edge technology glazing spacer resin, $\lambda = 0.17$ W/mK

Two values of thermal conductivity have been obtained from manufacturers for resins of the types used in the pour-and-de-bridge type of thermal break and warm edge technology glazing spacers. The lower value is for a resin which is used for the thermal breaks in aluminium window frames. The higher value has been quoted by a manufacturer for a resin which is used in warm edge technology glazing spacers.

Polyamide thermal breaks, $\lambda = 0.23$ W/mK

Significant data exists for the thermal conductivity of various polyamides, although the polyamide used in extruded thermal breaks may be glass-reinforced. The value given above has taken from general reference sources and is supported by data quoted by a manufacturer of this type of thermal break.

Solid EPDM rubber gaskets, $\lambda = 0.29$ W/mK

This value is the only one that could be obtained from a material supplier for an EPDM rubber. Values of thermal conductivity were actually available for two EPDMs: a hard EPDM with a value of 0.35 W/mK, and a soft EPDM with a value of 0.23 W/mK. It was suggested by the supplier that they typically supply EPDM rubber in an intermediate hardness, and so an average was taken. Although rubber materials may be subjected to a wide range of tests, thermal conductivity is not normally a property of interest.

Foam EPDM rubber gaskets, $\lambda = 0.15$ W/mK

Published data suggests that polymer foams have thermal conductivities in the range 0.03-0.1 W/mK. However, this is generally for rigid un-compressed foams. The value given above has been arbitrarily taken as a safe high value in the absence of reliable data to the contrary.

Silicone rubber gaskets, $\lambda = 0.25$ W/mK

This value has been suggested by two suppliers of silicone rubber and is close to the value of 0.27 W/mK given in the CIBSE Guide part A3. Some authorities suggest a value of 0.35 W/mK, but given the number of possible blends of any polymer it is not possible to say which value is most applicable.

Thermoplastic wedge gaskets, $\lambda = 0.20$ W/mK

It has not been possible to obtain any reliable suppliers data on thermoplastic rubber thermal conductivity, as used by the PVC-U window industry for wedge gaskets. However, at least one well-used TPR is based on a PVC blend with a small amount of nitrile rubber. It is assumed here that the nitrile part has a higher thermal conductivity than the PVC, and the value above is therefore slightly higher than for PVC-U.

Backing strip on wedge gaskets, $\lambda = 0.17$ W/mK

Wedge gaskets are often co-extruded with a rigid backing strip. It has been assumed that the material is PVC, and the thermal conductivity taken as such. Although this value differs from that taken above for PVC-U the effect on overall performance is not significant.

Butyl sealant based glazing tape, $\lambda = 0.24$ W/mK

The thermal conductivity of glazing tapes is difficult to assess because some forms of tape are polymer foams, and the thermal conductivity values determined for these foams may not relate to the foam as compressed into place. However, there is another type of glazing tape, consisting of a strip of butyl sealant, sometimes reinforced with rubber shims to prevent over-compression. This thermal conductivity is suggested in the latest draft for the European standard on calculation of heat transfer through glazing frames (EN 30077 Part 2).

B.3 Glazing and glazing edge materials

Glass, $\lambda = 1.0$ W/mK

This value originates from a paper by Geotti-Bianchini and Lohrengel (1993). Generally in a double glazing unit the thermal resistance of the glass is neglected for calculation purposes, although the edge effect may be slightly modified by different values. American practice has been to use a value of 0.8 W/mK.

Butyl sealant, $\lambda = 0.24$ W/mK

Several tables of data suggest this value for hot-melt butyl sealants as might be used for the primary seal in the edge detail of a double glazing unit.

Silicone sealant, $\lambda = 0.35$ W/mK

One manufacturer of silicone sealants suggested a value of 0.25 W/mK for a two-part silicone sealant as used for the secondary seal in glazing unit edge details. However, at least two general tables of data suggest the value given above, for sealants, and this higher value has been used here for the particular reason that with warm edge technology spacers the secondary sealant has a more significant effect and a high value gives the worst case. With aluminium edge spacers it does not actually make much difference which value is used.

Desiccant, $\lambda = 0.13$ W/mK

The desiccant is used in the glazing edge spacer to remove residual moisture from the gas-fill. This value is also suggested in the latest draft of the European standard EN 30077 Part 2.

Again it is not important what value is used with an aluminium spacer, but for a warm edge spacer this value may be more critical.

B.4 Warm-edge technology glazing spacers

Desiccant-filled butyl, $\lambda = 0.25$ W/mK

One type of warm-edge spacer uses a butyl sealant with a desiccant blended in. This value of thermal conductivity is an independently measured value, and correlates closely with the values for butyl-based materials given above.

Silicone foam rubber, low density $\lambda = 0.12$ W/mK, high density $\lambda = 0.22$ W/mK

Silicone foam rubber is also used to produce warm-edge spacers. Two values have been used for the thermal conductivity to demonstrate the possible effects on performance. The lower value has been quoted by a warm edge spacer manufacturer.

Glass-filled polycarbonate, $\lambda = 0.22$ W/mK

Glass-filled polycarbonate has been used to make warm edge spacers, but manufacturers data could not be obtained. This value has been derived by comparing data from a number of sources, and is close to the value given for polycarbonate in the CIBSE Guide part A3.

SS160 stainless steel, $\lambda = 14.3$ W/mK

Stainless steel is used as a warm-edge spacer material, because the properties are much better. The value above has been published by one such spacer manufacturer, and is confirmed in other sources of materials data.

B.5 Air in cavities

Air, conduction only, $\lambda = 0.025$ W/mK

This is a standard value for air, and may be found in many data books for air at room temperature.

Air, conduction/convection and radiation

For the air-space in the glazing units, and the air-space considered in the simulations of secondary glazing, the procedures defined in BS 6993 Part 1 have been used to determine the following equivalent thermal conductivities

8 mm glazing air	conventional glass	$\lambda = 0.0550$ W/mK
	one pane low-e glass	$\lambda = 0.0320$ W/mK
12 mm glazing air	conventional glass	$\lambda = 0.0700$ W/mK
	one pane low-e glass	$\lambda = 0.0355$ W/mK
16 mm glazing air	conventional glass	$\lambda = 0.0855$ W/mK
	one pane low-e glass	$\lambda = 0.0400$ W/mK
31 mm secondary glazing air	conventional glass	$\lambda = 0.1715$ W/mK

where the emissivities are 0.845 for conventional glass and 0.20 for the low-e coating.

Air, assumed conduction and radiation only

There are several small cavities in the various frames. From BS 6993 Part 1, assuming conduction and radiation only, the relationship between cavity thickness t and the effective thermal conductivity λ is

$$\lambda = 0.025 + 3.8t$$

where the radiation heat transfer is assumed to be between two parallel surfaces at the spacing t, with all surfaces having an emissivity of $\varepsilon = 0.85$.

This gives the following values of thermal conductivity

1.5 mm cavity (EPDM gaskets)	$\lambda = 0.03$ W/mK
3 mm cavity (various)	$\lambda = 0.04$ W/mK
6 mm cavity (various)	$\lambda = 0.05$ W/mK
12 mm cavity (PVC-U frames)	$\lambda = 0.07$ W/mK
23 mm cavity (PVC-U/aluminium composite frames)	$\lambda = 0.11$ W/mK

Note that only two decimal places are used - greater accuracy cannot be justified given the assumptions made for these cavities.

B.6 Summary

The values of thermal conductivity listed in this appendix have been used for all simulations presented in this report. It should be apparent that in many cases there is actually little proven measurement data for thermal conductivity, as this particular material property has not been widely asked for in the past. Although manufacturers may be able to provide data in some cases the source of the data is unknown, and original sources should be identified if possible. Many standards under development for calculation and simulation of heat transfer through structures will provide tables of standard values for use where other information is lacking.

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