B.C. Reference Procedure for Using THERM to Determine Window Performance Values for Use with the Passive House Planning Package

Version 1.1

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Note from the Passive House Institute

The content of this document and the accompanying tools have been independently reviewed and approved by the Passive House Institute (PHI), Darmstadt, who acknowledge the care and thoroughness with which these resources have been produced. PHI and Passive House Planners, Consultants and Certifiers registered with PHI are authorized to accept reports produced in full accordance with this guideline and associated reporting requirements as sufficient evidence of window performance in PHPP calculations and subsequent building certifications. Those intending to use this methodology for PH building certification should notify their certifier in advance of their intent to do so. Although every effort has been made to ensure its quality, PHI accepts no responsibility or liability for the accuracy, content, completeness, legality or reliability of the information contained within.

The methodology does not constitute Passive House Component Certification, nor does it replace the certification process which is offered exclusively through PHI. Use of the Passive House Certified Component logo is restricted to components which have completed the PHI Component Certification process and are in good standing with PHI.

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Preface

Canadian window manufacturers are now aware that federal and provincial governments intend to use a combination of incentives and regulations to dramatically improve the energy performance of windows to less than 1.0 W/(m²-K) by 2030. These actions flow from the December 2016 Pan-Canadian Framework on Clean Growth and Climate Change[1], Canada's plan to meet greenhouse gas emissions targets, grow the economy, and build resilience to a changing climate.

Manufacturers looking to develop products with U-factors of less than 1.0 W/(m²-K) may wish to consider the market opportunity presented by the growing Canadian market demand for affordable Passive House windows.

The methodology presented in this document was developed jointly by RDH Building Science Inc. and Peel Passive House Consulting Ltd. It was created specifically to clarify the differences between North American and Passive House window thermal energy performance standards, and to provide a way for North American window manufacturers and energy simulation practitioners to accurately determine the energy performance parameters required to qualify them for use in Passive House buildings designed to the International Passive House Standard (IPHS). It shows how the industry-standard and publicly available LBL THERM software, together with a Microsoft Excel worksheet, can be used to accomplish this in a manner recognized by the Passive House Institute.

This methodology enables window manufacturers to report the performance of their existing products in Passive House terms, and to design next-generation windows for the growing Canadian and North American Passive House building market.

The contributors to this guide aspire to foster a new dialog between the fenestration sector, which has a remarkable capacity for product innovation in greater comfort and better energy performance, and the high-performance construction sector, which is creating a fast-growing global market for very high-performance triple-paned windows with highly insulated frames.

A Reference Procedure

This document is titled "Reference Procedure" because it is the first methodology using LBL THERM software to be recognized by the Passive House Institute for use in certifying Passive Houses to the International Passive House Standard. The use of a uniform reference procedure is intended to allow PHPP window performance values using this methodology to be trusted and compared.

Acknowledgements

The contributors wish to acknowledge REHAU for permission to use the 4700 series window profiles for the vinyl window example in this document, and Pazen Fenster + Technik GmbH for the "ENERsign plus" wood window example.

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[1] https://www.canada.ca/en/services/environment/weather/climatechange/pan-canadian-framework.html

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Relevance of project to the B.C. Regulatory Context

In March 2017, in support of the Pan-Canadian Framework on Clean Growth and Climate Change, representatives of Natural Resources Canada convened a stakeholder workshop with Canadian Federal, Provincial and-Territorial governments to discuss an ambitious "market transformation program" for residential windows. The official meeting notes of this workshop outlined the following aspirational goals for residential windows in Canada:

Short term	By 2020, residential windows for sale in Canada meet an average U-factor of 1.6 W/m^2 (or ER 25)
Medium term	By 2025,
	All residential windows for sale in Canada meet a U-factor of 1.2 W/m^2
	Residential windows with a U-factor of ≤ 1.0 W/m^2 will be cost effective and commercially accessible for most end uses
Long term	By 2030, all residential windows for sale in Canada meet a U-factor of 0.8 W/m^2

Also in March 2017, the BC Ministry of Energy, Mines and Petroleum Resources (MEMPR) announced a "High Performance Window Certification Program" that offers financial incentives to encourage BC manufacturers to develop cost-effective, marketable high-performance windows. Accepting applications up to March 30, 2019, this program offers funding on a first-come, first-served basis of $25,000 for a newly-developed, tested and certified ENERGY STAR Most Efficient window product line, and $40,000 for a Passive House product line certification to the Certifiable Component level for PHI climate zone 2 or 3.

In April 2017, British Columbia became the first province in Canada to publish a building code roadmap to achieve the objectives of the Pan-Canadian Framework on Clean Growth and Climate Change. The BC Energy Step Code (Step Code) provides municipalities with a five-step pathway to Net Zero Energy (NZE) buildings by 2032, in which a Total Energy Demand Index (TEDI) level equivalent to that of Passive House is the fifth and highest step. The Step Code allows municipalities to adopt the higher steps sooner if they wish, and to allow more than one step to be in effect at any given time.

The use of predefined steps is expected to "standardize" the building code paths to the NZE goal and in this way to allow for more rapid expansion of design and construction expertise, and to create a market for very high-performance components such as windows, doors and glazed facades. Already one municipality, the city of Vancouver, requires all new civic buildings to be constructed to the Passive House standard, and several municipalities have zoned new developments exclusively for certified Passive House multifamily market housing.

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1   Introduction

This document is the result of a research project intended to help Canadian manufacturers participate in the growing demand for Passive House windows by developing a methodology recognized by the Passive House Institute (PHI) and based on North American software that can be used to calculate the performance values that are required by the Passive House Planning Package (PHPP) for glazed window and door products.

The methodology described here is based on using industry-standard North American software and is intended to help window manufacturers to:

1) Generate and report PHPP compatible performance values for existing products that may be able to meet Passive House requirements in Southern BC and Vancouver Island
2) Design new products that comply with Passive House performance requirements for one or more of the Canadian Passive House climate zones
3) Report PHPP values together with North American energy performance values in a standard format defined within this document

Note: Simulation reports intended to support window performance calculations in PHPP and subsequent building certifications used on a Passive House project must include all the reporting elements listed in Appendix G.

To facilitate adoption of this methodology and its acceptance by Passive House building designers and Canadian building officials, this procedure recommends a complete thermal simulation report. A standardized summary report format is also provided to permit reporting of both PHPP values and North American energy performance values determined according to the methods recognized by Canadian building codes (simulations according to the CSA A440.2 standard or simulation and physical testing according to the ANSI/NFRC 100 and ANSI/NFRC 200 standards).

1.1   The Need for Canadian Passive House Products

Many in the window industry regard certified Passive House windows as representing the pinnacle of energy performance, but they do not come close to meeting Canadian Passive House needs. Most of the windows in the Passive House Transparent Components Database are designed to meet the requirements of passive buildings in the temperate climate of Western Europe. They have suitable performance characteristics for southern British Columbia, but passive buildings in the rest of Canada require windows with even lower U-values and frame surface temperatures.

Passive building designers in Canada have identified a need for cold climate windows, designed for Passive House climate zones 1 and 2. There are only a very few products available for these climate zones, and the first manufacturers to develop products for this market will have access to an international market for passive buildings in cold climates.

1.2   Distinctive Features of the Passive House Approach

The Passive House approach to designing very low energy buildings prioritizes minimizing heat loss through the building enclosure to reduce annual heating energy demand to a very low level. This requires the enclosure to be highly insulated and very air tight. As insulation levels are increased, it becomes critically important to minimize heat loss at the transitions between roofs and walls, between walls where they meet at corners, and between floors and below-grade insulated foundations. Even the wall to window interface requires careful attention.

It is at these transitions where great care must be taken to minimize heat loss in highly insulated buildings, as even seemingly minor uninsulated (or under-insulated) components can result in large heat flows from interior to exterior. These zones of high heat transfer are called "thermal bridges", and the minimization of thermal bridges is one of the hallmarks of Passive House design.

The performance of Passive House buildings is evaluated using a Microsoft Excel-based tool called the Passive House Planning Package (PHPP). This tool accounts for all heat loss pathways, and all available heat gains, such as passive solar radiation through windows, and heat gains from internal sources in the building. The principal objective is to limit the annual heating demand to 15 kWh/m²/year, for any building, in any climate zone, along with several other performance targets.

The Passive House standard is not only concerned with limiting heating demand and energy use. The design and performance characteristics are also very much concerned with occupant health and comfort. This whole-building approach that focuses not only on minimizing heating demand, but also on occupant health and comfort, has led to the development of different energy performance criteria for windows and glass doors than are used in North America. These characteristics are summarized below.

1.3   Passive House Window Performance Criteria

Windows are critically important components of a Passive House building, and the Passive House standard stipulates specific performance criteria for these components that go beyond the window performance characteristics we are familiar with in North America.

As would be expected, the standard evaluates overall window U-values, but unlike the North American approach, window U-values are evaluated at the actual sizes used on the building. Evaluation at actual sizes is simplified because overall window U-values (U_W) are determined by adding up the heat losses through the window frame (U_f), through the glass (U_g), and through the insulating glass spacer which is treated as a linear thermal bridge (Ψ_g).

The evaluation of winter heat loss through windows also includes heat loss at the window-to-wall junction, one of the thermal bridges that become critically important in a highly insulated building. The rate of heat loss at the window-to-wall junction is modelled and reported with a linear thermal transmittance coefficient ($\Psi_{install}$). The magnitude of the heat loss at this junction can be reduced by using windows with less conductive frame designs, by aligning the window with the most highly insulated portion of the wall, and by insulating the perimeter of the window frames.

Occupant comfort is another feature of the Passive House standard that affects windows. First, all windows in the living areas of residential buildings must be operable. Second, overheating discomfort defined as an air temperature greater than 25°C, is limited to 5% of hours per year (recommended), and must not exceed 10%. Third, discomfort due to cold window surface temperatures (and the resulting cold air drafts) in winter is minimized by ensuring the average winter window surface temperature is no more than ~4°C colder than the average indoor temperature as perceived by building occupants. This not only ensures occupant comfort, it also allows the building's heating system to be simplified. When building occupants are as comfortable near a window as anywhere else in a room, there is no longer a need for radiators or hot air ducts below windows to make building occupants more comfortable.

The PHPP evaluates whether winter comfort criteria are achieved on the basis of the average actual size window U-values in the context of a specific building, with a specific orientation, in a specific Passive House climate zone.

In addition to comfort, Passive House buildings are designed to mitigate the risk of mould growth at windows, typically the coldest indoor surfaces of a building. This affects window frame designs by

requiring them to have winter surface temperatures above a temperature that could lead to mould growth. This window frame characteristic is modelled and reported as the temperature factor (f_{Rsi}) and is referred to as a "hygiene criterion" for window selection.

1.4 Software

Given the widespread availability, use, and familiarity of LBL THERM software across North America, this methodology is written for use with THERM and WINDOW version 7.4 which is available at no charge from the website of the Lawrence Berkeley National Laboratory (Berkeley Lab) at https://www.lbl.gov/.

All software used for simulation of Passive House windows must be validated against the EN ISO 10211 and 10077-2 standards. While software choices are evolving, 2D thermal simulation software that currently meet this criterion include HEAT2 by BLOCON, and flixo by infomind. THERM version 7.4 was validated as part of this project as demonstrated in Appendix J.

1.5 Scope

This document covers windows installed into vertical wall assemblies. Other types of transparent components such as skylights, curtain walls, and roof lights are not addressed here, and the specific methods described here may not be appropriate for assessing such components.

1.6 Application of Modelling Results to Certified Buildings

This methodology has been reviewed by representatives of the Passive House Institute, and subject to acceptance by the Passive House Certifier, is acceptable for qualifying windows for buildings certified to the Passive House standard. Certification of Passive House buildings does not require Certified Components to be used.

Models produced following the methodology described in this document may be used to support the PHI building certification process but will require additional supporting documentation to be provided to the Certifier, such as the models themselves (rather than a summary report) as well as test reports for non-standard thermal conductivity values. Project teams should discuss the simulation approach with their building Certifier early in the process to determine what additional information will be required.

1.7 Summary Report

To facilitate the adoption of this methodology and its acceptance by Passive House building designers and Canadian building officials, this document also recommends the use of the provided summary report format to report both PHPP values and North American energy performance values determined according to the methods recognized by Canadian building codes (simulations according to the CSA A440.2 standard or simulation and physical testing according to the ANSI/NFRC 100 and ANSI/NFRC 200 standards).

Manufacturers wishing to provide summary reports based on this methodology as evidence of their product qualifications shall accompany these with a complete simulation report meeting the requirements listed in Appendix G. Manufacturers are also encouraged to provide these reports under the seal of a qualified registered professional.

> Use of this methodology does not enable use of the PHI Certified Component logo by the manufacturer, which requires PHI Certification.

2   Methodology

The methodology described in this reference procedure is based on ISO 10211-2:2017 and is intended to be used in conjunction with that standard. In addition to describing the ISO 10211-2 calculation methodology in the context of THERM, the reference procedure also addresses specific PHI requirements for the evaluation of window thermal performance.

2.1   Passive House Component Evaluation Criteria

The Passive House standard has three reportable window performance characteristics determined by computer simulations:

1) **Component U-value** (U_w): The overall U-value of the window frame and glazing to the edge of the window frame, excluding heat loss at the window-to-wall junction

2) **Installed U-value** ($U_{w\ installed}$): The overall U-value of the window frame and glazing, including heat loss at the window-to-wall junction (see Figure 2.1).

3) **Frame temperature factor** (f_{Rsi}): A measure based on the minimum interior surface temperature of the window used to satisfy the "hygiene criterion" for minimizing the potential for mould. See Appendix A – Transparent Certification for further details.

Figure 2.1 Illustrating the difference between a model for a component U-value (U_W), and a model for an installed U-value which represents installation in a project-specific wall type ($U_{W,installed}$)

Window Component (U_W)   Installed Window ($U_{W,installed}$)
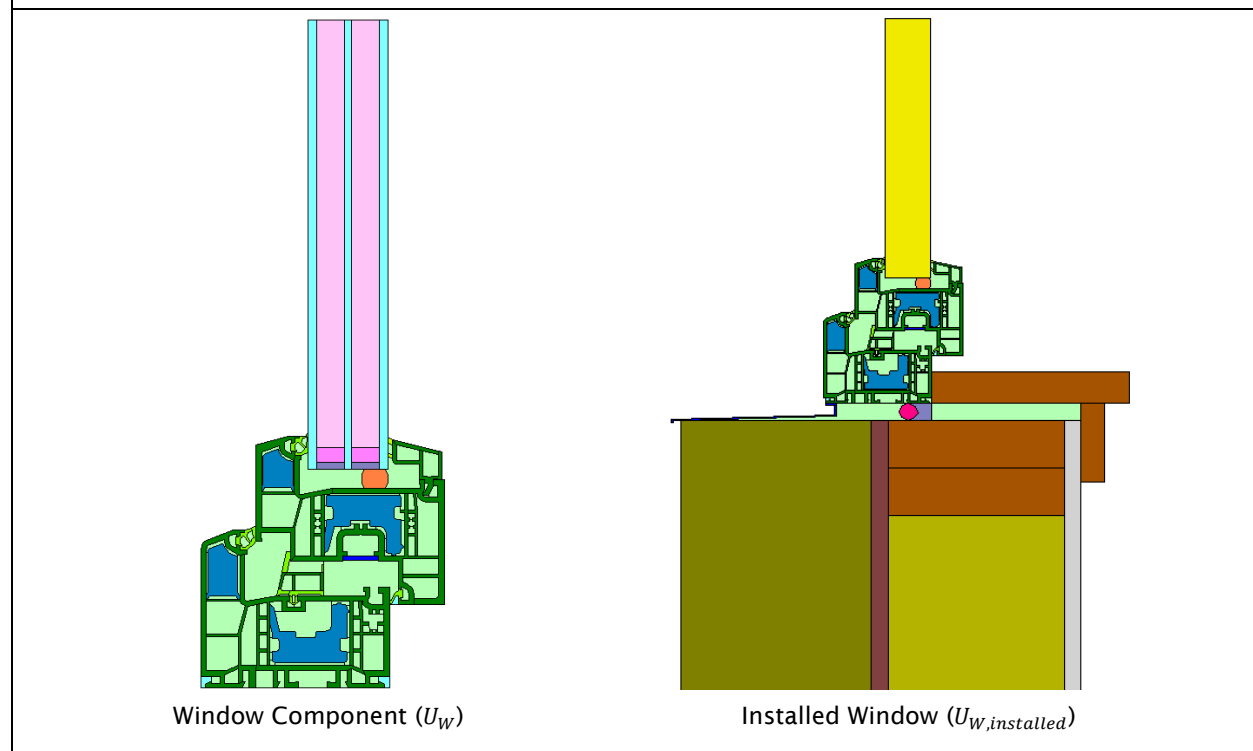
Windows are also critically important for the year-round thermal comfort of the occupants. For winter conditions, this is achieved by ensuring that the minimum average window surface temperature is not more than 4.2°K lower than the average interior operative temperature. The PHPP evaluates this based on
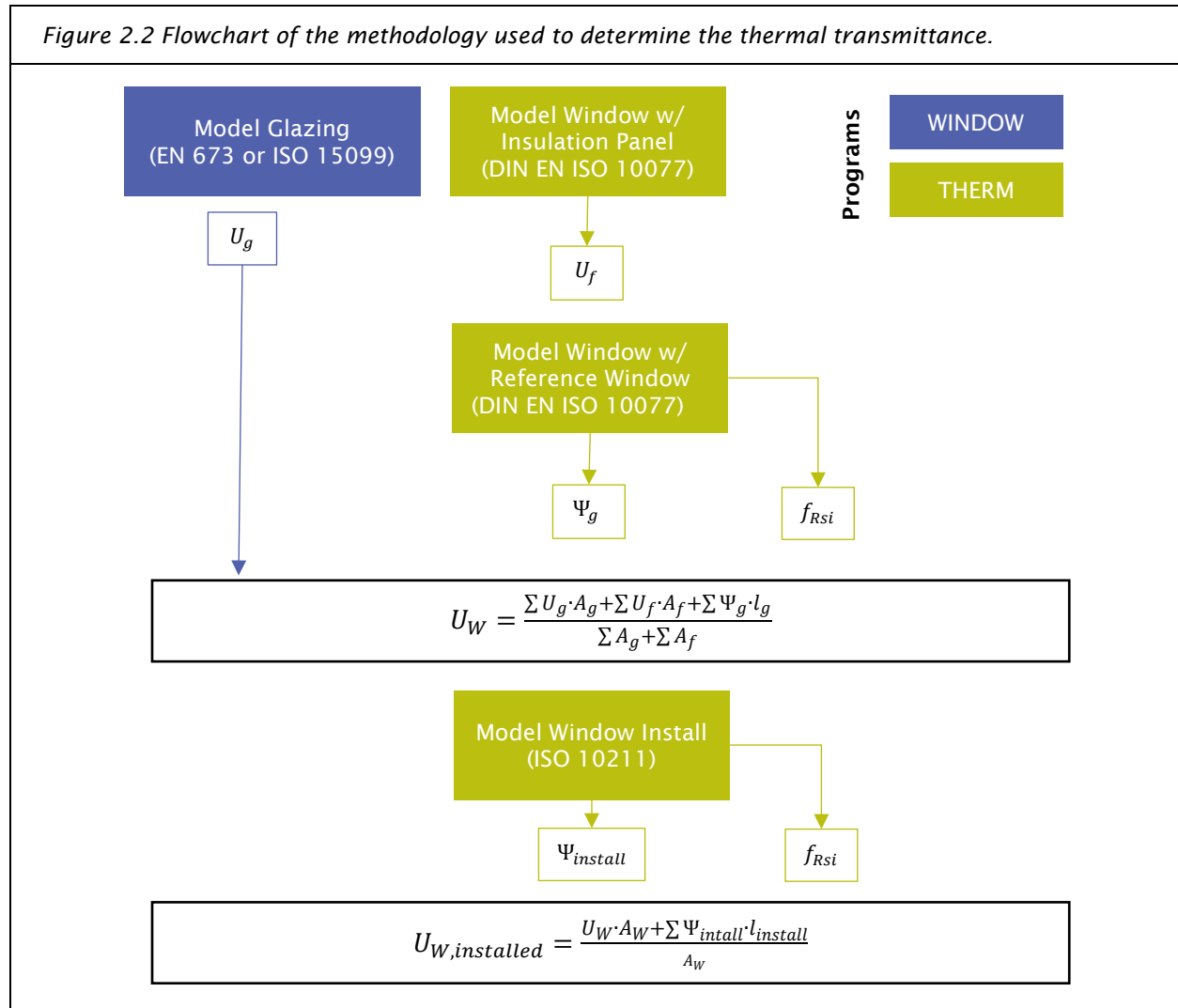
the window U-value. Refer to Appendix B – PHPP Evaluation of Comfort Criteria for more details on this property. For summer conditions, to minimize overheating, the PHPP estimates the number of hours during which the interior operative temperature is above 25°C. To mitigate the risk of overheating during warm periods of the year, designers may look to include shading devices, optimal window orientations, lower solar heat gain coefficients, increased ventilation, or mechanical cooling.

There is no single performance metric that addresses all comfort criteria. It is also possible that satisfying the winter comfort criteria will require windows with lower installed U-values than would be required to meet the building's thermal energy demand alone.

2.2 Modelling Procedure Overview

Two-dimensional thermal modelling of windows generally consists of recreating window geometry in a validated 2D thermal modelling software application and performing calculations on the software output to characterize a window's performance. The methodology outlined in this document assumes a general familiarity with 2D thermal modelling software, and specifically with THERM. For information about using THERM, please refer to the THERM/WINDOW Simulation Manual.

Figure 2.2 Flowchart of the methodology used to determine the thermal transmittance.

Model Glazing (EN 673 or ISO 15099)

U_g

Model Window w/ Insulation Panel (DIN EN ISO 10077)

U_f

Model Window w/ Reference Window (DIN EN ISO 10077)

Ψ_g

f_{Rsi}

Programs — WINDOW, THERM

$$U_W = \frac{\sum U_g \cdot A_g + \sum U_f \cdot A_f + \sum \Psi_g \cdot l_g}{\sum A_g + \sum A_f}$$

Model Window Install (ISO 10211)

$\Psi_{install}$

f_{Rsi}

$$U_{W,installed} = \frac{U_W \cdot A_W + \sum \Psi_{intall} \cdot l_{install}}{A_W}$$

To determine uninstalled window thermal performance, the PHI window modelling methodology requires three models for each frame cross-section (i.e., head, sill, jamb, connecting mullion, etc.):

1) Window frame with insulation panel, no spacer, and standard boundary conditions to determine the frame U-value (U_f)

2) Window frame with reference glazing, actual spacer, and standard boundary conditions to determine the spacer's linear thermal transmittance expressed as the glass psi value (Ψ_g)

3) Window frame with reference glazing, actual spacer, and modified boundary conditions to determine the frame temperature factor (f_{Rsi})

The difference between the first and second model is the glazing and spacer. The third model is identical to the first but differs in the boundary condition. In all three models, the window frame geometry remains the same.

To determine the installed performance of the window, two additional models are required per frame section to calculate heat loss around the window perimeter ($\Psi_{install}$) and the installed temperature factor (f_{Rsi}).

Figure 2.2 summarizes the methodology required to obtain PHPP energy modelling (PHPP) inputs. Each step in the modelling process is described in more detail in this procedure document.

2.3 General Modelling Guidelines and Assumptions

This section describes standard procedures and assumptions that are used throughout the modelling process and apply to all models, except where noted.

The guidelines described in this document are applicable for modelling both operable and fixed window frames. Manufacturers are encouraged to model fixed (non-operable) frames in addition to operable frames; however, fixed frames can be assumed to have the same characteristics as operable frames (including U_f, Ψ_g, and frame width[2]) in PHPP in cases where only the operable frame has been modelled.

Operable frames typically have poorer performance than fixed frames, so this will lead to PHPP modelling that is conservative. Furthermore, an operable window of the same rough opening dimensions as its fixed counterpart will generally allow for less solar heat gain due to its reduced glazing area. Project teams will therefore typically request access to fixed frame models to take advantage of increased solar heat gains and lower overall U-values to reduce space heating demand.

Figure 2.3 shows the various frame cross sections that may be modelled. For window certification, all sections of the operable product must be modelled, along with one connection product —either operable-to-fixed or operable-to-operable. The mullion may be a combination mullion formed by two abutting frames, or an integral mullion dividing two operator types. For project-specific modelling, only the sections present in the project windows must be modelled.

In cases where cross sections through different members of a window are identical, only one model needs to be produced. For example, if the jamb and head profiles are identical, one model could be used for both jamb and head inputs in PHPP.

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[2] In the PHPP frame width corresponds to the face dimension of a window frame as viewed from the exterior or the interior. See Figure 2.4 Illustrating the frame section terminology used in this procedure. Note that Ψ_g and $\Psi_{install}$ apply to the glazing edge and window rough opening perimeter lengths respectively.

Category	External frame dimensions (b * h) [m]	Frame sections to be calculated															Installation situations to be calculated[3]	Additional specifications
		bo	s	to	bof	sf	tof	th	sh	fm	m2	m1	m	t2	t1	t		
Window frame (wi)		X	X	X						(x)	(x)						EIFS + two others; Sliding doors: EIFS. Entrance door: Section bottom only EIFS.	/
Frame with fixed glazing (fx)	1.23 * 1.48				X	X	X						X					/
Window system (ws)	1.23 * 1.48, 2.46 * 1.48[4]	X	X	X	X	X	X	X	X	(X)	(X)	X	X	(x)	(x)	X		CE labelling[5], airtightness: Q_{100} ≤0.25 m³/(h*m)
Entrance door (ed)	1.10*2.20		X	X				X	X									Airtightness: (Q_{100} ≤2.25 m³/(h*m)), under climate load
Door system (ds)	1,10, 2,20 / 2,20, 2,20		X	X	(X)	(X)	(X)	X	X	(X)	(X)	(X)						As ed, with additional consideration of jamb details and/or double-leaf doors
Sliding door (sl)	2.4 * 2.5		X	X	X	X	X	X					X					Testing of airtightness
Curtain wall façade (cw)	Modulmaß 1.20 * 2.50				X	X	X					X	X			X	Lightweight roof construction	/
Glass roof (cwi) (45°)	see secton 3.7				X	X	X					X	X			X		/
Roof window (rw) (45°)	1.14 * 1.40	X	X	X														/
Skylight, rooflight, access hatch (sk) (0°)[6]	1.50 * 1.50	X	X	X	(X)	(X)	(X)										Reinforced concrete flat roof, lightweight roof construction	For access hatches no efficiency class will be given
Continuous rooflight	1.50 * 4.50				X	X	X					2						Three-dimensional thermal bridges are considered
Opening in glass roof (ocwi) (45°)	1.20 * 2.50	X	X	X													3 certified transom-mullion façades	/

X: included in the calculation   *X*: stated for informative purposes   (X): alternative

bo: frame section bottom, s: frame section side, to: frame section top, ..f: for frames with fixed glazing, th: threshold, sh: frame section side with window hardware, fm: flying mullion, m: mullion, t: transom, ..1: with one opening element, ..2: with two opening elements

The terminology used by ISO 10077 and PHPP to describe the window features to be modelled and the simulation results differs from that used by the North American fenestration industry. Figure 2.4 illustrates the frame cross-section terminology used throughout this procedure.

In PHPP, each unique window product type is first entered as a component on the Components worksheet (Figure 2.5). As stated in the introduction, one of the goals of this modelling procedure is to determine these inputs. The energy modeller is then able to select the appropriately defined window product from a dropdown menu on the "Windows" worksheet to model each individual window unit on a project.

The first row of window data in Figure 2.5 describes a single window frame (head, sill, and jambs), where all edges are in contact with an opaque assembly. In some cases, one or more of the four sides of a window frame will connect to another window frame. The connecting mullions will likely have different dimensions, constructions, and thermal performance. These mullions should be modelled so that on projects where these are present, they can be more accurately accounted for in PHPP. Window systems comprising of several connected frames (e.g., operable and fixed) are entered as two or more separate window components in PHPP.

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[3] Information, Criteria and Algorithms for Certified Passive House Components: Transparent Building Components, Version 5.1, 25.07.2017 kk/el

Figure 2.4 Illustrating the frame section terminology used in this procedure. Note that Ψ_g and $\Psi_{install}$ apply to the glazing edge and window rough opening perimeter lengths respectively.

Glass Height (l_g, U_g)

Frame Width (l_f, U_f)

Glazing Edge (Ψ_g)

Frame Thickness (b_f)

Window Height $(l_W, U_{W,CP})$

Installation $(\Psi_{Install})$
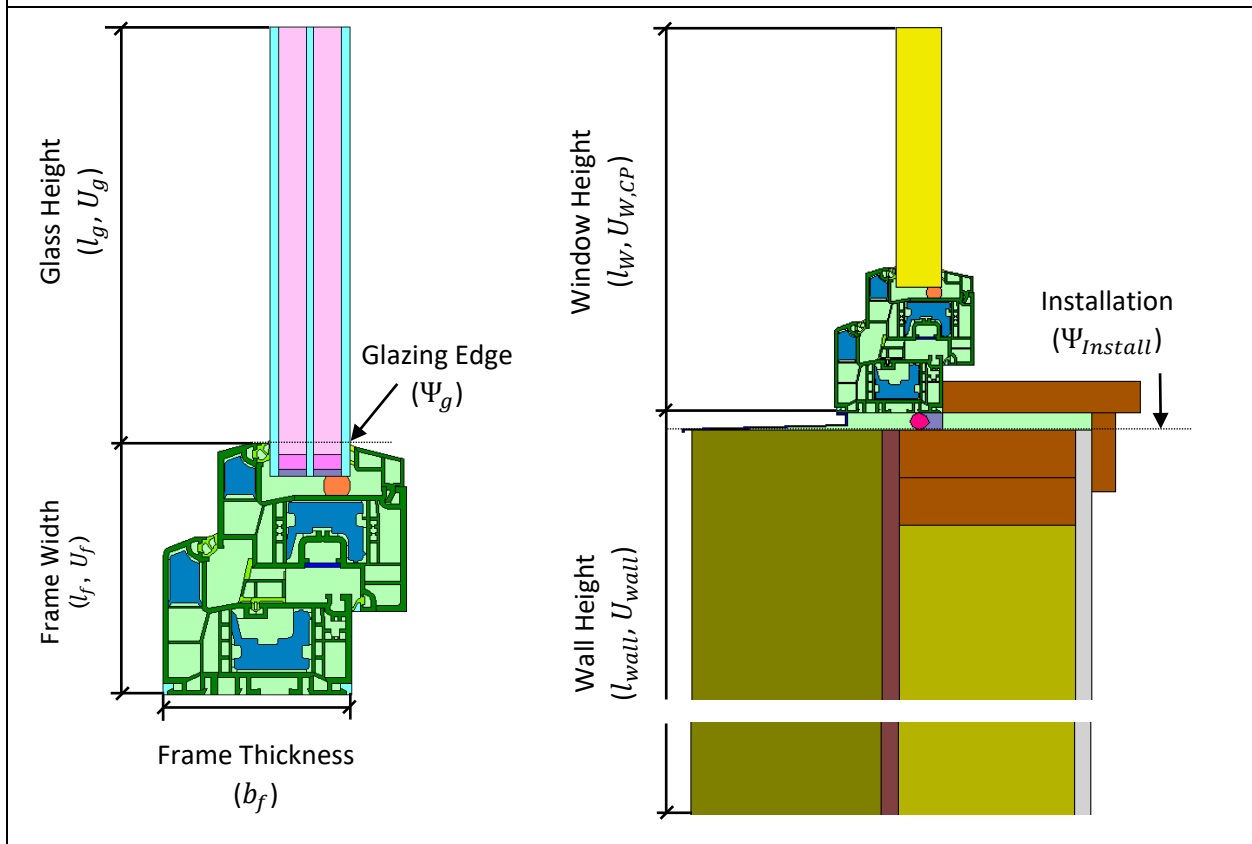
Wall Height (l_{wall}, U_{wall})

Figure 2.5 Screenshot of a portion of the PHPP Components worksheet in PHPP showing the field labels under which window performance characteristics are entered.

U_f

l_f

Ψ_g

$\Psi_{installation}$

2.3.1 Elements to Include

When simulating the window frame, all continuous elements should be modelled, including:

→ All primary frame materials (wood, aluminum, fibreglass, etc.)

→ Thermal breaks

→ Gaskets

→ Structural reinforcement within the frame (can be metal, fibreglass, PBT, polyamide, etc.)

→ Continuous glazing supports (e.g., PVC)

→ Continuous operating hardware (e.g., locking hardware)

Continuous Operating Hardware

PHI requires continuous operating hardware, such as those present for a locking system, to be accounted for. However, PHI also permits simplification of these elements. The simplified approach consists of modelling these elements as a 2 mm thick polygon assigned the properties of steel (50 W/m·K). The polygon should run the length of the metal element's connection to the frame.

Figure 2.6, Figure 2.7, and Figure 2.8 show cross sections through three common frame types and illustrate the various elements listed above.

Figure 2.6 Inward opening aluminum window frame. The operating hardware is represented by a continuous steel element 2 mm thick spanning the length of the connection to the frame.

Insulation

Thermal break

Hardware (2 mm thick steel)

Gasket

Insulation
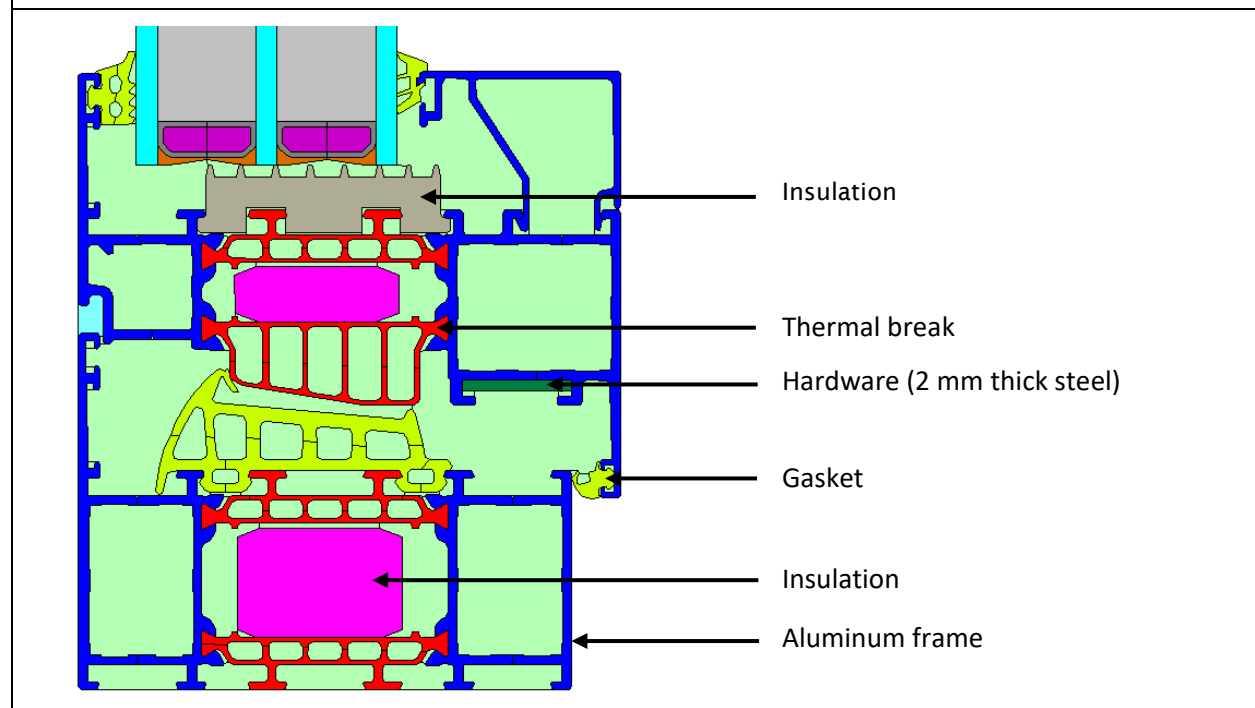
Aluminum frame

Figure 2.7 Inward opening wood frame window. Locking hardware is included (2 mm thick steel) along with the aluminum window cladding.

Aluminum window cladding

Continuous glazing support

Hardware (2 mm thick steel)

Gasket

Wood frame

Insulation
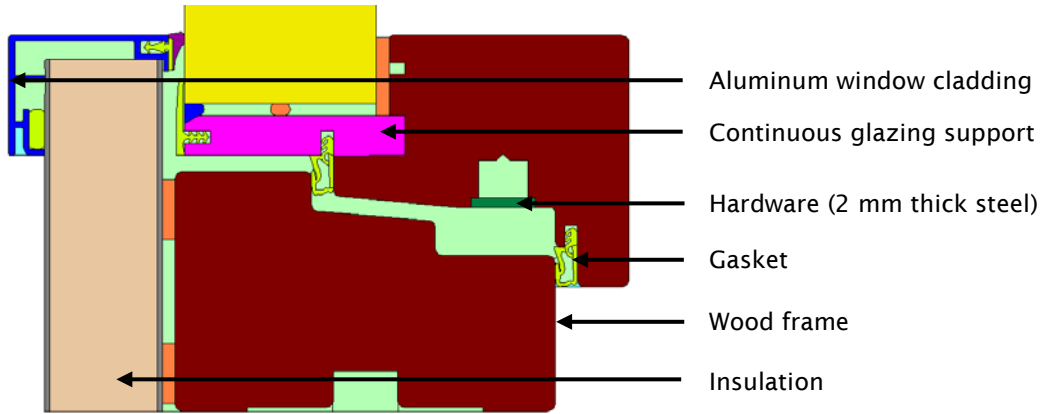
Figure 2.8 Inward opening PVC frame. Locking hardware is included (2 mm thick steel).

Continuous foam stripping

Insulation

Hardware (2 mm thick steel)

Gasket

Vinyl frame
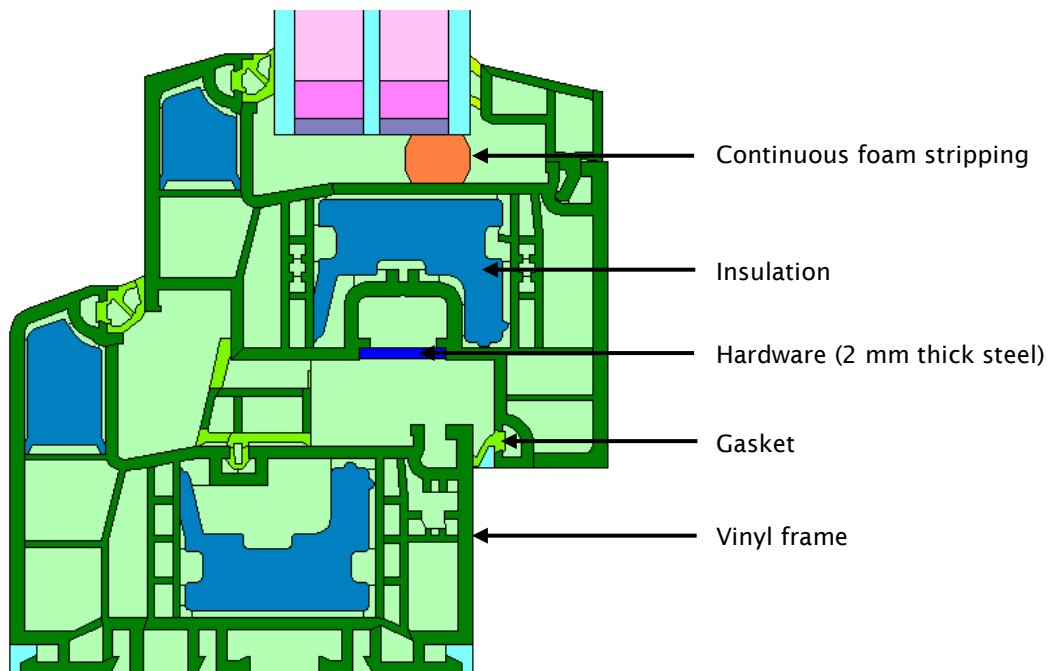
2.3.2 Elements to Exclude

Not all elements within a window frame need to be included in the thermal model. The following non-continuous elements are permitted to be excluded because they have been shown to have a negligible impact on the overall thermal performance of vertical windows:

→ Non-continuous elements such as shims

→ Non-continuous operating hardware such as handles

→ Non-continuous glazing supports

→ Screws for affixing frame to window opening

→ Fasteners for shading elements (these would be captured in a separate psi-install calculation)

2.3.3 Thermal Conductivities

Where proprietary materials are used, the thermal conductivity used in the model must be confirmed through independent third-party testing. Where test data is unavailable, standard thermal conductivities must be used. It is not acceptable to use manufacturer's reported data without third party verification. For a list of standard thermal conductivities, see Appendix D – Standard Material Thermal Conductivities.

In the absence of appropriate test data, the following hierarchy must be followed (listed from most to least preferred) to select the appropriate thermal conductivity of a material:

1) Standard thermal conductivity values per Annex D of EN ISO 10077-2 and EN ISO 10456 taken at a mean temperature of 10 °C

2) Standard thermal conductivity values from a national testing or certification organization

3) For proprietary materials where a manufacturer claims performance better than what is listed in Annex D of EN ISO 10077-2 or EN ISO 10456, the manufacturer must provide:

   a) Test data
   b) Testing protocols

   Upon review of the provided test data, it may be necessary to

   a) Derate the manufacturer's stated value to obtain a design value – following the procedures described in ISO 10456 for temperature, age, and convection.
   b) Further derate the manufacturer's reported data by a safety factor of 25% if no test reports are available or the testing protocol is determined to be insufficient.

Some materials require additional consideration:

→ Non-isotropic materials such as fibreglass (see Fibreglass Conductivity)

→ Timber. EN ISO 10077-2 provides standard conductivities for various wood species in Annex D

Where there is doubt about a material's thermal conductivity, the modeller is advised to contact PHI or a PH Certifier to determine a suitable thermal conductivity for thermal modelling.

Emissivity

ISO 10077-2's (and ISO 15099's) procedure for determining effective thermal conductivities of unventilated and semi-ventilated air cavities depends on the emissivity of the bounding surfaces. The higher the emissivity, the greater the radiative heat flow across the frame cavity. For the purpose of this

procedure, a default emissivity of 0.9 should be assumed for all common materials. Metallic surfaces may be assigned emissivities from Table D.3 of ISO 10077-2.

Fibreglass Conductivity

PHI does not recognize a standard thermal conductivity for fibreglass, as the plastic composite varies, as does the ratio of composite to glass. Where suitable third-party test data is available, these should be used. Otherwise, the thermal conductivity of fibreglass may be determined as follows:

$$\lambda_{fiberglass} = f_{glass} \cdot \lambda_{glass} \cdot r_{glass} + (1 - f_{glass}) \cdot \lambda_{composite} \cdot r_{composite}$$

Equation 1

Where,

f_{glass} = percentage of glass fibres

λ_{glass} = thermal conductivity of glass, 1.00 W/m·K

r_{glass} = a constant

1.1 where fibres are oriented perpendicular to the direction of main heat flow, or

2.2 where fibres are parallel to the direction of main heat flow

$\lambda_{composite}$ = thermal conductivity of the composite. If the composite is unknown then polyamide is assumed, 0.250 W/m·K

$r_{composite}$ = 1.1

It is possible that within a single frame that the direction of the glass fibres will vary. Where this is the case, two values for $\lambda_{fibreglass}$ will need to be calculated. The factor used for r_{glass} will vary in these cases, based on the description above, while other variables will remain the same.

Note: Equation 1 is generally valid for small glass fractions. At high glass fractions, it is possible for $\lambda_{fiberglass}$ to be greater than 1. $\lambda_{fiberglass}$ should be no greater than the thermal conductivity of the highest conductivity element (typically the glass fibres) and can be assumed to be equivalent to the highest thermal conductivity when this is the case.

Example Calculation:

A manufacturer has confirmed that the percentage of glass in their fibreglass frame is 35%, but is unsure of the details of the plastic composite. The glass fibre direction is parallel to the direction of heat flow.

The effective thermal conductivity of the frame material is determined as follows:

Since the plastic composite is unknown, λ composite = 0.250 W/m·K is assumed

$$\lambda_{fiberglass} = f_{glass} \cdot \lambda_{glass} \cdot r_{glass} + (1 - f_{glass}) \cdot \lambda_{composite} \cdot r_{composite}$$

$$\lambda_{fiberglass} = 0.35 \cdot 1.00 \cdot 2.2 + (1 - 0.35) \cdot 0.25 \cdot 1.1$$

$$\lambda_{fiberglass} = 0.949 \, W/m \cdot K$$

In this example, the thermal modeller would use 0.949 W/m·K for the thermal conductivity of fibreglass when simulating the frame. Readers familiar with the standard thermal conductivity of fibreglass per NFRC 101 will note that the calculated value is more than three times more conductive than the default NFRC value.

2.3.4 Air Cavities (Equivalent Thermal Conductivity Method)

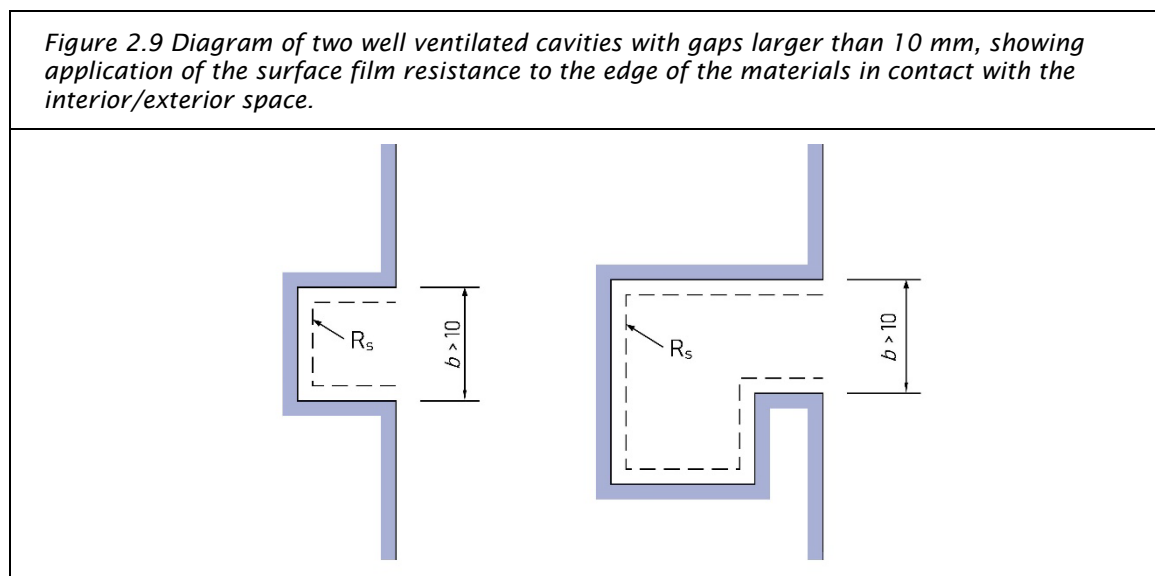ISO 10077-2:2017 provides two methods to account for frame cavities:

1) Equivalent Thermal Conductivity (ETC) Method

2) Radiosity Method

The BC Reference Procedure adopts the first of these two methods. Simulations performed as part of the development of this procedure showed that THERM version 7.4 can automatically perform calculations per the Equivalent Thermal Conductivity (ETC) method. Refer to Appendix J – ISO 10077 Validation of THERM 7.4.

The ETC method represents air cavities within a frame as polygons with an equivalent thermal conductivity such that the conductive, convective, and radiative heat flows can be solved together as conduction through the frame.

An important aspect of the ETC method is the correct classification and division of cavities. When following the ETC method, the following rules apply:

1) Well-Ventilated Cavities (Gap > 10 mm): Air cavities connected to the interior or exterior space by a gap larger than 10 mm are not modelled as air cavities (i.e. no polygon will be created to fill the space). When the gap is larger than 10 mm, the edge of the materials in contact with the interior or exterior space are instead assigned boundary conditions based on their location and the geometry of the surrounding elements (Figure 2.9).

Figure 2.9 Diagram of two well ventilated cavities with gaps larger than 10 mm, showing application of the surface film resistance to the edge of the materials in contact with the interior/exterior space.

2) Slightly-Ventilated Air Cavities (2 mm < Gap ≤ 10 mm): Air cavities connected to the interior or exterior space by a gap larger than 2 mm but less than or equal to 10 mm (2 < and ≤ 10 mm) are considered slightly-ventilated. (Figure 2.10)

The equivalent thermal conductivity of slightly-ventilated air cavities is two times that of an unventilated cavity. In THERM, slightly-ventilated air cavities are assigned the material "Frame Cavity - CEN Simplified (Slightly Ventilated)".

Figure 2.10 Examples of slightly ventilated cavities and grooves
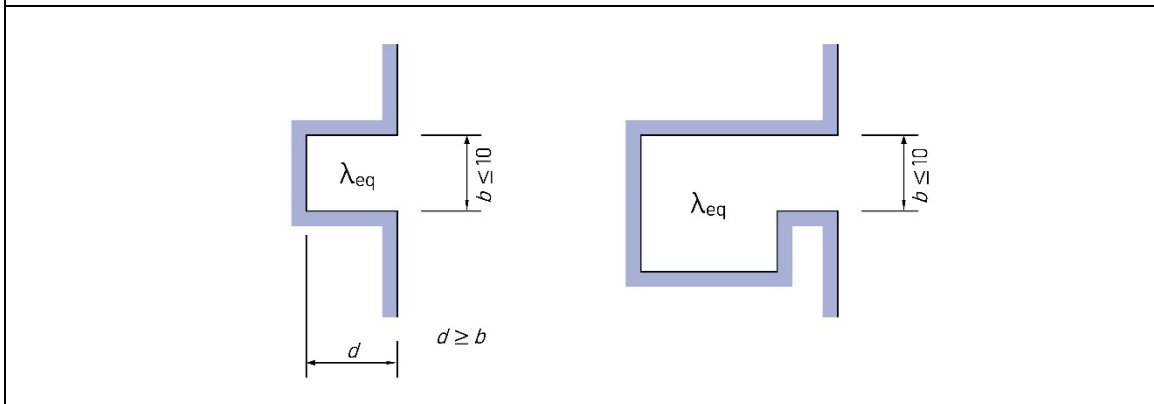
3) <u>Unventilated Air Cavities (Gap ≤ 2 mm or no gap):</u> Air cavities within a frame profile or in contact with an adiabatic boundary are considered unventilated (Figure 2.11). Air cavities connected to either the interior or exterior space by a gap less than or equal to 2 mm (≤ 2 mm) are also considered unventilated.

In THERM, unventilated air cavities are assigned the material "Frame Cavity - CEN Simplified". This material will automatically calculate an equivalent thermal conductivity for the air cavity, based on the formulas provided in EN ISO 10077-2. An example of this calculation is provided in Appendix H – Unventilated Cavities per EN ISO 10077-2.

4) <u>Division of Air Cavities:</u> Where an air cavity has a dimension or an interconnection with another cavity less than or equal to 2 mm (≤ 2 mm), those cavities should be modelled as separate closed polygons.

> **Note 2.3.4.1**: The appropriate division air cavities per the ISO 10077 is not always clear. When dividing air cavities, the modeller should consider the following:

→ Dividing lines should be made between two points or a point and a line segment, but never between two line segments.

→ Avoid creating unnecessary air cavity divisions. In general, air cavities should only be divided when there is a restriction to air flow.

> **Note 2.3.4.2:** When starting from an existing NFRC model, it may be necessary to delete existing frame cavity divisions (based on a 5 mm throat dimension) to meet the ISO 10077 requirements (2 mm throat dimension).

Figure 2.11 Example of an air cavity in contact with the adiabatic boundary condition and modelled as an unventilated air cavity (a) and an example of an air cavity connected to an adjacent air cavity by a dimensions less than or equal to 2 mm (b).

13 mm

a) an unventilated air cavity connected to the adiabatic boundary

5.1 mm   2 mm

b) a semi-ventilated air cavity connected to the exterior by an air gap > 2 mm but ≤ 10 mm, and

an unventilated air cavity connected to an adjacent air cavity by a gap ≤ 2 mm
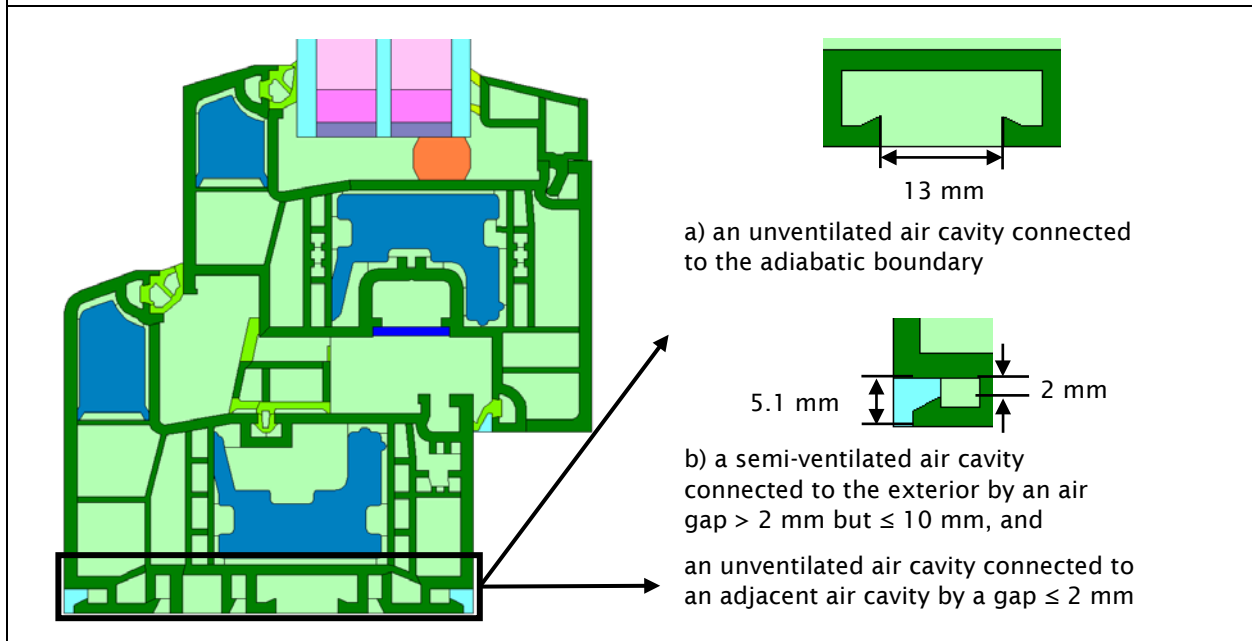
2.3.5   Glazing Inset Depth & Height

The glazing should be modelled to sit within the frame at the same depth that it will sit in the actual frame. Figure 2.12 shows an example where the glazing is inset 15 mm from the frame edge, also known as the sightline. The sightline is measured from the most protruding surface of the primary frame material, ignoring gaskets. Depending on the frame profile, this could mean measuring from either the interior or exterior side of the frame.

> **Note 2.3.5.1:** This definition of the sightline is different from the NFRC approach, which defines the position of the sightline from the highest opaque member (frame, spacer, gasket, shading system, etc.).

Figure 2.12 Example of glazing inset depth. Glazing insertion depth is measured from the sightline to the bottom of the glass. Remember to include continuous glass supports if present.

15 mm

Sightline
(measured from tallest point on the primary frame material)
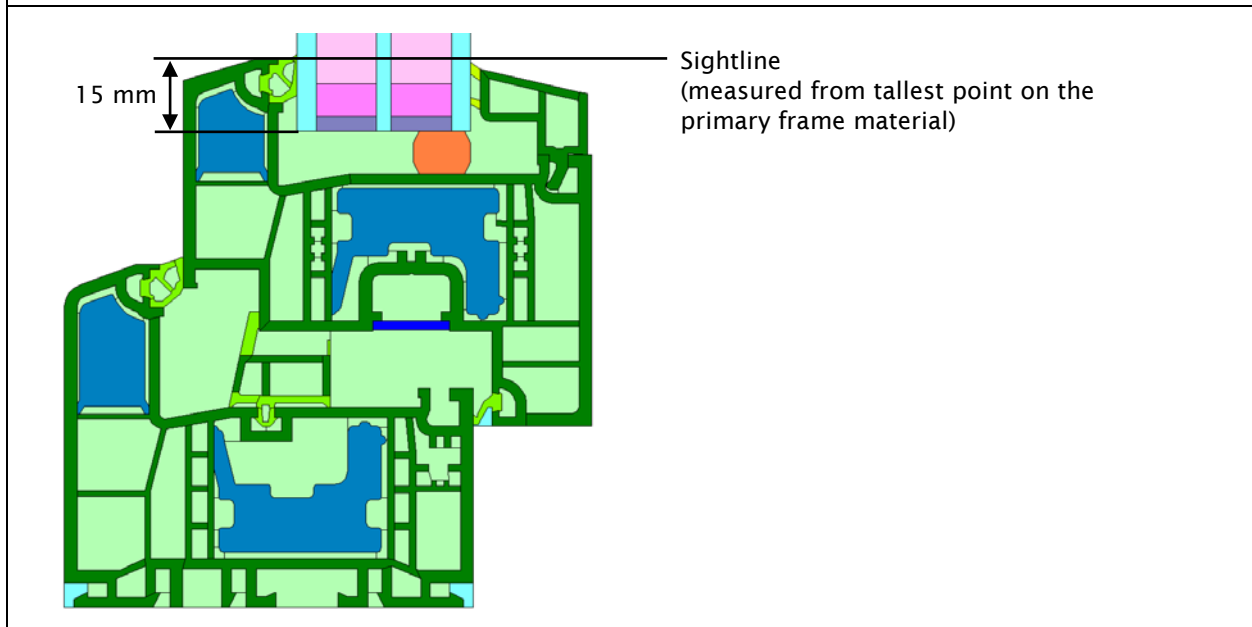
The minimum glass height is the larger of 190 mm or three times the width of the IGU. The glass height is measured from the sightline. In the case of connecting mullions, each IGU must protrude 190 mm or three times the IGU width. Figure 2.13 illustrates the sightline and glass height measurement.

Figure 2.13 Example of glass length. Glass length is measured from the sightline to the top edge of the glass. The minimum glass length is the larger of 190 mm or three times the width of the IGU.

Glass Width

Glass Height

(The larger of 190 mm or 3x the glass width)

Sightline
(measured from primary frame material)
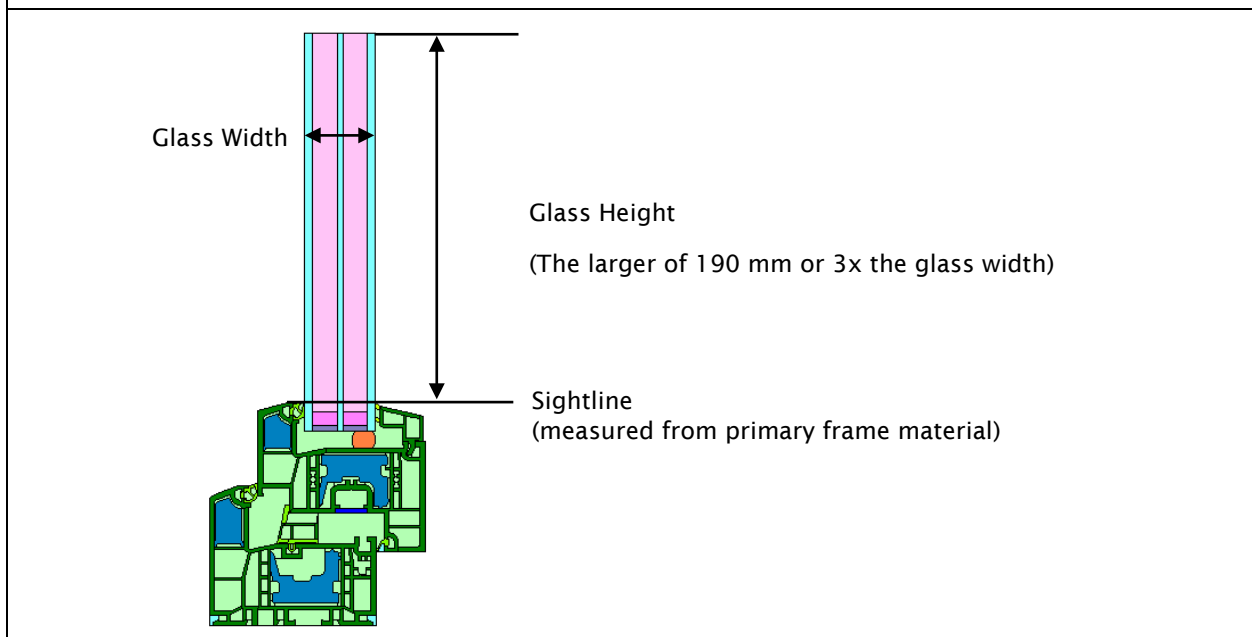
2.3.6 Boundary Conditions

This section describes each boundary condition that is used in one or more models. Not all boundary conditions will be used in all models. See Section 3 for details on which boundary conditions are to be used in each model.

Exterior

All exterior surfaces are to be modelled with an R_{se} of 0.04 m²·K/W, and a temperature of -10 ˚C. This boundary condition is applied to both frame and glazing exterior surfaces.

Note 2.3.6.1: Center-of-glass (U_g) values are simulated at an exterior temperature of 0 °C per ISO 10077-2 and EN 673.

Note 2.3.6.2: When simulating an installed window, there may be exterior surfaces that are not exposed to normal wind conditions (e.g., insulation behind a rainscreen cavity). Per the PHI thermal modelling conventions, R_{se} may be set equal to the interior surface film resistance for the direction of heat flow (e.g., 0.13 m²·K/W for horizontal heat flow). Recall that that the rainscreen cavity and elements beyond (i.e., strapping and cladding) are not modelled.

Interior

Three different boundary conditions are applied to the interior surfaces, following the methodology of Annex E of EN ISO 10077-2:

1) Interior_{Normal}

   a) R_{si} = 0.13 m²·K/W and 20 °C

2) Interior _{Reduced}

   a) $R_{si,reduced}$ = 0.20 m²·K/W and 20 °C

3) Interior$_{fRsi}$

   a) $R_{si,frsi}$ = 0.25 m²·K/W and 20 °C

The Interior_{Reduced} boundary condition is applied at interior edges or junctions between two interior surfaces to account for the reduced radiation/convection heat transfer. For each such surface, the reduced radiation/convection boundary condition is applied from the most protruding surface where the edge/junction occurs along all surfaces up to 30 mm measured perpendicularly to the depth of the protrusion. All other interior surfaces will have the Interior_{Normal} boundary condition applied to them. Figure 2.14 provides a graphical representation of the guidelines for application of the Interior_{Reduced} boundary condition. Figure 2.15 displays an example with the proper boundary conditions applied to a full frame model.

> **Note 2.3.6.3:** Additional boundary conditions apply when determining the center-of-glass U-value (U_g). These boundary conditions are described in more detail in Appendix F and are not applied when determining U_f or any of the other window frame parameters ($\Psi_g, \Psi_{install}, f_{Rsi}$).

Figure 2.14 Reproduction of Figure B.1 from ISO 10077-2 showing the distance over which the increased surface resistances apply. Three cases may apply.
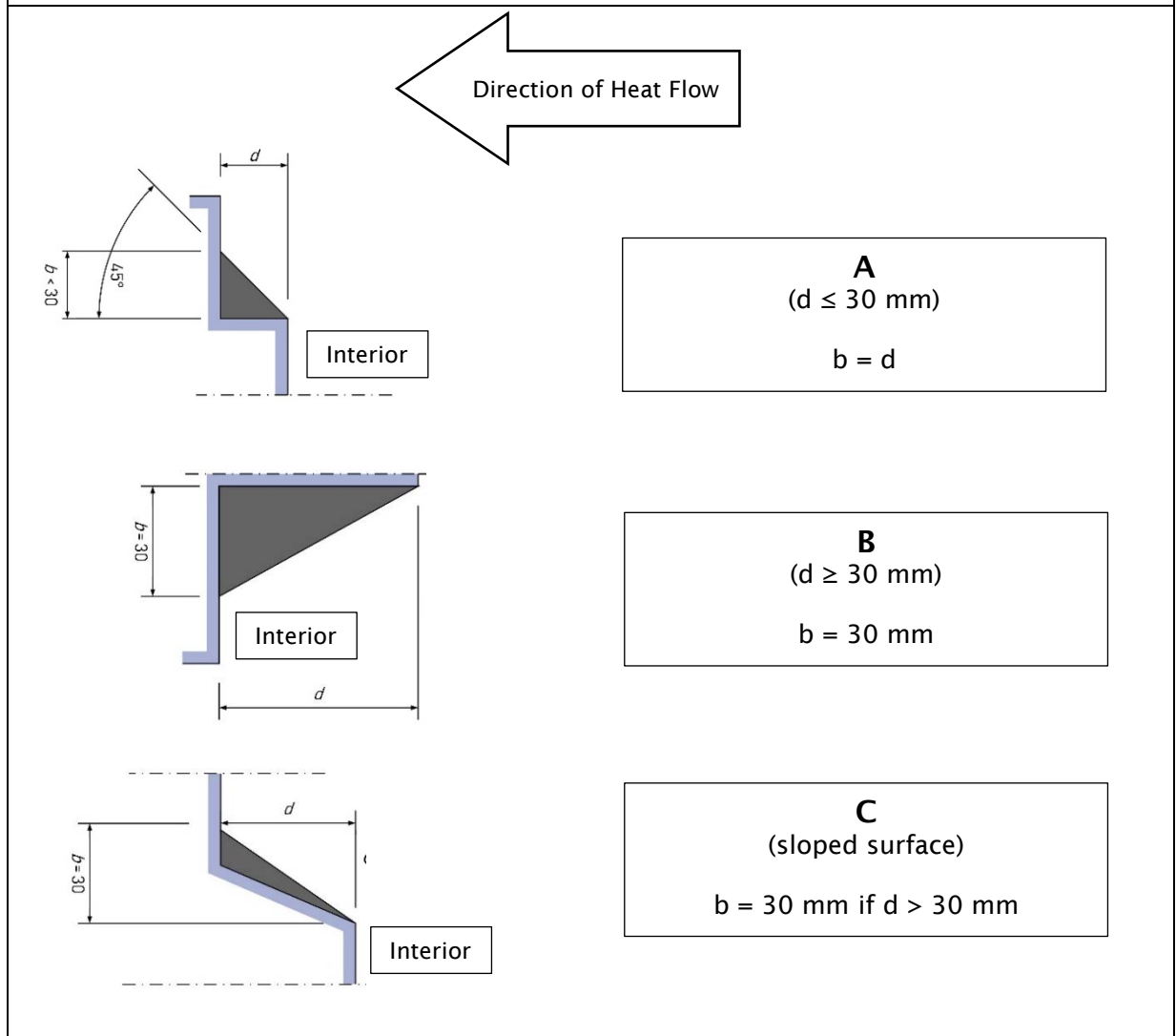
Figure 2.15 displays an example in which a protrusion (measured parallel to the direction of heat flow) is greater than 30 mm in depth (34.8 mm), Figure 2.14, case B. The Interior, Reduced Boundary Condition is thus applied the maximum distance of 30 mm along the perpendicular axis.

Figure 2.15 Example of a frame model with the boundary conditions applied. Note how the reduced interior boundary is applied by first measuring the dimension parallel to the direction of heat flow (label d). In this example, b = d since d ≤ 30 mm. Also note that b is measured from d.
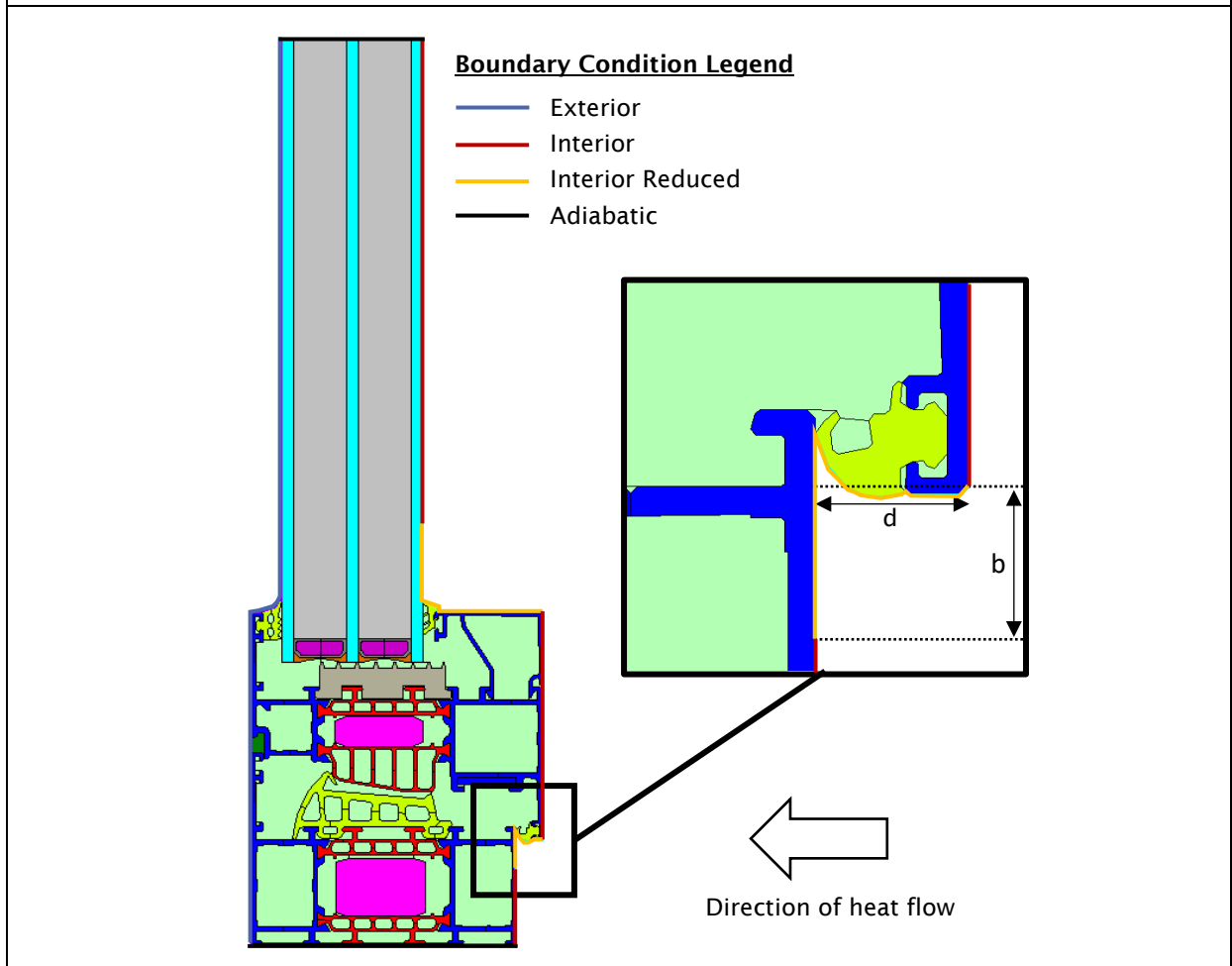
The third interior boundary condition is used when determining the minimum interior surface temperature or the temperature factor (f_{Rsi}). When determining f_{Rsi}, all interior surfaces are assigned an increased air film resistance of 0.25 m²K/W. There is no reduced version of this boundary condition. ISO 13788 *Hygrothermal Performance of Building Components* describes the intent of the increased surface resistance as follows:

> "4.4.1, For condensation or mould growth on opaque surfaces, an internal surface thermal resistance of 0,25 m²·K/W shall be taken to represent the effect of corners, furniture, curtains or suspended ceilings, if there are no national standards."

Adiabatic

The final boundary condition is the adiabatic boundary located at cut-off planes (i.e., edges of the model). An adiabatic boundary is one through which no heat flows. For a window frame model, the cut-off planes are the outside (short) edge of the glazing, as well as the outside edge of the frame (the edge touching the window opening). In cases where there are air gaps along the outside edge of the frame, the outside edge facing the window opening of these air gaps will also be assigned as adiabatic. See Figure 2.16 for an indication of the appropriate edges to be assigned the adiabatic boundary condition.

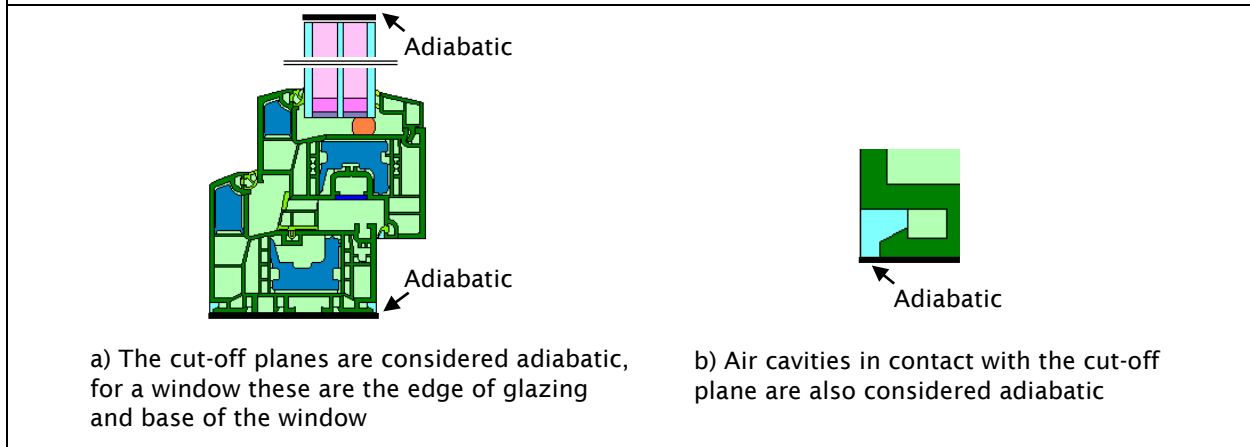Figure 2.16 Adiabatic boundary condition at edges of model

a) The cut-off planes are considered adiabatic, for a window these are the edge of glazing and base of the window

b) Air cavities in contact with the cut-off plane are also considered adiabatic

Table 2.1 summarizes the boundary condition temperature and surface film resistances decribed above and used in this procedure.

TABLE 2.1   BOUNDARY CONDITION SUMMARY

BOUNDARY CONDITION	RESISTANCE (M²K/W)	TEMPERATURE (˚C)
EXTERIOR	0.04[1]	-10
EXTERIOR (U_g)	0.04	0
INTERIOR, NORMAL	0.13	20
INTERIOR, REDUCED	0.20	20
INTERIOR, FRSI	0.25	20
ADIABATIC	N/A	N/A

[1] Resistance value may be increased to account for areas protected from normal wind conditions. Refer to note 2.3.6.2.

2.3.7   Modelling in THERM: U-factor Tags

For each boundary condition that is applied, THERM allows the user to set a 'U-factor surface' tag that groups the simulated heat flow through similarly tagged surfaces. Surfaces that use the same tag appear together in the U-Factors results panel. Appropriate use of U-factor tags is essential for extracting results from THERM for use in the calculations described later in this document (see Section 3). Figure 2.17 shows an example of the THERM U-factor results panel with multiple U-factor tags applied. U-factor surface tags are listed on the left, with results shown in the columns to the right.

THERM will automatically generate boundary condition line segments along the perimeter surface of the model. Each boundary condition segment is assigned a specific boundary condition type and U-factor surface tag, which may be modified by double-clicking on the boundary line segment. This will open the Boundary Condition Type dialog box, as shown in Figure 2.18. The second drop-down menu allows for the assignment of a U-factor surface tag to the selected boundary condition segment.

To speed up this process, multiple boundary condition line segments can be selected at once. This is useful in cases where there are many individual segments that require the same boundary condition and

U-factor tag. Hold the shift key to select multiple segments from the first selected segment to the second in a counter-clockwise manner.

Figure 2.17 THERM U-factor results panel with multiple U-factor tags applied

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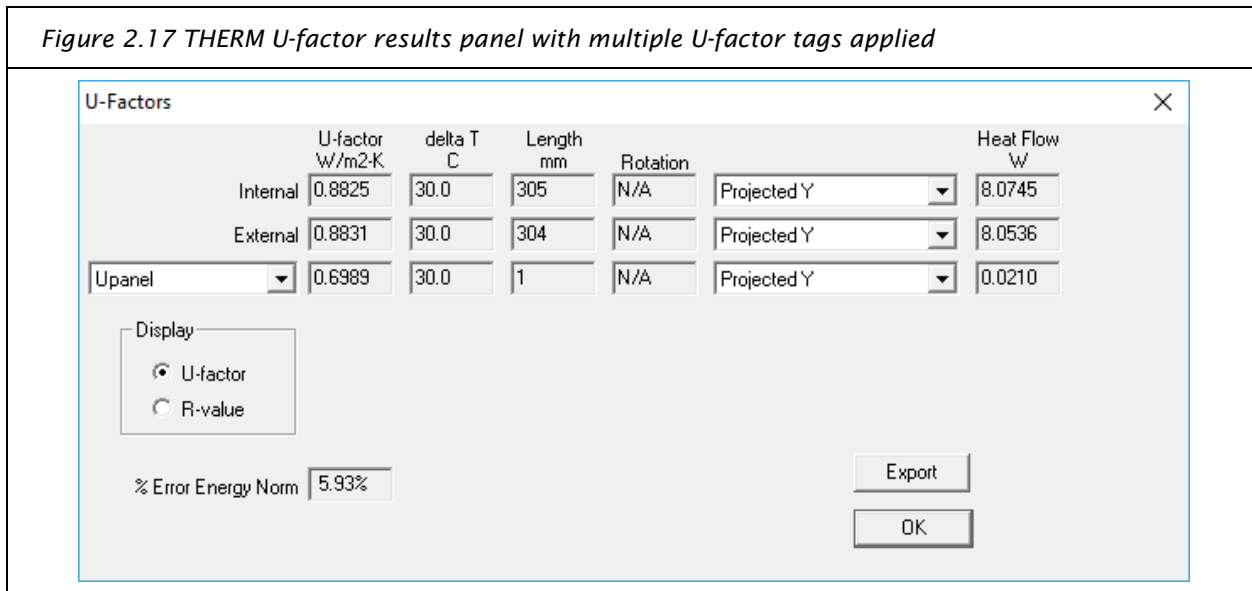
Figure 2.18 Setting a U-factor tag in THERM using the Boundary Condition Type dialog box. Multiple line segments can be selected by holding down shift and selecting in a counter-clockwise manner.
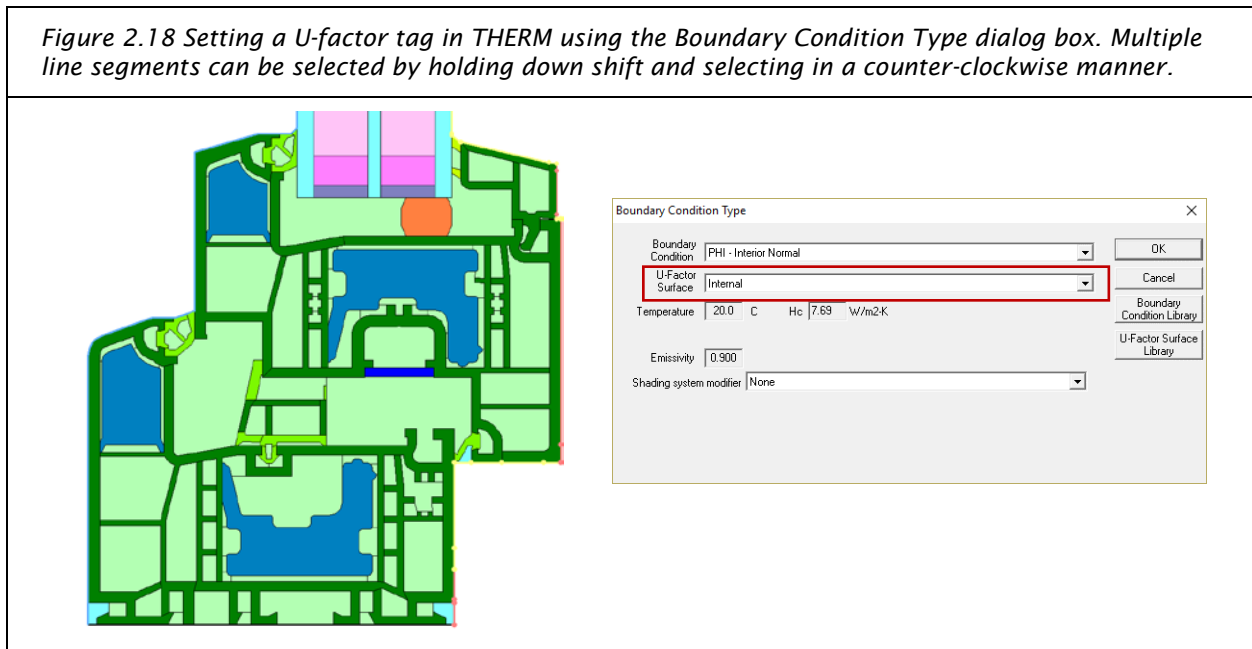
Required U-factor Tags

Three U-factor Surface tags are required to perform the calculations discussed in this document:

1) **Internal**: Applied to all internal surfaces, including both the frame and the glazing or panel

2) **External**: Applied to all external surfaces, except as noted for U_{panel}

3) U_{panel}: Applied to the last 1 mm of the glazing panel next to the model's exterior glazing edge. This is a simple method for determining the center-of-glass U-value of the glazing panel, as it can be done in the existing model.

Use of the U_{panel} Tag to Calculate Center-of-Glass U-value

The U_{panel} U-factor tag described here can be used to calculate the center-of-glass U-value of the glazing panel. This can be done by applying the tag to a 1 mm U-factor sliver at the edge of the glass in the existing model, eliminating the need to construct a separate model for this purpose. (Figure 2.19)

This 1 mm sliver is used in the calculations described in Section 3. The process is the same for insulation panels as for the reference glazing package modelling.

To add a 1 mm U-value sliver to the glass panel:

a) Ensure THERM has Metric units selected
b) Type 1 on the keyboard to bring up the Step Size menu and set the Step Size to 1 mm.
c) Select the appropriate polygon
d) Zoom close to the external corner of the model
e) Insert a new point
f) Select the 'Move Points' tool
g) Hover over the newly inserted point
h) Press the keyboard arrow in the direction of the glass surface
i) Hover over the corner vertex
j) Press the keyboard arrow parallel to the direction of the surface, away from the model's adiabatic edge
k) Press Enter

An alternative approach is to draw a 1 mm square at the edge of the glazing, run the BC tool, delete the 1 mm polygon, then re-run the BC tool. When the boundary condition tool is run selecting the "Use all of the properties of any existing or deleted boundary conditions" option, this will create a 1 mm segment to which a boundary condition can be applied without impacting the original polygon. The boundary condition should be the same as the rest of the glazing (Exterior, 0.04 m2K/W), but should be assigned the U_{panel} U-factor Surface Tag.

Figure 2.19 Simulating the center of glass U-value (for use in U_f calculations) can be done in the same THERM file as the frame by creating a 1 mm line segment at the exterior edge of the glass furthest away from the frame.
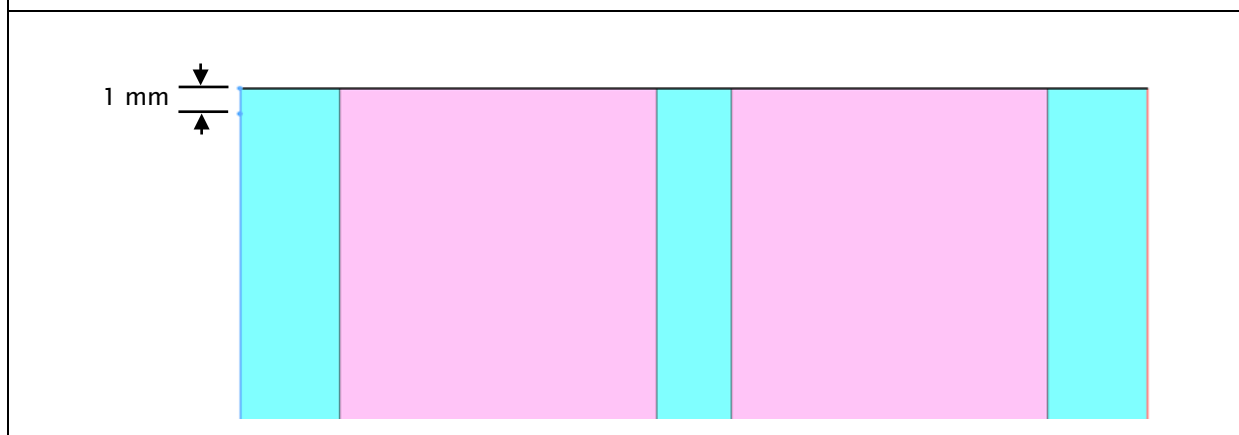
It is also possible to calculate the U-value using a separate model comprised of the element on its own, but the sliver method is preferable as it allows this calculation to be done within a single model, reducing the chance of errors or inconsistencies that can be introduced as a result of managing multiple models.

3 Modelling Process and Step-by-Step Guidelines

3.1 General Frame Modelling Procedures

Three models are required to determine the uninstalled thermal performance of a window or glazed door frame section:

1. U_f Model: to determine the U-value of the frame;

2. Ψ_g Model: to determine the psi-value of the glazing spacer; and

3. f_{Rsi} Model: to determine the hygiene criteria evaluation.

The following sections describe the modelling procedure for each model. Sets of models are required for each unique frame profile. The general modelling guidelines and assumptions described in Section 2.3 apply to all models.

3.1.1 Modelling in THERM: Error Checking

To verify whether interior and exterior surfaces are assigned properly to the model, the U-factors results panel should be reviewed after each model is completed. The total heat flow of all interior boundary conditions should equal the total heat flow of all exterior boundary conditions to at least two decimal places (Figure 3.1). If this is the case, then the boundary conditions have likely been applied correctly. Because THERM requires each individual surface to have a boundary condition applied to it, it is easy to miss or incorrectly assign small segments, such as on curved window frame edges or gaskets. This method will help to catch such errors.

The U$_{panel}$ should also be checked to ensure that it shows a length of 1 mm. If a length longer than this appears, another surface has likely been assigned this surface tag, which may lead to incorrect results.

Figure 3.1 THERM results output showing that heat flow through the external (blue) and through the internal (red) surfaces are equal within two decimal places.
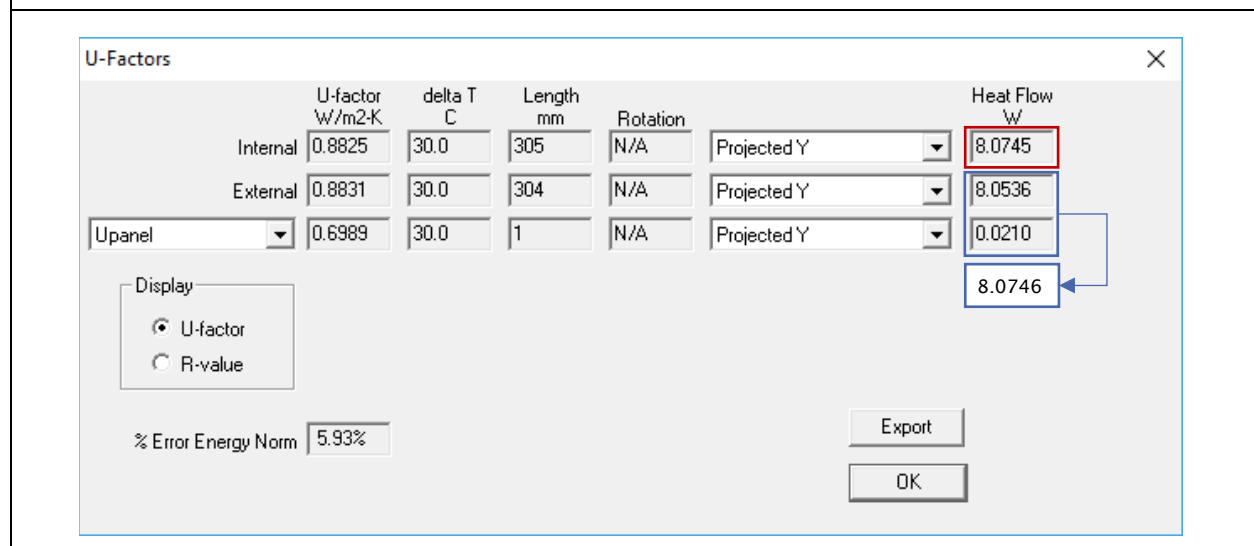
It is also useful to measure the distance between the edges of the reduced interior boundary conditions. When heat flow is in the x-direction, the change in y should equal the change in x unless the change in x

is larger than 30 mm, then the change in y equals 30 mm. This can be checked using the Tape Measure tool as shown in Figure 3.2.

Figure 3.2 When heat flow is in the x-direction, the change in y should equal the change in x (for changes in X ≤ 30 mm).

Tape Measure

Length of this line is: 34.789 mm
dx: 24.600
dy: 24.600

OK

Direction of heat flow

(x-direction)

a) Change in x is equal to the change in y, unless the change in x is larger than 30 mm

---
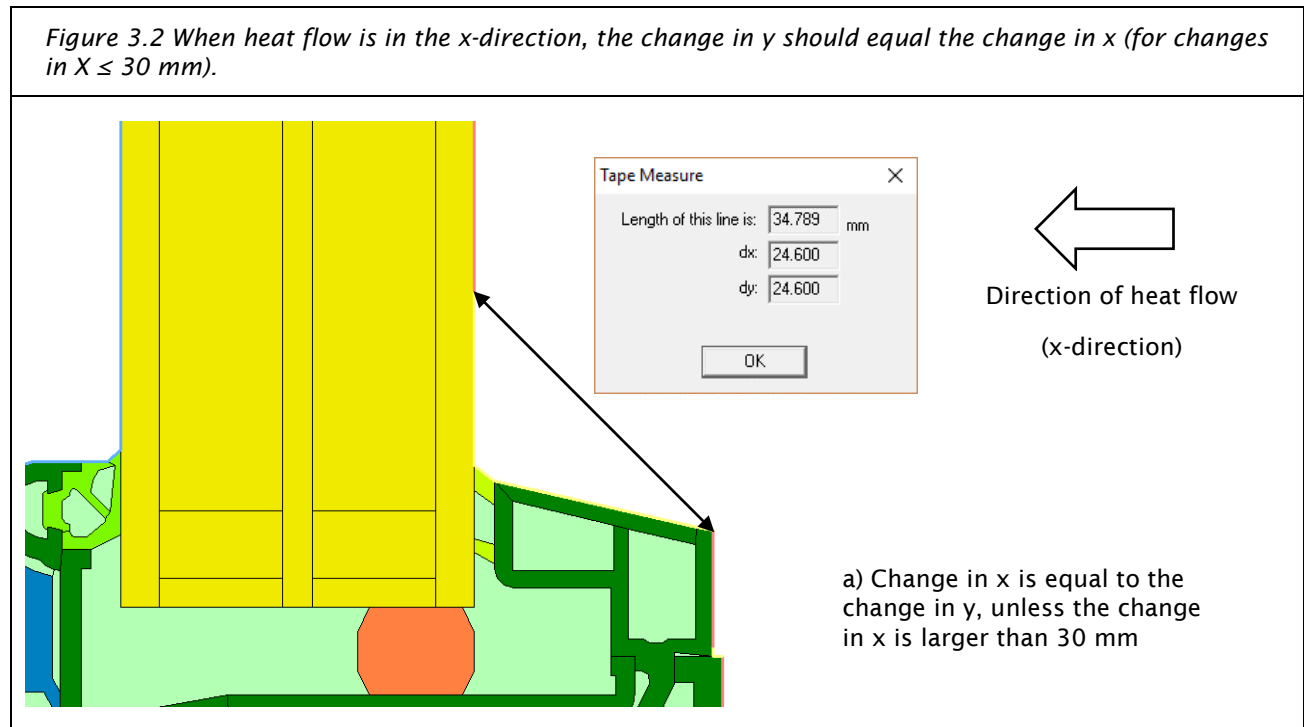
3.2 U_f Model

The BC Reference Procedure begins with the U_f model. The Ψ_g and f_{Rsi} models will be built using the U_f model as a base. The difference between the models will be discussed in each section.

3.2.1 Model Geometry and Materials

Insulation Panel

When determining U_f, the glazing is replaced by a polygon of the same width and height as the IGU. The polygon is assigned a thermal conductivity of 0.035 W/m·K and is referred to subsequently as the insulation panel. In cases where the spacer and/or sealant is not flush with the bottom edge of the glazing, the insulation panel can be modelled as completely rectangular. In this case, the insulation panel should be flush with the bottom edge of the glass. Figure 3.3 shows an example insulation panel.

Figure 3.3 Example of a vinyl window frame with a insulation panel (λ=0.035 W/m·K)

Panel Height

(The larger of 190 mm or 3x the glass width)

Insulation Panel (λ=0.035 W/m·K)

a) Isotherms at the edge of the insulation panel are parallel indicating the model height is sufficient
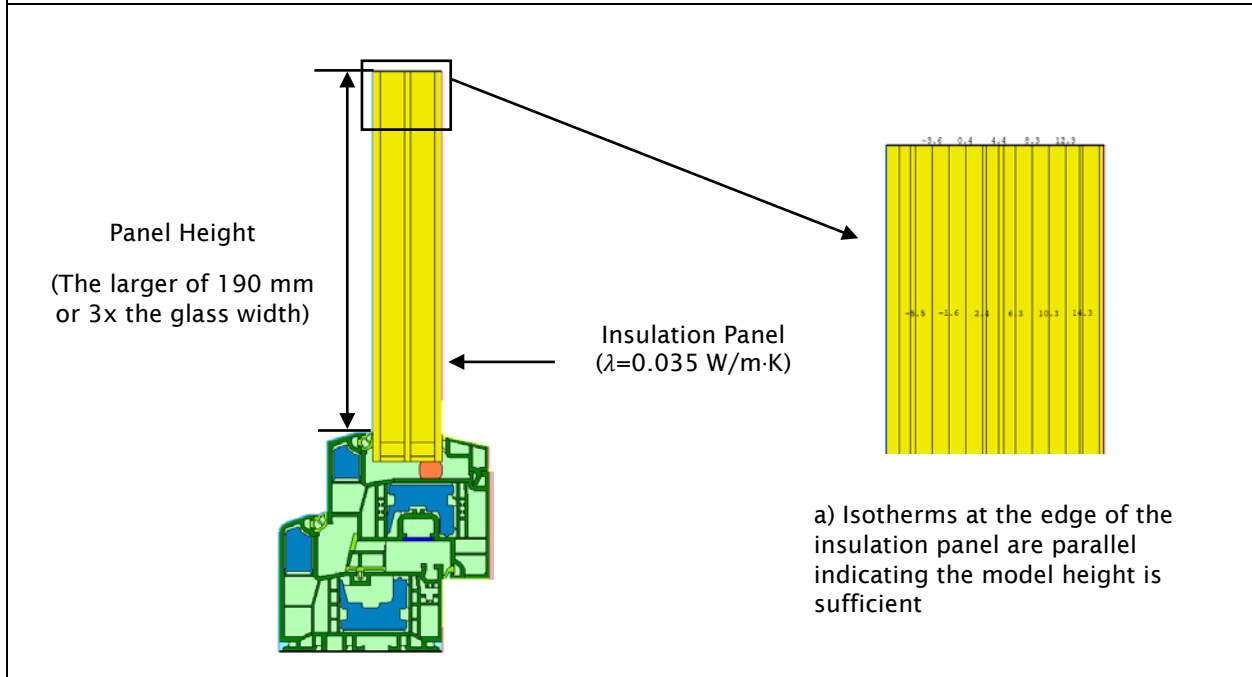
Insulation Panel Height

As described in section 2.3.5, the glazing (and panel) shall extend past the sightline (excluding gaskets) a minimum of three times the IGU width. For a typical triple pane IGU ≤ 60 mm, a glass height of 190 mm should be used. Quadruple pane IGUs may require a larger panel height.

Thermal modellers are encouraged to check that the isotherms at the outside edge of the insulation panel are parallel. If the isotherms are not parallel at the model's edge after the calculation is run, the panel height is insufficient to achieve one-dimensional heat flow and the panel height should be increased.

Frame Geometry

The frame should be modelled following the guidelines described in Section 2.3.

3.2.2   Boundary Conditions

Exterior (U-factor tags: External and U_{panel})

All exterior surfaces should use the Exterior, Normal Boundary Condition (see section 2.3.6). This applies to both the window frame and the glazing surfaces.

All exterior surfaces (except for the 1 mm sliver discussed in 2.3.7) should have the same U-factor tag applied. This includes all BCs applied to both the insulation panel and the frame between the Adiabatic glazing edge and frame edge. (See Figure 3.4)

Interior (U-factor tag: Internal)

Interior window frame and glazing surfaces are assigned boundary conditions based on the requirements of Annex E of ISO 10077-2, as described in Section 2.3.6.

All interior surfaces should have the same U-factor tag applied. This will allow an overall heat flow to be extracted and is used in calculating results. (Figure 3.4)

Model Edges

Model edges shall be set to the adiabatic boundary condition as described in Section 2.3.6.

Figure 3.4 Example of a vinyl window frame with U-factor tags shown

Upanel
(1 mm)

External

Internal
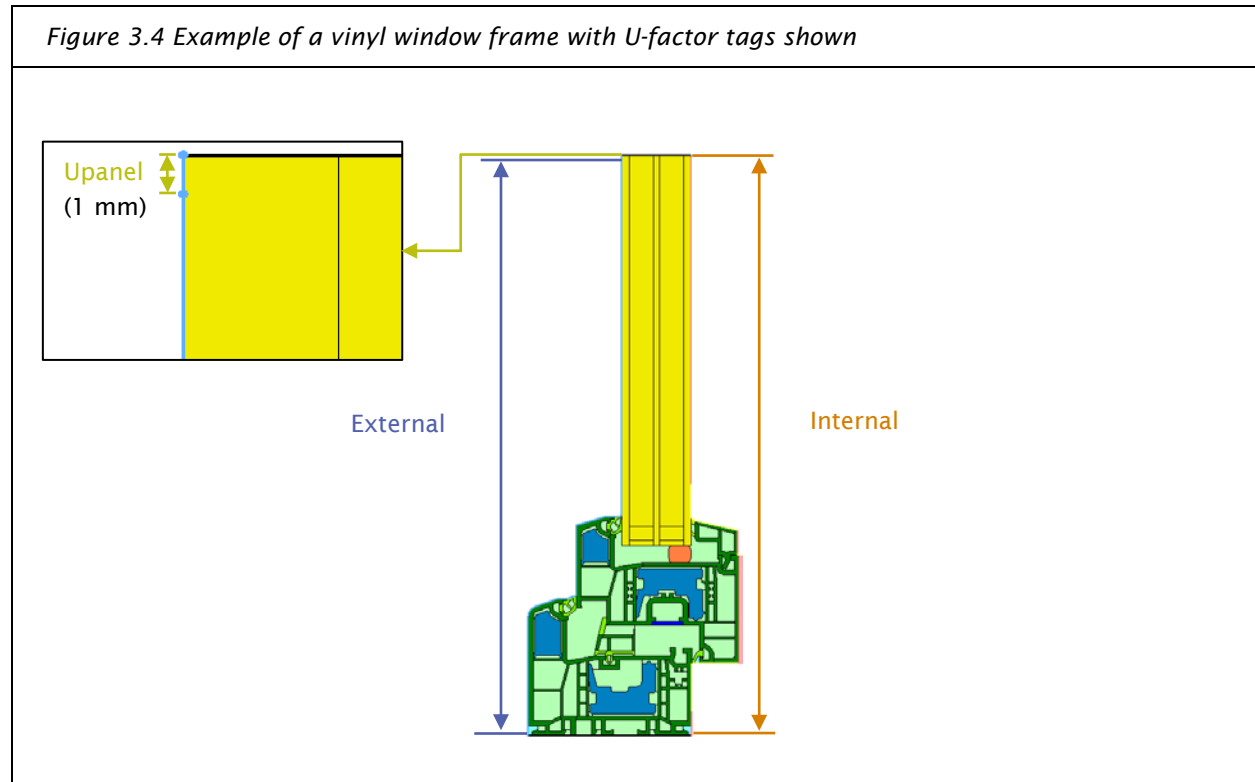
3.2.3   Calculation of U_f

The U-value of the frame (U_f) is determined using Equation 2.

$$U_f = \frac{L_f{}^{2D} - U_p * b_p}{b_f}$$

Equation 2

Where,

U_f = Frame U-value reported to 3 decimal places (W/m²·K)

$L_f{}^{2D}$ = Thermal conductance of the model (W/m·K)

U_p = U-value of the glazing panel (W/m²·K)

b_p = Length of the glazing panel protruding beyond the sightline (see Section 3.2.1) (m)

b_f = Length of the frame, measured from the sightline to the adiabatic edge of the frame (m)

3.2.4   Calculation of L_f^{2D}

L_f^{2D} is not directly output from THERM, but can be obtained from the U-factor results panel using Equation 3.

$$L_f{}^{2D} = \phi_i \times b_i$$

Equation 3

Where,

ϕ_i is the U-factor, Internal (W/m²·K). Based on the heat flow through all interior surfaces.

b_i = U-factor length, Internal (m). The length over which ϕ applies (i.e., all surfaces to which the 'Internal' U-factor tag has been applied).
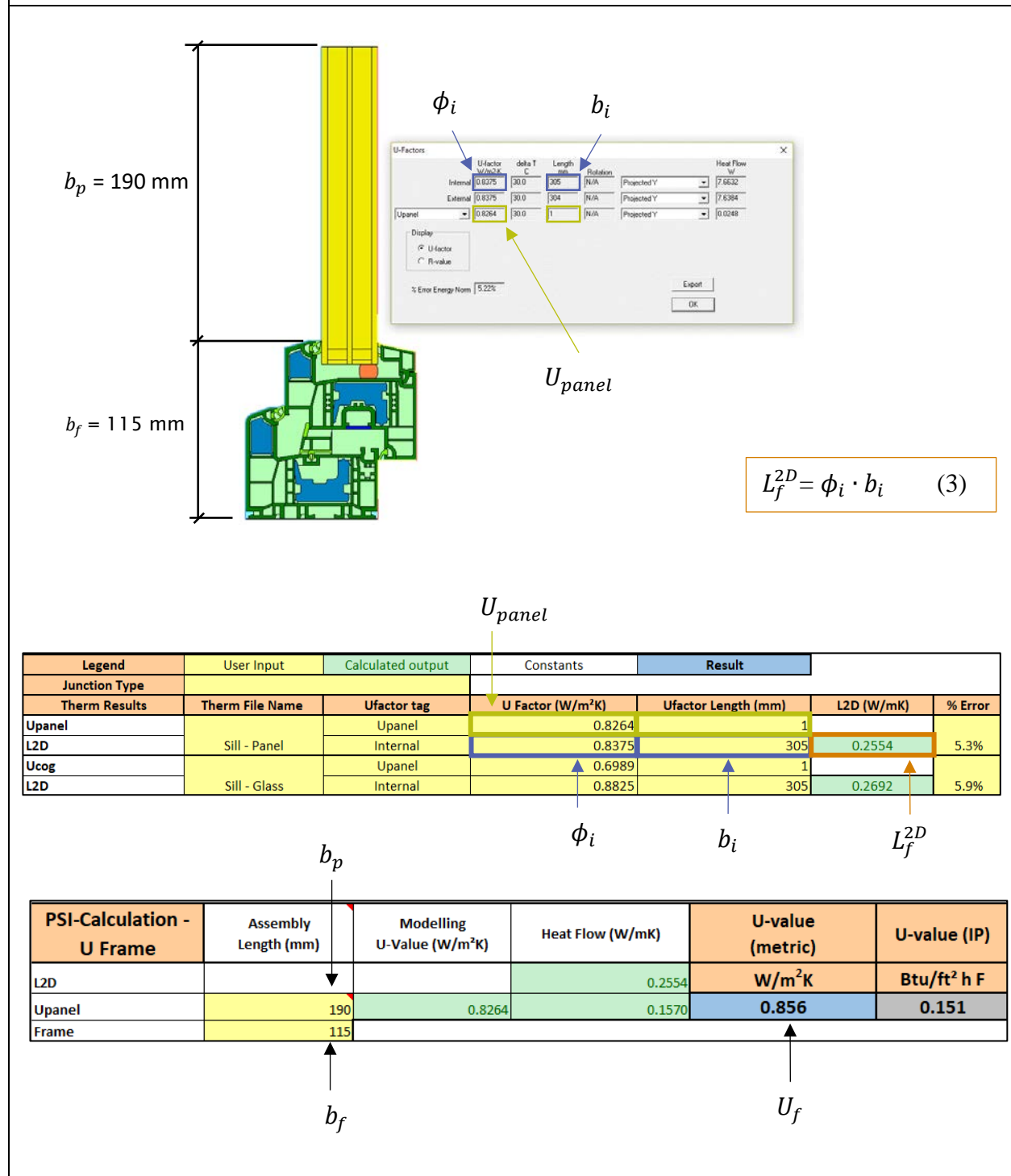
3.2.5   Calculation of U_p

U_p is obtained directly from the U-factor results of the U_{panel} tag. The procedure for setting up and applying the U_{panel} tag is discussed in Section 2.3.7.

Figure 3.5 shows an example of the above calculations performed using the Excel calculator included with this procedure document.

3.2.6   Example

Figure 3.5 Example THERM output showing the U-factor tags and calculation results. User is required to enter data into the yellow cells. L_f^{2D} and U_f are calculated automatically.

$$L_f^{2D} = \phi_i \cdot b_i \qquad (3)$$

b_p = 190 mm

b_f = 115 mm

Legend	User Input	Calculated output	Constants	Result	
Junction Type					
Therm Results	**Therm File Name**	**Ufactor tag**	**U Factor (W/m²K)**	**Ufactor Length (mm)**	**L2D (W/mK)**	**% Error**
Upanel		Upanel	0.8264	1		
L2D	Sill - Panel	Internal	0.8375	305	0.2554	5.3%
Ucog		Upanel	0.6989	1		
L2D	Sill - Glass	Internal	0.8825	305	0.2692	5.9%

ϕ_i b_i L_f^{2D}

PSI-Calculation - U Frame	Assembly Length (mm)	Modelling U-Value (W/m²K)	Heat Flow (W/mK)	U-value (metric)	U-value (IP)
L2D			0.2554	**W/m²K**	**Btu/ft² h F**
Upanel	190	0.8264	0.1570	**0.856**	**0.151**
Frame	115				

b_p b_f U_f

3.3 Psi-Spacer Model

The model shall be identical to the U_f model, except where noted below.

3.3.1 Model Geometry & Materials

Glazing

The glazing package shall be modelled with individual polygons for each layer of glass and each gas fill layer.

The length and width of the glazing shall be the same as the insulation panel in the U_f model.

Glass layers shall be modelled with a conductivity of 1.0 W/m·K. By default, each pane of glass is modelled to be 4 mm thick, unless otherwise specified by the manufacturer.

Gas layer conductivity/conductivities are calculated such that the overall U-value of the glazing package matches the appropriate Reference Glazing U-value shown in Table 3.1.

TABLE 3.1   REFERENCE GLAZING REQUIREMENTS BY PASSIVE HOUSE CLIMATE ZONE

CLIMATE ZONE	REFERENCE GLAZING [W/(M²K)]
1. Arctic	0.35
2. Cold	0.52
3. Cool-Temperate	0.70
4. Warm-Temperate	0.90
5. Warm	1.10
6. Hot	1.10
7. Very Hot	0.90

Note 3.3.1.1: Although not required, it is acceptable for project specific simulations to set the reference glazing U-value to the center-of-glass U-value of the project's glazing.

To calculate the effective thermal conductivity of the fictitious gas layers, the following formula from EN ISO 10077-2 is used:

$$U_g = \frac{1}{h_i + \Sigma \frac{d_g}{\lambda_g} + \Sigma \frac{d_a}{\lambda_a} + h_e} \qquad \text{Equation 4}$$

Where,

U_g = Reference Glazing U-value (W/m²·K), refer to Table 3.1 above

h_i = interior surface resistance (0.13 m²·K/W)

d_g = thickness of each glazing layer (m)

λ_g = conductivity of each glazing layer (1.0 W/m·K)
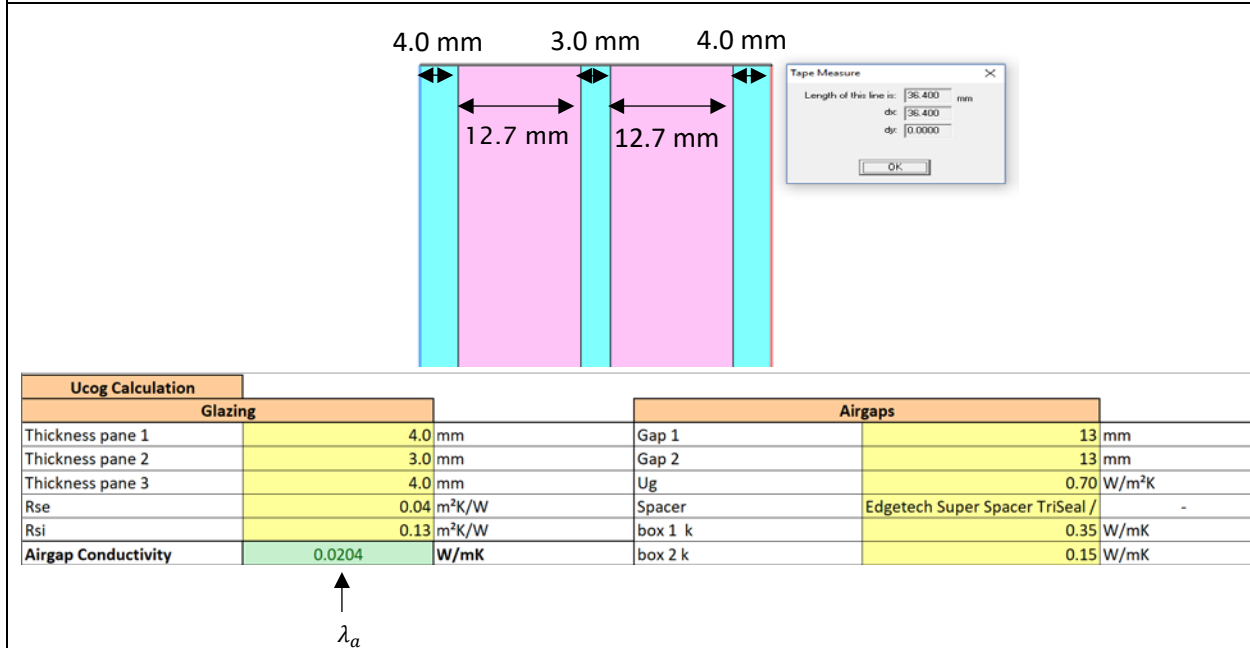
d_a = thickness of each gas layer (m)

λ_a = conductivity of each gas layer (W/m·K)

h_e = exterior surface resistance (0.04 m²·K/W)

Solving for λ_a will determine the appropriate thermal conductivity for the material representing the gas layers. The effective thermal conductivity should be calculated to 4 decimal places. An example is shown in Figure 3.6.

Figure 3.6 Example THERM output showing calculation of the thermal conductivity of the fictitious gas layers for a triple pane window in a cool-temperate climate.
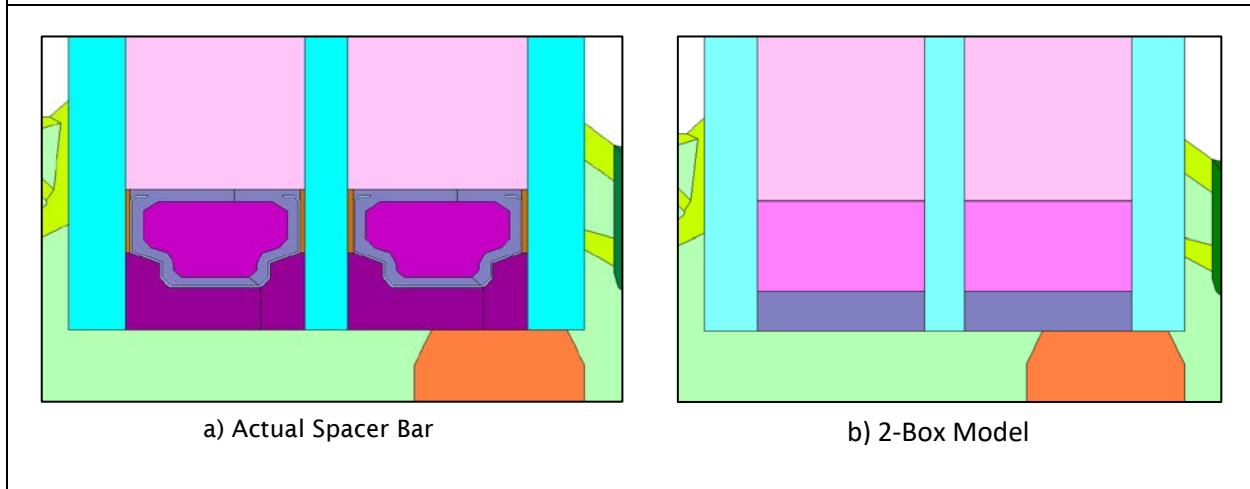

Ucog Calculation					
Glazing			**Airgaps**		
Thickness pane 1	4.0	mm	Gap 1	13	mm
Thickness pane 2	3.0	mm	Gap 2	13	mm
Thickness pane 3	4.0	mm	Ug	0.70	W/m²K
Rse	0.04	m²K/W	Spacer	Edgetech Super Spacer TriSeal /	-
Rsi	0.13	m²K/W	box 1 k	0.35	W/mK
Airgap Conductivity	0.0204	W/mK	box 2 k	0.15	W/mK

λ_a

Spacer Bar

When modelling the spacer, the user has two options:

4) Model the spacer based on its actual makeup. All materials present in the spacer are to be included when using this method. Figure 3.7 a) shows an example of a model using this method

5) Model the spacer using a simplified 2-Box model. A 2-Box models consists of two polygons – one to represent the spacer, one to represent the sealant – that result in the same heat flow as if the spacer and sealant were modelled with their actual dimensions. Determining the appropriate thermal conductivity for the two polygons is beyond the scope of this procedure. However, numerous spacer bars have 2-Box models already created; see the Passive House Institute's Component Database, or certificates produced by the Warm Edge Working Group (Bundesverband Flachglas). The Passive House Institute can also produce 2-Box models for use in this modelling, for a fee. Figure 3.7 b) shows an example of a model using the 2-Box method.

Figure 3.7 Example of a window model with (a) an actual spacer bar modelled and (b) an equivalent 2-Box model

| a) Actual Spacer Bar | b) 2-Box Model |

3.3.2 Calculation of Ψ-Spacer

Ψ_{spacer} is determined following Equation 5:

$$\Psi_{spacer} = L_\psi{}^{2D} - (U_p \cdot b_p) - (U_f \cdot b_f)$$

Equation 5

Where,

$L_\psi{}^{2D}$ = Thermal conductance of the model (W/m·K)

U_p = U-value of the glazing (W/m²·K)

b_p = Length of the glazing protruding beyond the most protruding element of the frame to the edge of the glazing (0.190 m or greater, see Section 2.3). This will generally be the same length as the U_f model (m)

U_f = U-value of the window frame (W/m²·K), as calculated in Section 3.2.3.

b_f = Length of the frame, measured from the most protruding element of the frame to the adiabatic edge of the frame. This should be the same length as the U_f model (m)

3.3.3 Calculation of $L_\psi{}^{2D}$

$L_\psi{}^{2D}$ is not directly output from THERM but can be determined from the U-factor results window in the same manner as for the U_f model. Two values are required to calculate this:

$$L_\Psi{}^{2D} = \phi_i \times b_i$$

Equation 6

Where,

ϕ_i is the U-factor, Internal in W/m²·K. Based on the heat flow through all interior surfaces

b_i = U-factor length, Internal in m. The length over which ϕ applies (i.e., all surfaces)

3.4 Temperature Factor Model

The model shall be identical to the Psi-Spacer model, except where noted below.

3.4.1 Boundary Conditions

The boundary conditions assigned shall be identical to the Psi-Spacer model, except where noted below.

Interior

All interior surfaces shall be assigned the Interior, f_{Rsi} boundary condition where R_{si} = 0.25 m²K/W. This boundary condition will replace all Interior, Normal and Interior, Reduced boundary conditions.

3.4.2 Calculation of f_{Rsi}

The temperature factor, f_{Rsi}, is determined using Equation 7.

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \qquad \text{Equation 7}$$

Where,

f_{Rsi} = temperature factor based on the minimum interior surface temperature (unitless, value is compared to requirements in Appendix A – Transparent Component Certification based on climate zone)

θ_{si} = minimum interior surface temperature from the f_{Rsi} model

θ_e = outside temperature (-10 °C)

θ_i = inside temperature (20 °C)

3.4.3 Example

To extract the minimum surface temperature from THERM, the simplest method is to utilize the 'Temperature at Cursor' option. This can be enabled by opening the 'View' drop down menu and clicking on 'Temperature at Cursor'.

This will display the temperature wherever the mouse is placed on the model. The interior surfaces can then be manually scanned to determine the lowest temperature. Displaying isotherms simplifies this task by indicating temperatures across the model, allowing quicker pinpointing of the lowest temperature. Typically, the lowest temperatures are at or near the junction between the glazing and the frame, but the modeller should inspect the entire model to identify the lowest temperature point.

Figure 3.8 shows an example of the lowest temperature point.

Figure 3.8 Example showing the lowest temperature point, which in this example is at the junction between the glazing and the frame.

11.4 °C
$f_{Rsi} = 0.71$
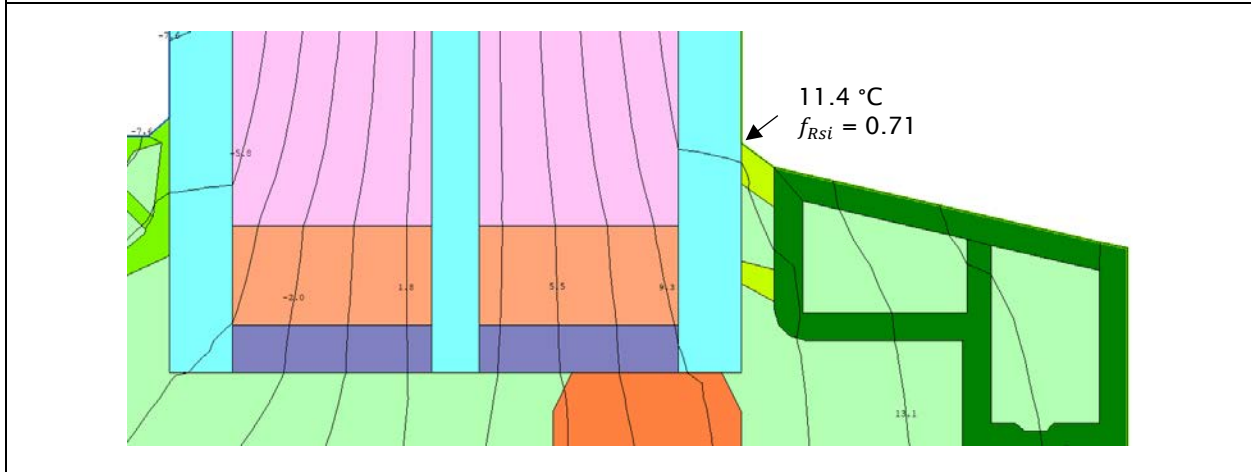
3.5 Glazing Modelling

For entry into PHPP, information about the specific glazing package that will be used on a project is required. This glazing's characteristics will differ from the glazing that is modelled in Sections 3.3 and 3.4, which use the climate specific reference glazing.

Glazing is entered into PHPP with two characteristics:

1. g-value (similar to SHGC)

2. U_g (centre-of-glass U-value)

Figure 3.9 shows two sample glazing entries in PHPP v 9.6a.

Figure 3.9 Screenshot from the Components worksheet in PHPP. Two glazing packages (IGUs) are shown.

Glazing				Glazing
	Recommended glazing type to start planning:			
	Triple thermally insulated glazing (Please consider the comfort criterion!)			
ID	Description		g-Value	U$_g$-Value
				W/(m²K)
01ud	Triple-low-e Kr08		0.50	0.70
02ud	Triple-low-e Kr12		0.50	0.58
03ud				

PHI allows for U_g to be calculated according to either EN 673 or ISO 15099. However, the g-value (SHGC) must be calculated according to EN 410. These calculations can be performed using the LBNL program WINDOW version 7.4 so long as the software is configured correctly, and the proper libraries are used. See Appendix F – WINDOW Program Setup.

With WINDOW correctly configured, glazing packages can be modelled as normal. If modelling to EN 673, ensure that the Environmental Conditions are set to 'CEN', and EN 410 gas layers are used. Figure 3.10 shows an example glazing package with these key elements highlighted. The IG height and width should be set to 1000 mm by 1000 mm.

Figure 3.10 Example of a triple panel window modelled to the EN 673 and EN 410 standard. The environmental conditions have been changed to CEN and the gas layers have been adjusted. In addition, WINDOW has been configured to perform the calculations.
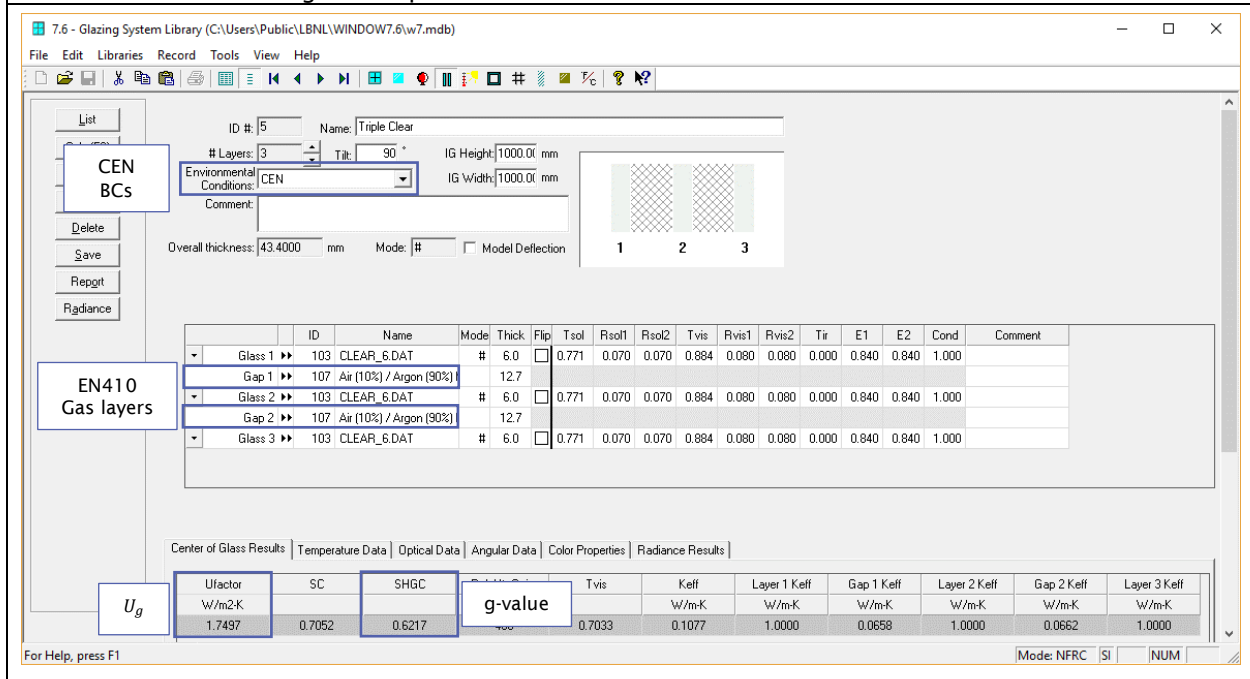
3.6 Psi-Install Model

Windows in Passive House projects are ultimately assessed based on their installed performance. This accounts for thermal bridging introduced by the connection of the window frame to the wall. To determine the impact of the install on the overall window performance, windows are modelled based on the project-specific details that have been developed by the project team. On projects with multiple wall assemblies or multiple window types, this can result in multiple install details, each of which will require its own models (head, jamb, and sill). The great variety of install details means it is difficult to generalize results. This section demonstrates the process for an EIFS wall.

Window installation thermal bridges are typically the longest thermal bridge present on Passive House projects, so it is important to ensure these junctions are well thought out. As a frame of reference, the Passive House 'default' value is 0.04 W/m·K, which assumes well thought out construction and is often used early in design as a placeholder until better information is available. Good detailing can reduce the psi-install to < 0.01 W/m·K, while bad detailing can lead to values of 0.1 W/m·K or greater. To improve detailing at the head and jambs, frames can have insulation installed over top of a portion of the frame, either inside or outside, depending on the direction of operation of the frame. Passipedia's *Basic principles for windows - research on energy efficient modernisation*[4], article gives information on window detailing, with additional examples.

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[4] https://passipedia.org/planning/refurbishment_with_passive_house_components/thermal_envelope/windows?s%5b%5d=window&s%5b%5d=detail

3.6.1   Model Geometry and Materials

Two elements are required for the psi-install model: the window, and the wall. For the window model, the U_f model built in Section 3.2 can be used. When constructing the wall model, ensure that the isotherms are parallel at the outside edges of the model. This can generally be achieved by modelling the wall with a length of 1000 mm, or three times the assembly thickness, whichever is greater.

The guidelines for selecting thermal conductivities discussed in Section 2.3.3 should be followed.

Any continuous materials that are present at the window opening that deviate from the standard assembly construction should be included in the wall. This includes elements such as window mounting systems, additional wall framing, drywall or other finish materials, and conductive elements such as window flashings. Thin (< 1 mm), non-metallic layers, such as self-adhered membrane materials, do not need to be included in the model. Figure 3.11 shows an example of a window sill installation detail.

*Figure 3.11 Example of a window sill install model. Window is modled (by default) 10 mm from the rough opening.*
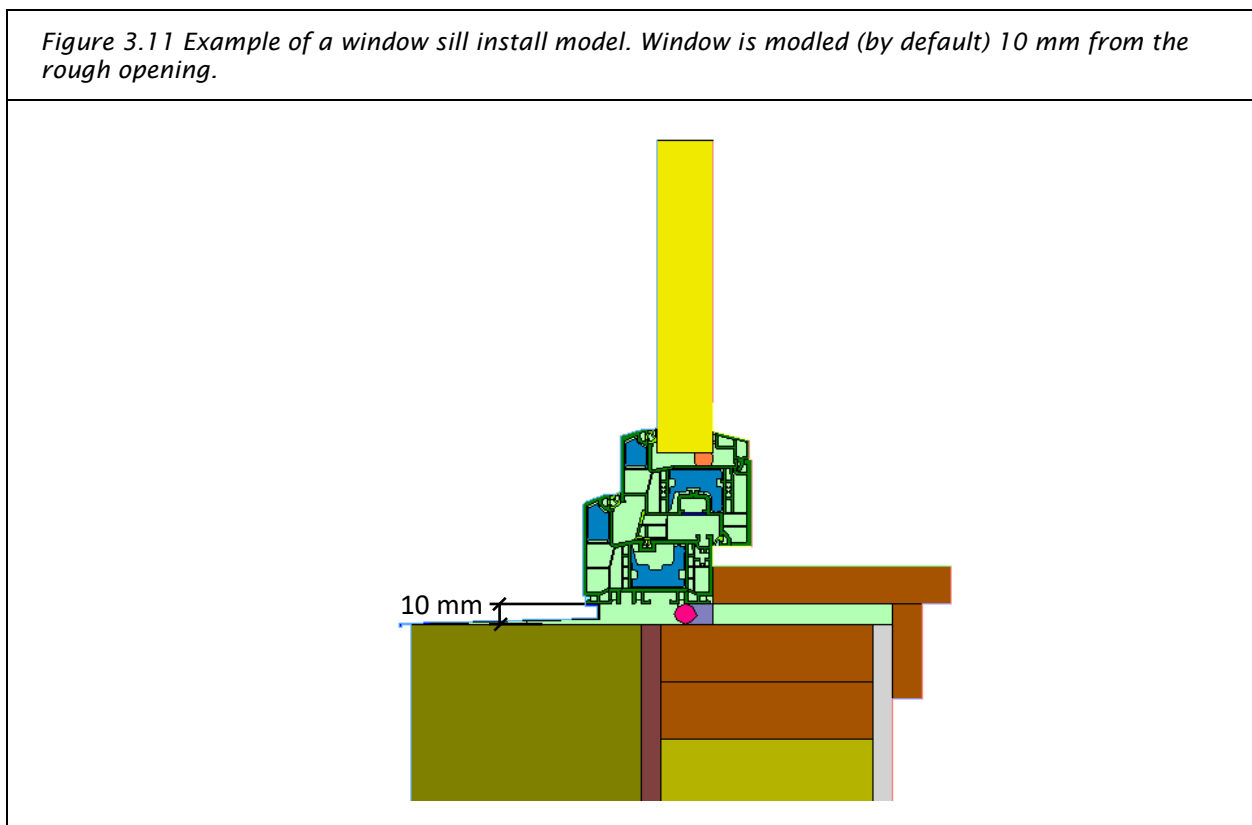
By default, the window frame should be modelled 10 mm away from the window rough opening, and the cavity filled with whatever material will be placed between the window and the rough opening in construction. Typical materials include air, low-density insulation, and sealants.

3.6.2   Boundary Conditions

Interior boundary conditions for all elements other than the window frame should follow ISO 10211. Boundary conditions for various building elements and orientations are shown in Figure 3.12 .

Figure 3.12 Surface resistance values for various building enclosure elements and orientations
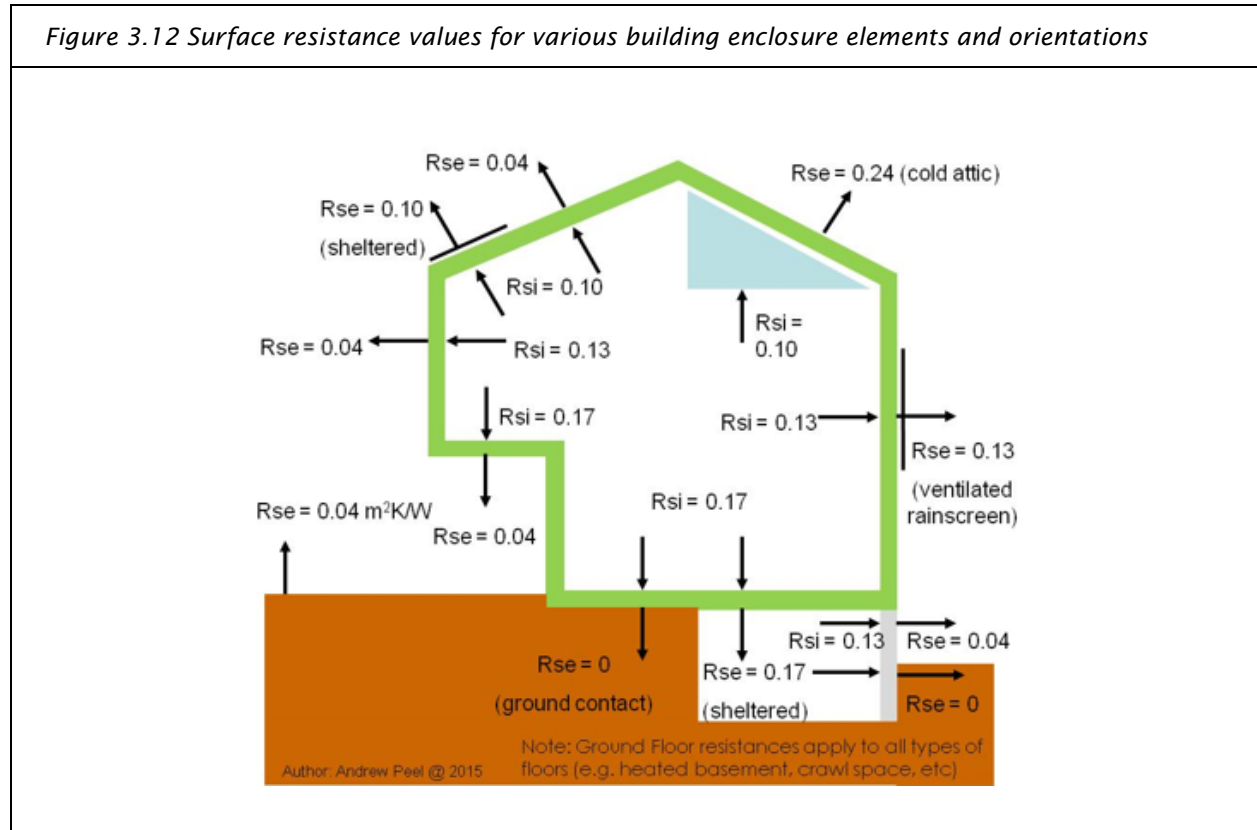
3.6.3   Modelling in THERM: U_{factor} Surface Tags

As with the window models, proper U-factor Surface Tag application is necessary for extracting results from this model.

→ All interior surfaces should have the *Internal* tag applied. This will allow the determination of an overall model heat flow, once the calculation is run.

→ A 1 mm sliver should be created on the exterior side of the wall assembly furthest away from the window following the procedure discussed in Section 2.3.7. This will allow determination of a U_{wall} value, once the calculation is run.

→ All exterior surfaces should have the *External* tag applied, except for the 1 mm sliver discussed directly above, which should have a U_{wall} tag applied to it.

Figure 3.13 shows an example of the U-factor tag assignment.

Figure 3.13 Example of a window installation detail (sill) showing the appropriate U-factor tags
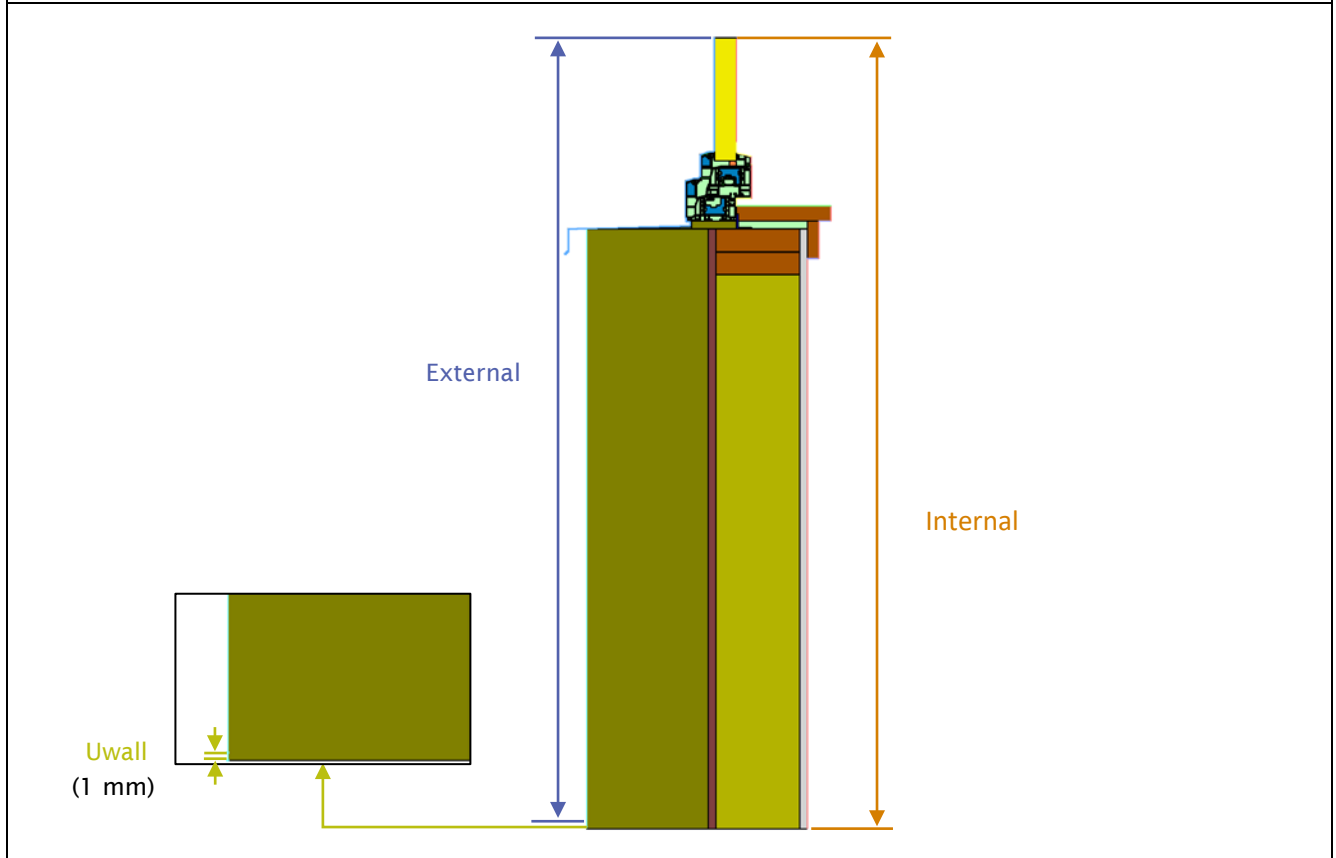
Once the junction model has been built and the calculation run, the psi-install can be calculated. This is done using the formula,

$$\psi_{install} = L^{2D}_{junction} - L^{2D}_{window} - U_{wall} \times l_{wall}$$

Equation 8

Where,

$\psi_{install}$ = Psi-install (W/m·K)

$L^{2D}_{junction}$ = Total model heat flow (W/m·K)

L^{2D}_{window} = Window model heat flow (W/m·K), obtained from U_f model (Section 3.2)

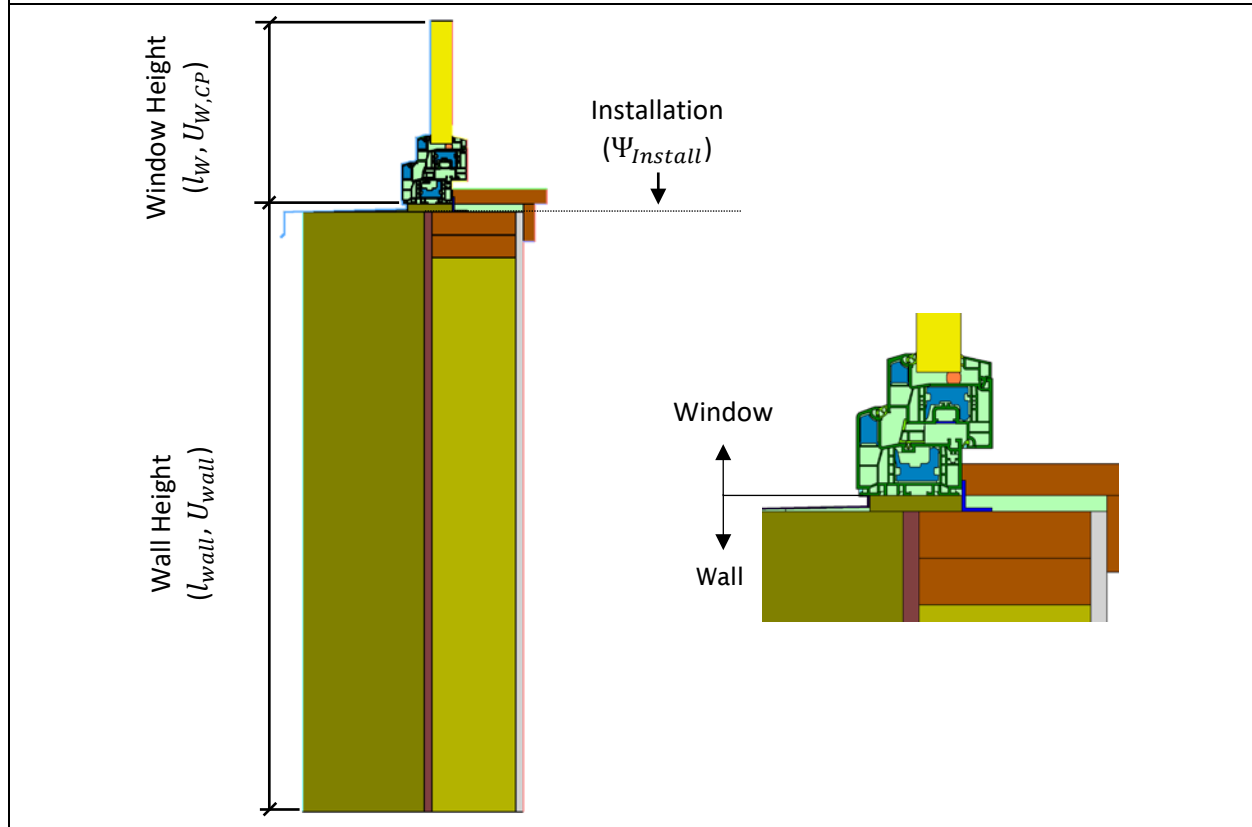U_{wall} = U-value of the wall (W/m²·K)

l_{wall} = Modelled length of the wall (meters)

This calculation compares the heat loss through the junction model to the heat loss through the window and wall on their own. By subtracting the heat flow attributable to these two elements from the simulated junction model, the result is the heat loss attributable to the window install.

L^{2D}_{Frame}, is obtained from the U_f model for the window included in the installation model.

l_{wall} is measured from the wall's adiabatic edge to the bottom of the window frame. However, the perimeter length used in the $\Psi_{install}$ calculations is measured from the rough opening. Figure 3.14 shows an example of this measurement.

Figure 3.14 Example showing how the height of the wall is measured. l_{wall} is measured from the wall's adiabatic edge to bottom of the window frame.

3.6.4   Calculating λ_{eff} of Non-Homogenous Wall Assemblies

U_{wall} in Equation 8 is the effective clear-field U-value of the wall assembly adjacent to the window. Due to the limitations of 2D simulation approaches it is necessary to replace non-homogenous layers (such as insulated frame cavities) with new materials with effective thermal conductivities that account for the different heat flows through the various elements contained within the assembly.

> **Note 3.6.4.1:** Although the simulated U_{wall} should closely match the clear-field U-value of the wall assembly entered into PHPP, it is more important that the U-value used in the calculation of $\Psi_{install}$ is the U-value simulated in the $\Psi_{install}$ model. For this reason, it is strongly recommended that the U-value of the wall assembly entered into Equation 8 be obtained using the 1 mm sliver approach previously discussed.

To determine the effective thermal conductivity of a non-homogenous layer, a separate thermal model of the wall assembly is required. This model should include the repeating elements that deviate from the primary insulation. The width of the model should be equal to one full spacing of the repeating elements. For example, in the case of wood studs that repeat on 406 mm (16 inch) centres, the model length would be 406 mm. The repeating elements are centered in the model. A more complete discussion of cut-off planes is provided in ISO 10211. Figure 3.15 presents an example of this approach.

Note 3.6.4.2: Many software packages, including THERM, require non-zero air film resistances. For this reason, it is recommended to include standard air film resistances and sheathing in the model and then to subtract these additional layers (air films and sheathing) from the result to obtain the effective conductivity of the non-homogenous layer. Refer to Figure 3.15.

Note 3.6.4.3: Figure 3.15 illustrates the calculation approach for a 2x6 wood framed wall. For calculations intended for use in Passive House projects, all layers of the wall assembly should be included (e.g., exterior insulation if present) when calculating k_{eff}.

Figure 3.15 Example of a model the procedure used to calculate the effective R-value of a wood frame wall cavity
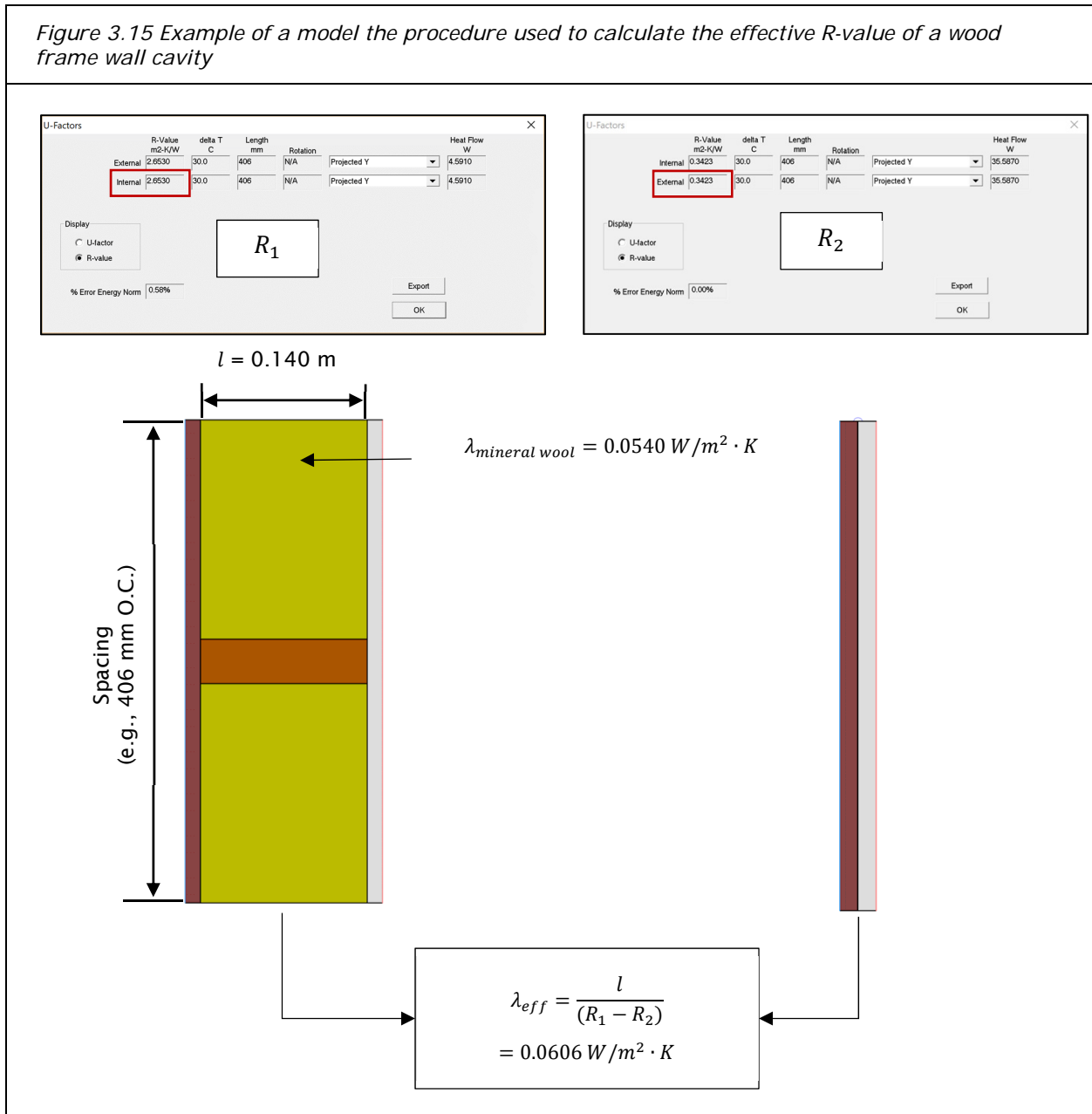
Once the wall model has been constructed, the junction model then needs to be updated with the new material assignment that accounts for the thermal bridging in the wall. This is done using Equation 9.

$$\lambda_{eff} = \frac{l}{(R_1 - R_2)} \qquad \text{Equation 9}$$

Where,

λ_{eff} = Equivalent thermal conductivity of wood frame cavity (W/m·K)

R_1 = The effective R-value of the wall assembly including wood framing, insulation, sheathing, and air films (m²·K/W)

R_2 = The effective R-value of the homogenous layers, i.e., sheathing, and air films (m²·K/W)

l = width of the framed cavity (m)

Note 3.6.4.3: This blended thermal conductivity approach for the treatment of non-homogenous layers is generally acceptable for use in determining linear thermal transmittance values, where the impacted assemblies are subtracted from the final result. Results from this approach should not be used in any other context, such as the determination of assembly R-values. This approach is also not suitable for accounting for highly conductive intermittent thermal bridging elements. ISO 10211 provides further guidance on determining when a blended layer can be used.

Equivalent thermal conductivity results calculated for a given material thickness using this approach should not be applied to different material thicknesses, spacings, etc.

In cases where there are multiple non-homogenous layers of differing thicknesses or with different non-homogenous elements, a separate calculation should be carried out for each layer. For example, for an assembly with two wood stud layers, one being 140 mm (5.5 inches) in thickness, another being 89mm (3.5 inches) in thickness, two separate calculations should be performed.

3.6.5   Calculation of $L^{2D}_{junction}$

$L^{2D}_{junction}$ is not directly output from THERM, but can be obtained from the U-factor results panel using Equation 10.

$$L^{2D}_{junction} = \phi_i \times b_i \qquad \text{Equation 10}$$

Where,

ϕ_i is the U-factor, Internal in W/m²·K. Based on the heat flow through all internal surfaces

b_i = U-factor length, Internal in m. The length over which ϕ applies (i.e., all surfaces to which the 'Internal' U-factor tag has been applied).

With the U-factor Tags applied as described in Section 3.6.3, the overall model heat flow ($L^{2D}_{junction}$) can be determined based on results shown in the U-factor Results panel, as shown in Figure 3.16.

Figure 3.16 Example of a U-Factor Results panel showing ϕ_i and b_i.
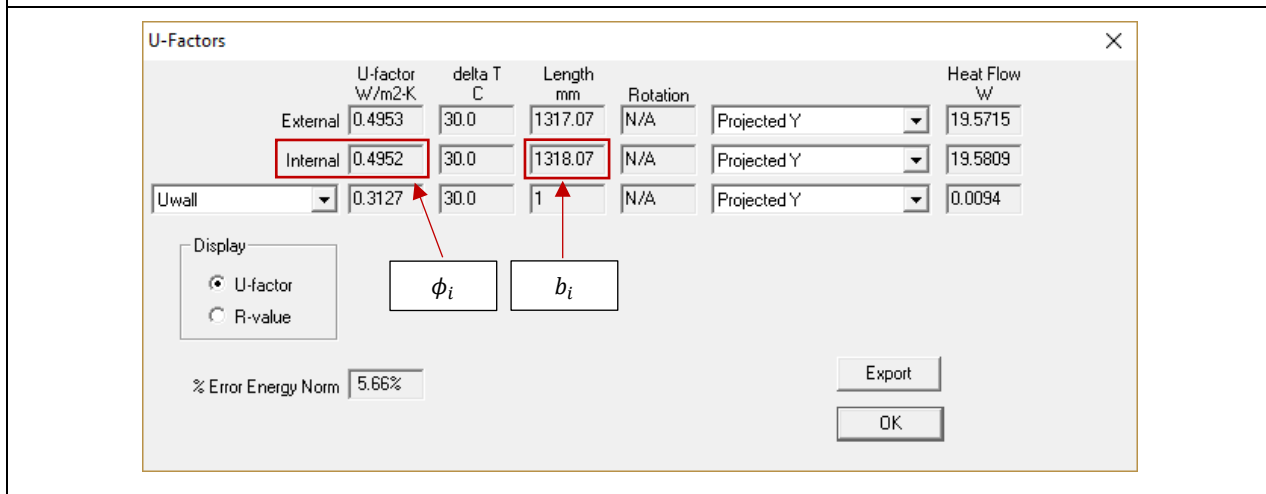
U_{wall}, homogeneous assemblies

To obtain U_{wall}, results can also be extracted from the U-factors results panel. As discussed in Section 3.2.4, with the length of this U-factor tag set to 1 mm, the U-factor result can be extracted directly for use in Equation 8. The length is equal to the height of the wall (adiabatic edge to base of window).
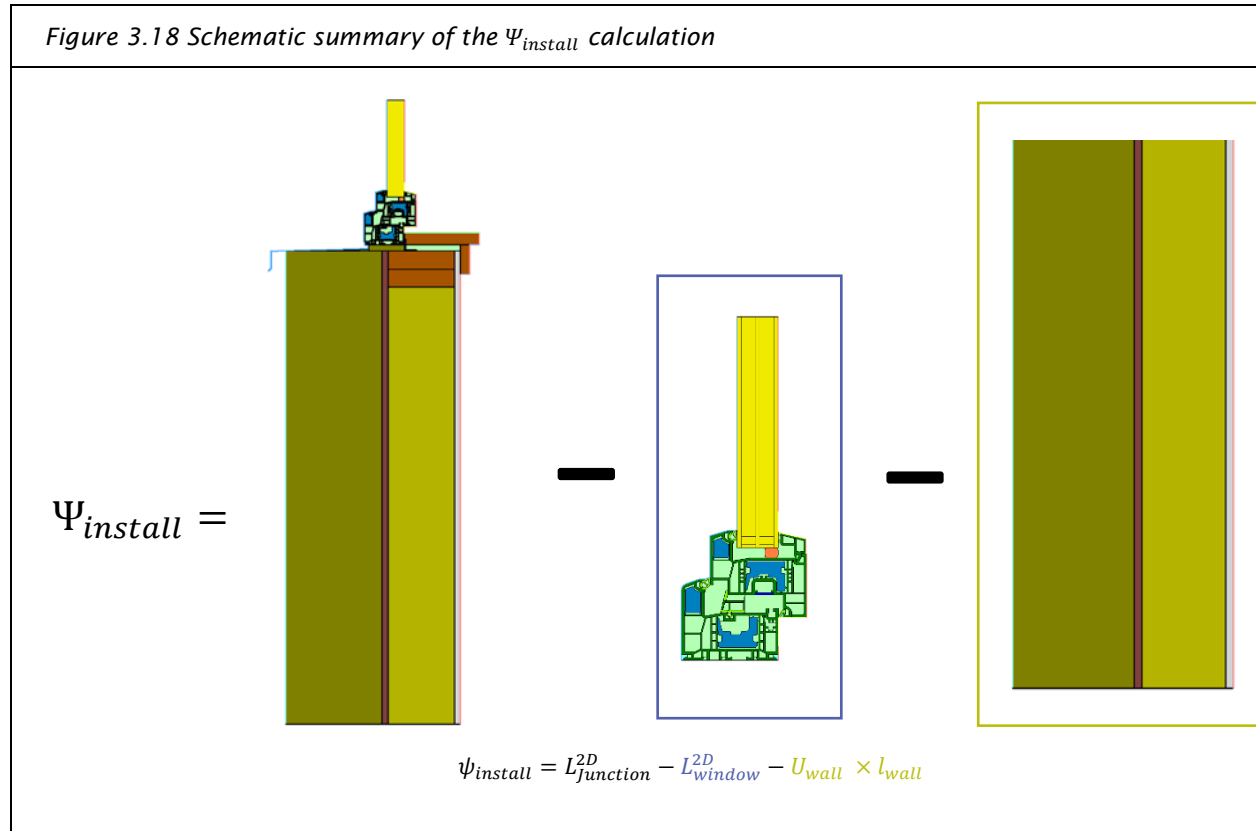
Figure 3.17 Example of a U-Factor Results panel showing U_{wall}
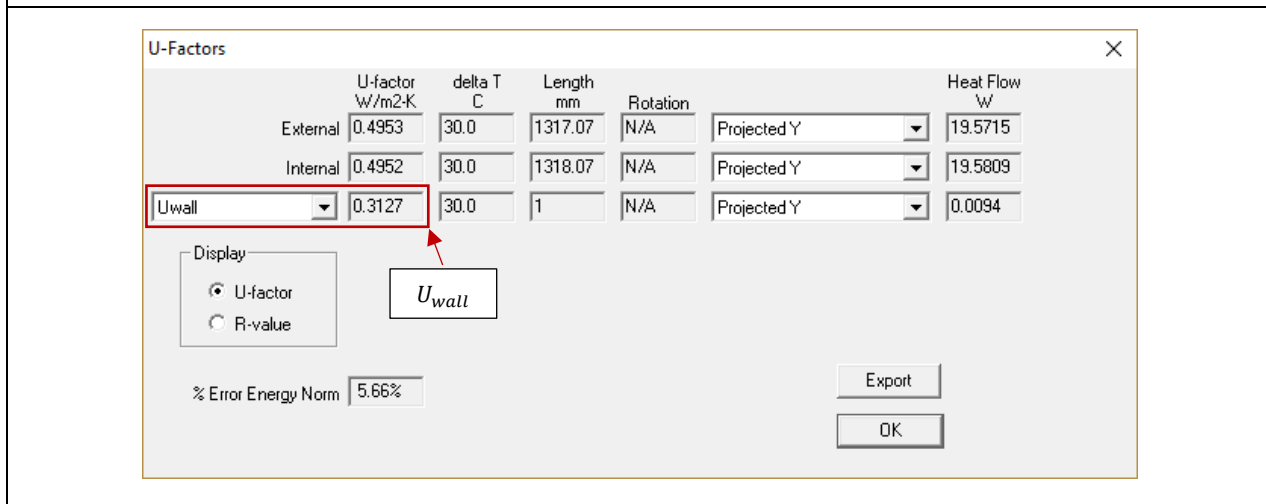
L2D$_{window}$

To obtain L2D$_{Window}$, a similar process is followed, but using the window frame model. Refer to section 3.2.4.

Figure 3.18 Schematic summary of the $\Psi_{install}$ calculation

$$\Psi_{install} =$$

$$\psi_{install} = L^{2D}_{Junction} - L^{2D}_{window} - U_{wall} \times l_{wall}$$

This result can then be carried back to Equation 8 to determine $\Psi_{install}$.

3.7   Temperature Factor Model, Install

Similar to the window frame on its own (Section 3.4), the window install detail is also evaluated for the temperature factor. The model shall be identical to the $\Psi_{install}$ model, except for use of the f_{Rsi} interior boundary condition.

END OF THE PROCEDURE

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Appendix A – Transparent Component Certification

Products targeting Passive House component certification are required to meet performance targets for multiple parameters, based on the climate zone for which the product is being certified. Figure A.1 shows these requirements.

Figure A.1 Passive House window performance parameters by PHI climate zone. Reproduced with permission from PHI.

Climate zone	Hygiene criterion $f_{Rsi=0.25 m^2K/W} \geq$	Component U-value[1] [W/(m²K)]	U-value installed [W/(m²K)]	Reference glazing [W/(m²K)]
1 Arctic	0.80	0.40	0.45	0.35
2 Cold	0.75	0.60	0.65	0.52
3 Cool-temperate	0.70	0.80	0.85	0.70
4 Warm-temperate	0.65	1.00	1.05	0.90
5 Warm	0.55	1.20	1.25	1.10
6 Hot	None	1.20	1.25	1.10
7 Very hot	None	1.00	1.05	0.90

1 The following applies for inclined (45°) and horizontal (0°) components: the actual U_g value of the glazing used for the reference inclination, determined according to DIN EN 673, alternatively according to ISO 15099, should be used. The limit value in the installed state is the same as the limit value of the uninstalled component. The limit value of the component U-value for inclined building components compared to the limit value of the vertical component is increased by 0.10 W/(m²K), while that of the horizontal component is increased by 0.20 W/(m²K). Exception: in cool-temperate climates the limit value of the inclined component is increased by 0.20 W/(m²K), while that of the horizontal building component is increased by 0.30 W/(m²K).

A.1 Hygiene

The hygiene requirement for transparent components sets limits that restrict the minimum interior surface temperature at the coldest point of the interior surface. This criterion eliminates the potential for condensation at interior window surfaces, avoiding mould growth.

Evaluation of this requirement is based on the result of the f_{Rsi} temperature factor calculation described in Section 3.4.

A.2 Component U-Value

To report the U-values of certified components, standard glazing U-values are used as discussed in the main text of this document. In reality, multiple glazing packages are available for a specific window frame, which can impact the overall U-value. To demonstrate the overall performance level of certified frames with different glazing packages, PHI certificates may display U_W values for four different standard U_g values, based on a standard window size. Figure A.2 shows an example extracted from one such certificate.

Figure A.2 Example of the impact of U_g on the window U_W value from a PH certificate.
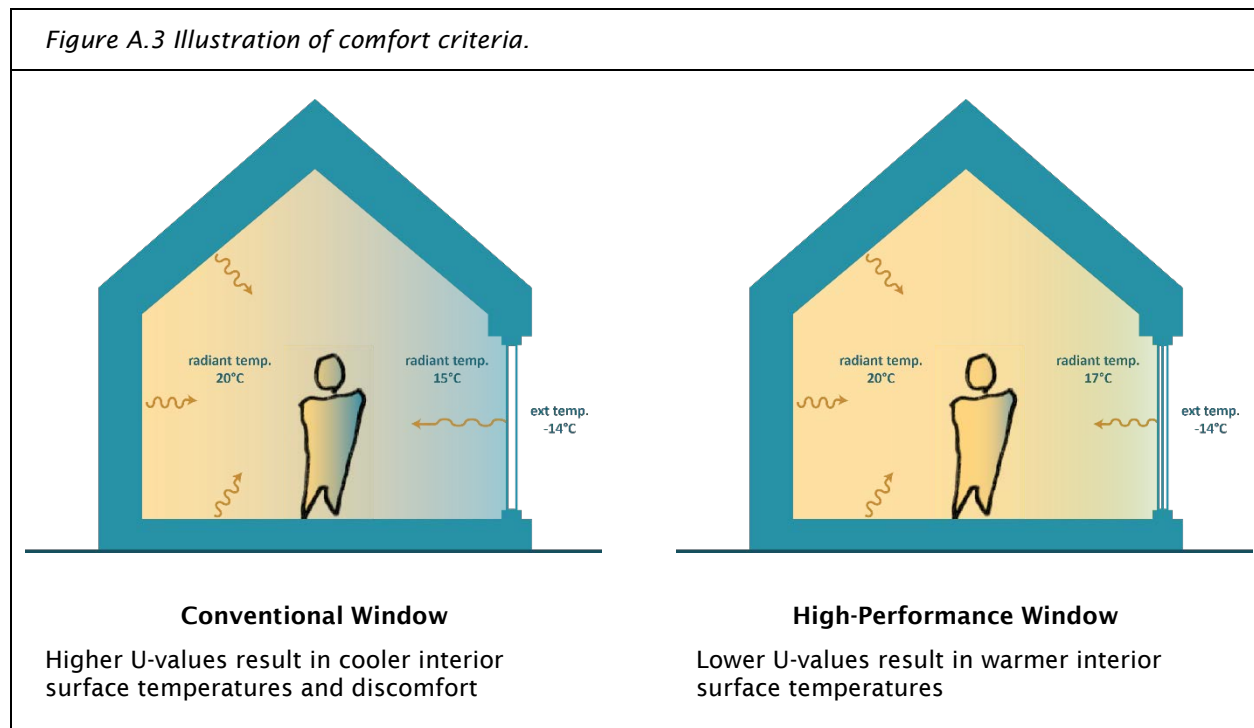
Explanation

The window U-values were calculated for the test window size of 1.23 m × 1.48 m with U_g = 0.70 W/(m² K). If a higher quality glazing is used, the window U-values will improve as follows:

Glazing	U_g =	0.70	0.64	0.58	0.52	W/(m² K)
		↓	↓	↓	↓	
Window	U_W =	0.79	0.75	0.71	0.67	W/(m² K)

A.3 Comfort

While product certification assumes standard sizes for windows, projects targeting Passive House certification must ensure that all glazed elements present in the project that are in frequently occupied spaces are able to maintain high average interior surface temperatures (no more than a 4.2˚K deviation from the interior operative temperature). Frequently occupied spaces are defined as spaces/rooms where longer periods of time are spent, such as bedrooms, kitchens, offices, and bathrooms. Examples of spaces where the comfort criteria can be ignored would include mudrooms or windows in storage rooms. Surface temperature differences greater than 4.2˚K can lead to radiant heat deprivation and convective air currents, resulting in lowered occupant comfort and satisfaction. Where there is doubt on a project about whether a specific window is required to meet the comfort criteria, this should be discussed with the project's certifier.

Figure A.3 Illustration of comfort criteria.

Conventional Window

Higher U-values result in cooler interior surface temperatures and discomfort

High-Performance Window

Lower U-values result in warmer interior surface temperatures

For the purposes of the comfort evaluation, the operative temperature is assumed to be 22˚C.

The evaluation of this criteria is carried out through calculation using the formula:

$$U_{installed} \leq \frac{4.2K}{(-0.03 \times \cos\beta + 0.13)\frac{m^2K}{W} \times (\theta_{op} - \theta_e)}$$

Where,

β = angle of inclination to horizontal

θ_{op} = operative temperature (22 ˚C)

θ_e = exterior temperature (-10 ˚C)

Requirements for the criteria are set based on the climate zone for which the component is being evaluated. Figure A.1 shows the requirements for each of the seven climate zones defined by the Passive House Institute (PHI). Detailed descriptions of the calculation methodology for each the requirements are provided in Section 3.

For typical windows and glazed doors, results (U_f, Ψ_g) are reported for the head, jamb, sill, and mullions individually. Separate models are required for each unique frame profile. For example, the minimum number of models required to characterize an installed operable window is nine: three each for the head sill and jamb. Recall that for each window perimeter frame section, there is a model with the reference glazing and spacer, a model with the insulation panel, and a model showing the window installation. If the window product comprises of additional lites immediately adjacent then an additional set of models is required for the connecting mullion and any additional frame elements (head, sill, jamb) that differ from the first set of models. Figure A.4 shows an example result table from a PHI certificate for an operable window with a fixed sidelite, and a total of three different sill conditions.

Figure A.4 Example of performance data for a window with three sill conditions, one fixed, and two operable.

EuroLine Windows Inc. Series 4700, ThermoPlus PHC Spacer I Abstandhalter: SuperSpacer Tri-Seal		Bottom Unten	Top Oben	Side Seitl.	Bottom fixed Unten fest	Top fixed Oben fest	Side fixed Seitl. fest	Bottom barrier-free Unten barri-erefrei	Side door Seite Tür	Flying mullion Stulp	Mullion Pfosten	Mullion Pfosten	Mullion fixed Pfosten fest	Bottom 2 Unten 2	Transom Kämpfer	Transom Kämpfer	Transom fixed Kämpfer fest
Temperaturefactor Temperaturfaktor	$f_{Rsi=0.25m^2k/W}$	0,74	0,74	0,74	0,73							0,73		0,74			
Frame width Rahmenbreite	b_f [mm]	115	115	115	72							141		142			
U-value frame Rahmen-U-Wert	Uf [W/(m²K)]	0,78	0,78	0,78	0,70							0,76		0,74			
Ψ-glass edge Glasrand-Ψ-Wert	Ψg [W/(mK)]	0,027	0,027	0,027	0,026							0,026		0,027			

A.4 Spacers

As discussed in Section 3.3.1, spacers can be modelled either based on their actual structure, with all materials and geometry included (more time-intensive), or using a simplified 2-box model. If using a spacer that does not have a 2-box model, the modeller can contact the Passive House Institute to create such a model for a fee.

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Appendix B – PHPP Evaluation of Comfort Criteria

Comfort is assessed on a project-specific basis in PHPP independently of component certification. In the PHPP, evaluation of comfort criteria is based on the project's location-specific winter design temperature. Each window or door is evaluated on the basis of its actual size installed U-value ($U_{W,installed}$), the specified U_g value, and the $\Psi_{Install}$. When window data are entered into PHPP, this evaluation is carried out automatically. Figure B.1 shows a screenshot taken from the Windows worksheet of PHPP v9.6a, showing one window that does not satisfy the comfort evaluation as indicated by the red mark in the Comfort column.

Figure B.1 Example of a window that does not conform with the Comfort criterion in the PHPP

The comfort evaluation in PHPP is separate from the f_{Rsi} temperature factor, the overall window comfort criterion property of a window frame. When selecting windows for a Passive House project, both the f_{Rsi} temperature factor and the PHPP installed window surface temperature should be considered.

Climate zones for many Canadian locations can be seen in Appendix C – Climate Zones of Canadian Cities.

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Appendix C – Climate Zones of Canadian Cities

The climate zone for each city is provided in the Passive House Planning Package.

CITY	CLIMATE ZONE	CITY	CLIMATE ZONE
Abbotsford, BC	Cool-temperate	Victoria, BC	Cool-temperate
Blue River, BC	Cold	Whistler, BC	Cool-temperate
Brandon, MB	Cold	Whitehorse, YT	Arctic
Calgary, AB	Cold	Winnipeg, MB	Cold
Campbell Island, Dryad Point, BC	Cool-temperate	Yellowknife, NWT	Arctic
Charlottetown, PEI	Cold		
Cranbrook, BC	Cold		
Edmonton, AB	Cold		
Fort St. John, BC	Cold		
Fredericton, NB	Cold		
Halifax, NS	Cool-temperate		
Hope, BC	Cool-temperate		
Kamloops, BC	Cool-temperate		
Kelowna, BC	Cool-temperate		
Merritt, BC	Cool-temperate		
Moncton, NB	Cold		
Montreal, QB	Cold		
Nelson, BC	Cool-temperate		
Ottawa, ON	Cold		
Prince George, BC	Cold		
Quebec City, QB	Cold		
Regina, SK	Cold		
Saint John, NB	Cold		
Saskatoon, SK	Cold		
Smithers, BC	Cold		
St. John's, NL	Cold		
Sydney, NS	Cold		
Thunder Bay, ON	Cold		
Toronto, ON	Cool-temperate		
Upper Squamish, BC	Cool-temperate		
Vancouver, BC	Cool-temperate		

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Appendix D – Standard Material Thermal Conductivities

The following table provides list of common window materials with their associated thermal conductivity and emissivity taken from ISO 10077-2. Please refer to ISO 10077-2 Annex D, as well as EN 10456 for additional materials.

GROUP	MATERIAL	CONDUCTIVITY (W/m·K)	EMISSIVITY[1]
Frame	Aluminium Si Alloys (painted)	160	0.90
	Steel (galvanized, painted, or powder coated)	50	0.90
	Stainless steel, [b] austenitic or austenitic-ferritic	17	0.30
	PVC (polyvinylchloride), rigid	0.17	0.90
	Hardwood	0.18	0.90
	Softwood	0.13	0.90
Glass	Soda lime glass	1.00	0.84
	Polycarbonates	0.20	0.90
Thermal Break	Polyamide 6.6 with 25 % glass fibre	0.30	0.90
	Polyethylene HD, high density	0.50	0.90
	PU (polyurethane), rigid	0.25	0.90
	PVC-U (polyvinylchloride), rigid	0.17	0.90
Weather Stripping	PCP (polychloroprene), e.g. Neoprene	0.23	0.90
	EPDM (ethylene propylene diene monomer)	0.25	0.90
	PVC, flexible (PVC-P) 40 % softener	0.14	0.90
	Pile weather stripping (polyester mohair)	0.14	0.90
	Elastomeric foam, flexible	0.05	0.90
Sealant & Glass Edge	Butyl (isobutene), solid/hot melt	0.24	0.90
	Polysulfide	0.40	0.90
	Silicone, pure	0.35	0.90
	Polyisobutylene	0.20	0.90
	Silica gel (desiccant)	0.13	0.90
	Silicone foam, medium density [*]	0.17	0.90

[1] Emissivities based on ISO 10077-2 Annex D Table D.3

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Appendix E – Reporting Template

Use of a uniform report format as defined in this Appendix is encouraged to facilitate recognition and acceptance of evaluation reports based on the methodology in this document.

General Report Requirements

Reports of window thermal properties determined using this methodology shall include the following information, in the order provided:

1) Report shall include all of the following information on the Title page (and following pages, if necessary)

    a) Report date
    b) Simulation date
    c) Identification of window product manufacturer
    d) Location and contact information of the manufacturer
    e) Description of the window system:

        i) window product or product line name, including identifying characteristics such as series and model numbers that distinguish the specimen from similar products offered by the manufacturer
        ii) When the window manufacturer uses lineal profiles common to other manufacturers, the manufacturer of the lineal profiles and the profile series identification shall also be reported

    f) Identification of individual or firm issuing the report
    g) Name, address and contact information for the business, organization or individual that issued the report
    h) Name, qualification and professional designation (if applicable) of the simulator who performed the analysis
    i) Name, signature, qualification and professional designation (if applicable) of the individual who reviewed the analysis and signed the report

2) Report shall include, as a separate page, a Summary of Results in the form of the example provided.

3) Report shall contain the following additional information to support the analysis:

    a) A revision history to record the initial issue date as well as the date and description of changes from the previous version each time the report is reissued after modification.
    b) Dimensioned profile drawings of head, sill, jamb, and all other frame sections evaluated in the report. Drawings to clearly identify individual parts with reference to the bill of materials
    c) Bill of materials that clearly notes material type and finish and cross-referenced with the drawings
    d) THERM isotherms for all frame sections evaluated in the report.
    e) Comprehensive description of the insulating glass component including overall unit thickness rounded to the nearest mm, identification of each pane's thickness, each gap width, each low-emissivity coating (coater name, coating name, and emissivity), type of gas fill, percent of gas fill, description of spacer name and unique model identification, spacer material, and each sealant. Laminated glass description to include overall pane thickness, thickness of each glass ply, interlayer type by name, interlayer material, and interlayer thickness.
    f) Comprehensive description of the transparent window or door framing system, sufficiently detailed to allow verification of the window specimen(s), including but not limited to:

  i) Framing material and framing joinery method

  ii) Operating type

  iii) All continuous hardware included in the models

  iv) Gaskets, weatherstrips, sealants

  v) Glazing characteristics including width

  vi) Glazing method

g) Where installed thermal performance is modelled, the report shall also include

  i) Dimensioned architectural drawings showing the installation details including window placement, attachment method, and materials specific to the construction. Where non-continuous elements are present (framing, clips, etc.,) the typical size and spacing of these elements shall be noted

  ii) A comprehensive table of results including:

   (1) Profile name, detail, or other traceable ID, cross-referenced to the drawings

   (2) Frame widths

   (3) Calculated values for all glazing options, as appropriate. If a climate specific default value has been assumed for reporting of the overall window and installed window performance, this value shall be stated.

    (a) U_g

    (b) g-value

   (4) Calculated values for all frame profiles:

    (a) U_f

    (b) Ψ_g

    (c) U_W

    (d) f_{Rsi}

   (5) Calculated values for all installed details:

    (a) $\Psi_{Install}$

    (b) f_{Rsi}

    (c) $U_{W,installed}$

h) All thermal modelling files and accompanying calculation spreadsheets. File names to be cross-referenced to the drawings.

i) A statement that the report relates only to the fenestration products simulated.

j) A statement that the report shall not be reproduced, except in full, without the approval of the simulation company.

k) A statement that the report has been prepared in conformance with the B.C. Reference Procedure for Using THERM to Determine Window Performance Values for Use with the Passive House Planning Package version 1.0 and the applicable standards referenced therein.

Summary of Results

An example for presenting a Summary of Results is shown on the following page.

TRANSPARENT BUILDING COMPONENT PERFORMANCE SUMMARY

Results Determined According to the "BC Reference Procedure for Using THERM to Determine
Window Performance Values for Use with the Passive House Planning Package" (Version 1.1)

Manufacturer:	
Product Name:	
Address:	
Phone:	
Email:	

U_W (W/m² · K)	
Passive House	**NFRC**
U-	U-

[Insert Model Output]

	Passive House (EN 673/ISO 10077-2)				NFRC (NFRC-100)		
	Category: Choose an item.				Product Type: Choose an item.		
Spacer							
U_{Glass} (W/m² · K)							
Width (mm)							
Height (mm)							
Frame Section	**Width mm**	U_f W/m² · K	Ψ_g W/m · K	$f_{Rsi=0.25}$	**Width mm**	U_f W/m² · K	U_{edge} W/m² · K
Head / Top							
Sill / Bottom							
Jamb / Side							
Vertical Meeting Rail							

The thermal modelling results presented in this report were determined in general accordance with the applicable modelling standards: ☐ EN673:2011, ☐ ISO 10077-2: 2017, ☐ ISO 15099: 2003, ☐ NFRC 100 − 2017.

Modelled By:	Certified Professional Stamp & Review Comments
Firm:	
Address:	
Phone:	
Email:	Date:

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Appendix F – WINDOW Program Setup

Setup Steps

1) Ensure that version 7.4 (or later) of WINDOW is being used.

2) Select the EN673 Calculation Standard WINDOW→File→Preferences→Thermal Calcs:
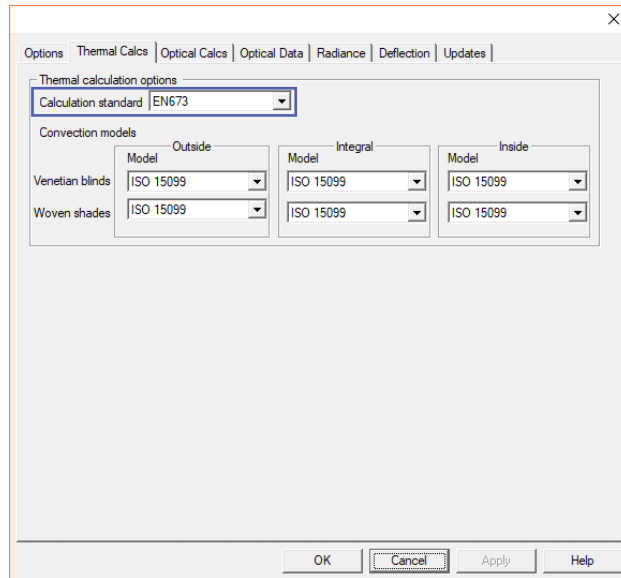
3) Load the prEN_410.std standard file WINDOW→File→Preferences→Optical Data. For reference, the standard file (at the time of writing) for NFRC modelling is W5_NFRC_2003.std:
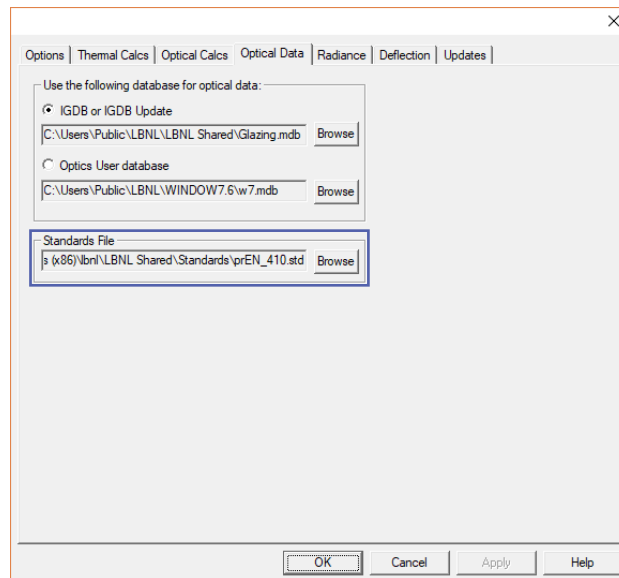
4) Import the EN 673 gas library from: https://windows.lbl.gov/software/window/7/w7_t7_EN673.html.

5) Set the environmental conditions to the following:

U-Factor: Inside	Inside Air Temperature:	20 ˚C
	Model:	Fixed combined coefficient
	Combined Coefficient:	$3.6 + 4.4 \cdot \frac{\varepsilon}{0.837}$ W/m²·K
SHGC: Inside	Inside Air Temperature:	25 ˚C
	Model:	Fixed combined coefficient
	Combined Coefficient:	$3.6 + 4.4 \cdot \frac{\varepsilon}{0.837}$ W/m²·K
	For a typical IGU, with an interior side emissivity of 0.84 (i.e., no low-e coating on the interior surface) the combined coefficient is 8.0. For IGUs with interior low-e coatings, the combined coefficient will be lower.	
U-Factor: Outside	Outside Air Temperature:	0 ˚C
	Model:	Fixed combined coefficient
	Combined Coefficient:	23 W/m²·K
SHGC: Outside	Outside Air Temperature:	30 °C
	Direct Solar Radiation	500 W/m²
	Model:	Fixed combined coefficient
	Combined Coefficient:	23 W/m²·K

The default values for the environmental conditions are shown in Figure H.1 below.

Figure H.1 CEN environmental conditions for an interior surface emissivity of 0.84 (typical).

The default values for the environmental conditions are shown in Figure H.1 below.
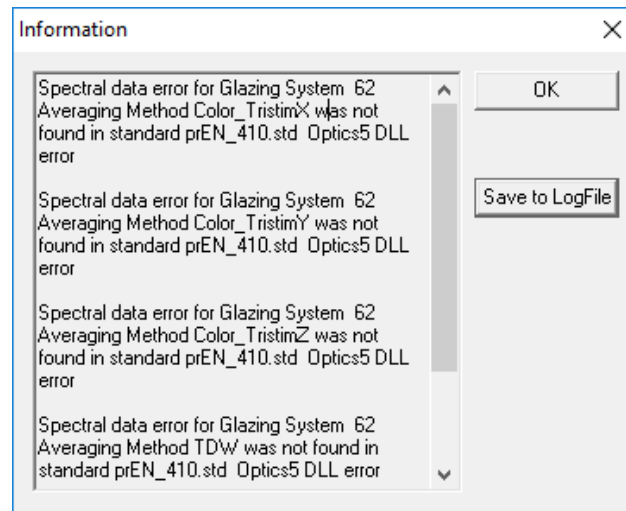
Figure H.1 CEN environmental conditions for an interior surface emissivity of 0.84 (typical).
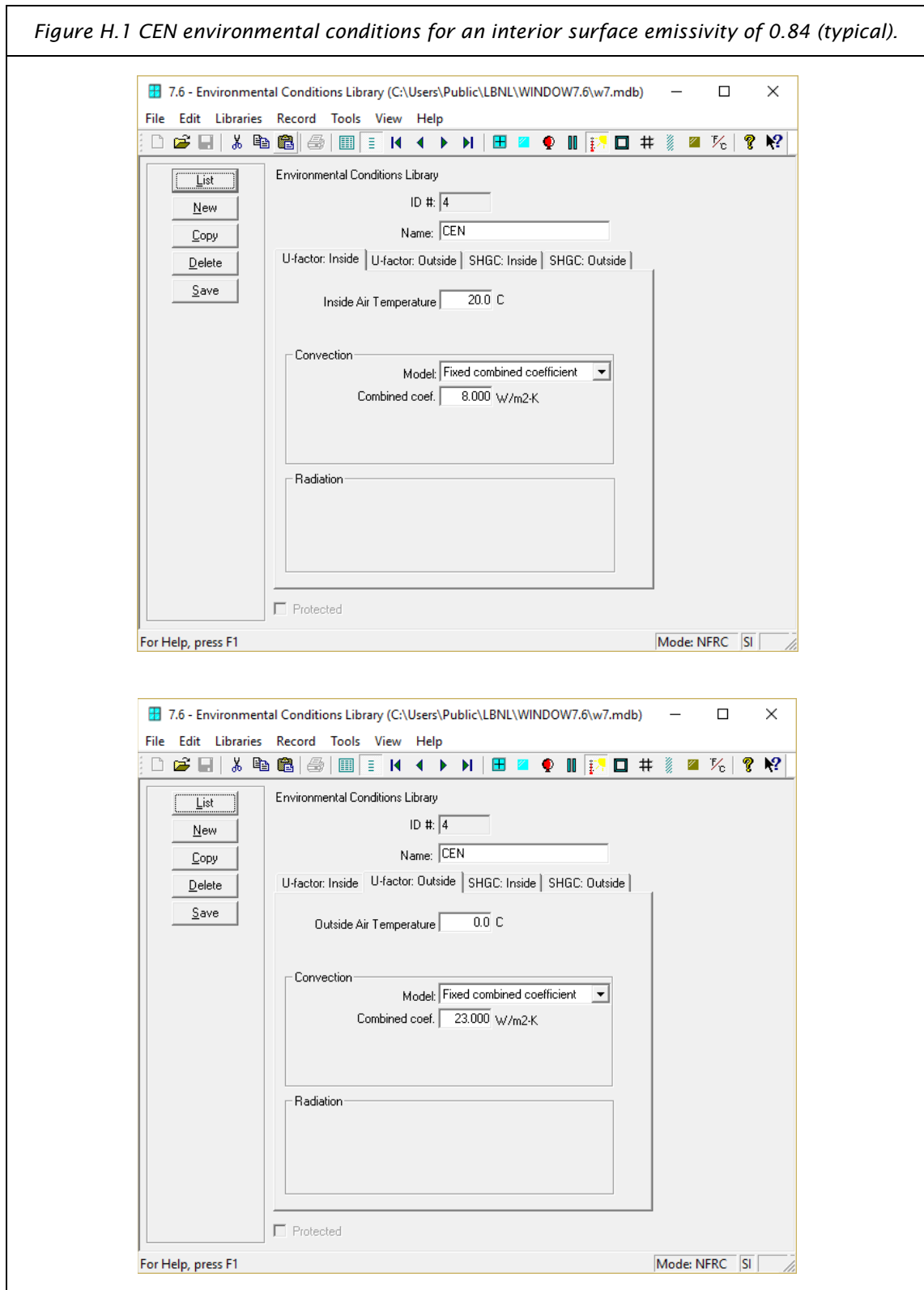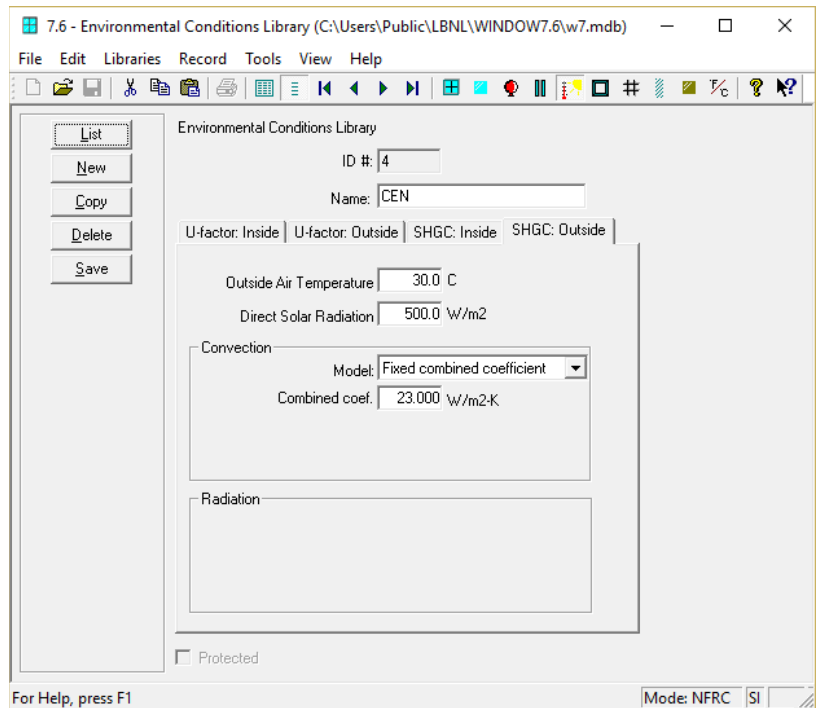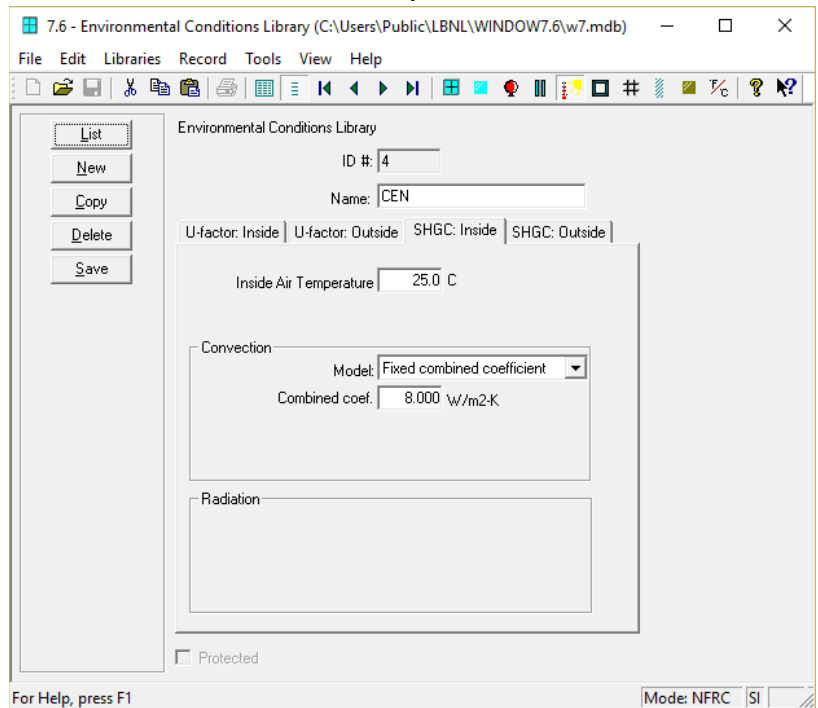
False "Spectral Data Error" Message

When calculating the performance of an IGU following this method, the following information message will appear.

This is normal, and the user may click OK to continue.

Shading Systems Not Supported

WINDOW 7 cannot be used to model shading systems with the EN 673 Thermal Model. The WINDOW software knowledge base states:
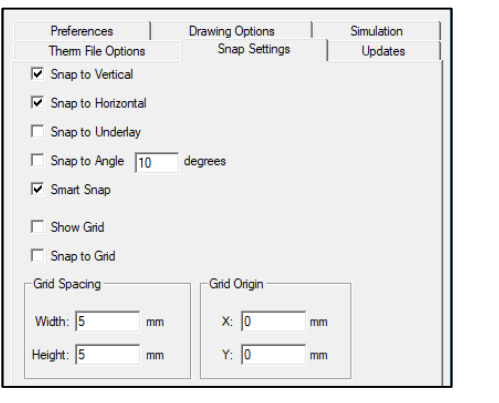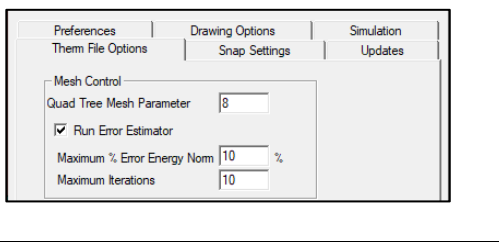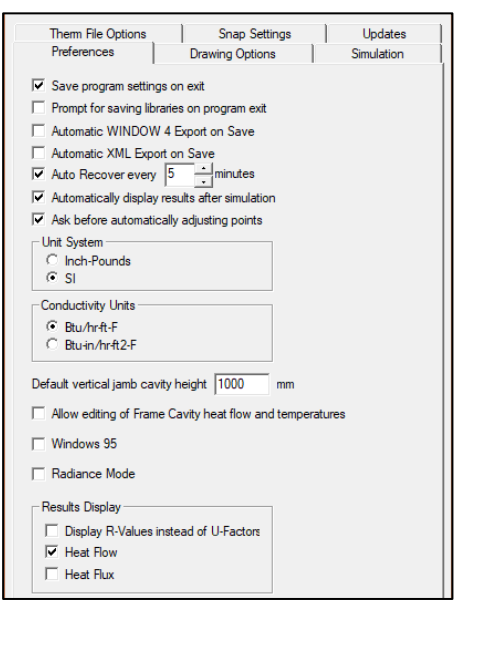
> The EN 673 Thermal Model (set in File / Preferences / Thermal Calcs tab) cannot be used to model shading systems. The program will produce results, but they will most likely not be correct.
>
> (https://windows.lbl.gov/tools/knowledge-base/articles/do-not-model-shading)
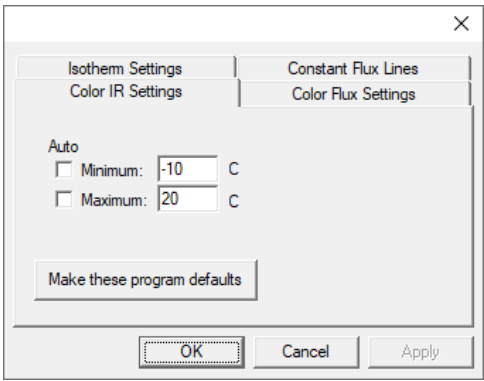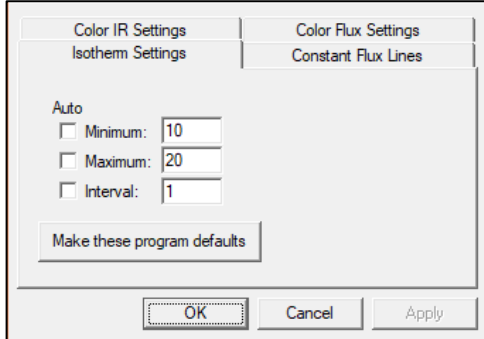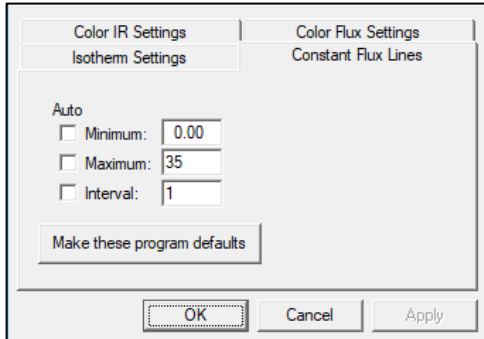
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Appendix G – THERM Program Setup
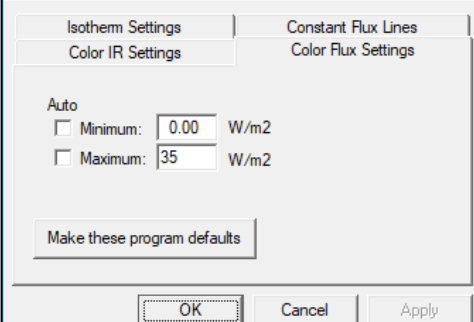
The following standard options, libraries, and calculation parameters must be applied before beginning any modelling using this methodology. These differ from the default values applied upon initial installation of THERM, and are assumed to have been applied by the user throughout this document.

Menu:	THERM Options → Preferences
Snap Settings	Check the following: → Snap to Vertical → Snap to Horizontal → Smart Snap
THERM File Options	Check the following: → Quad tree mesh: 6 (up to 8) → Maximum % error: 10% → Maximum iterations: 10
Preferences	Check the following: → Set to SI Units → Check Heat Flow

The program settings may reset to the default values when the program is closed. However, it is possible to change the default settings by modifying the .ini file located by default at C:\Users\Public\LBNL\Settings. The .ini file may be edited by opening it up as a .txt file.

Menu:	Libraries → UFactor Names
UFactor Names	Add the following names: → Internal → External → Upanel
Boundary Conditions	Libraries → Boundary Condition Library → Load Lib → BCv1.lib (found in folder Source material for preloading THERM)
Material Library	Libraries → Material Library → Load Lib → a_materials_v1.lib (found in folder *Source material for preloading THERM*)

	Calculation → Display Options → Advanced
Colour IR Settings	Change the temperature range: → Set "Minimum" to -10 °C → Set "Maximum" to 20 °C Isotherm Settings / Constant Flux Lines Color IR Settings / Color Flux Settings Auto ☐ Minimum: -10 C ☐ Maximum: 20 C Make these program defaults OK Cancel Apply
Isotherm Settings	→ Set "Minimum" to -10C → Set "Maximum" to 20C → Set "Interval" to 1C Color IR Settings / Color Flux Settings Isotherm Settings / Constant Flux Lines Auto ☐ Minimum: 10 ☐ Maximum: 20 ☐ Interval: 1 Make these program defaults OK Cancel Apply
Constant Flux Lines	→ Set "Minimum" to 0 W/m → Set "Maximum" to 35 W/m → Set "Interval" to 1 W/m Color IR Settings / Color Flux Settings Isotherm Settings / Constant Flux Lines Auto ☐ Minimum: 0.00 ☐ Maximum: 35 ☐ Interval: 1 Make these program defaults OK Cancel Apply

| Colour Flux Setting | → Set "Minimum" to 0 W/m2

→ Set "Maximum" to 35 W/m2 |

Isotherm Settings ǀ Constant Flux Lines
Color IR Settings ǀ **Color Flux Settings**

Auto
☐ Minimum: `0.00` W/m2
☐ Maximum: `35` W/m2

Make these program defaults

OK Cancel Apply |

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Appendix H – Unventilated Cavities per EN ISO 10077-2 ETC Method

THERM version 7.4 can automatically calculate the equivalent thermal conductivity of a frame cavity according to the Equivalent Thermal Conductivity (ETC) method described in ISO 10077-2. The purpose of this appendix is to present a worked example of the calculations following the ETC method.

In addition to the ETC method, ISO 10077-2:2017 introduced a second method for the treatment of frame cavities. However, the second method, known as the Radiosity method cannot be evaluated using THERM version 7.4 and is not described in this reference procedure. Refer to ISO 10077-2:2017 for more information on the Radiosity method.

Figure H.1: Transformation of a non-rectangular cavity to a rectangular cavity (ISO 10077-2, Figure 15)

LEGEND

A	area of the equivalent rectangular air cavity
A'	area of the true cavity
d, b	depth and width of the equivalent air cavity
d', b'	depth and width of the smallest circumscribing rectangle

---
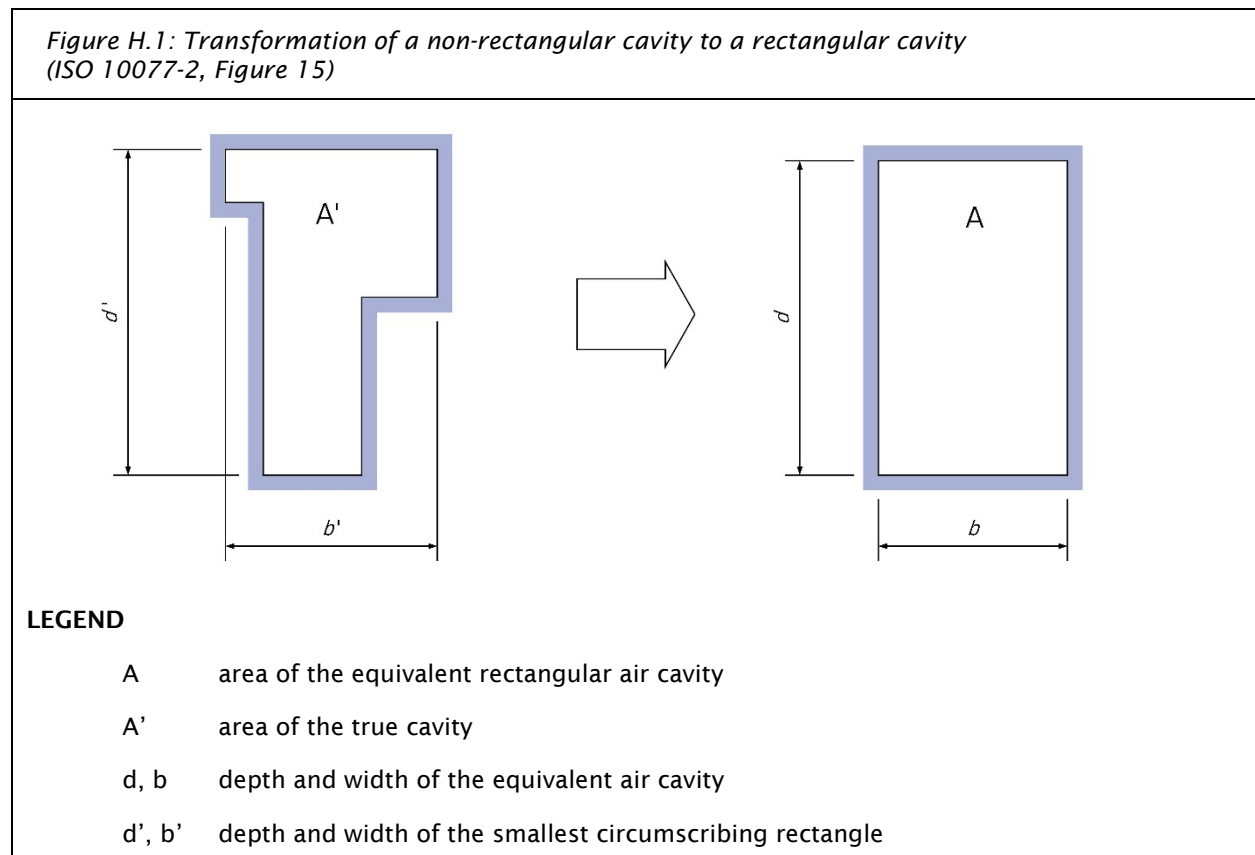
The equivalent conductivity of unventilated air cavities is calculated using the formula:

$$\lambda_{eq} = \frac{d}{R_s}$$

Where,

λ_{eq} the equivalent conductivity (W/m·K)

d the dimension of the cavity in the direction of the heat flow (m)

R_s the thermal resistance of the cavity, as calculated below

Where a cavity has a dimension or an interconnection with another cavity that does not exceed 2 mm, those cavities will be considered in separate calculations.

The thermal resistance of the cavity is calculated using the formula:

$$R_s = \frac{1}{h_a + h_r}$$

Where,

R_s the thermal resistance of the cavity

h_a the convective heat transfer coefficient, as calculated below

h_r the radiative heat transfer coefficient, as calculated below

The convective heat transfer coefficient is calculated using the formula:

If b < 5 mm,

$$h_a = \frac{C_1}{d}$$

Where,

C_1 a constant, 0.025 W/(m·K)

d   the dimension of the cavity, perpendicular to heat flow (Figure J.1)

Otherwise,

$$h_a = \max \left\{ \frac{C_1}{d}; C_2 \, \Delta T^{\frac{1}{3}} \right\}$$

Where,

C_1 a constant, 0.025 W/(m·K)

C_2 a constant, 0.73 W/(m·K)$^{4/3}$

ΔT the maximum surface temperature difference in the cavity (K)

If no other information is available, use ΔT = 10 K, for which

$$h_a = \max \left\{ \frac{C_1}{d}; C_3 \right\}$$

Where,

C_1 a constant, 0.025 W/(m·K)

C_3 a constant, 1.57 W/(m·K)

The radiative heat transfer coefficient is calculated using the following formula:

$$h_r = 4 \times \sigma \times T_m^3 \times E \times F$$

Where,

σ the Stefan-Boltzmann constant, 5.67×10^{-8} W/(m²·K)⁴

E the inter-surface emittance, $(\frac{1}{e_1} + \frac{1}{e_2} - 1)^{-1}$

F the view factor of a rectangular section, $\frac{1}{2}(1 + \sqrt{1 + (\frac{d}{b})^2} - \frac{d}{b})$

Values should be given to two decimal places. If no other information is available, use $e_1 = 0.90$ and $e_2 = 0.90$

If no other information is available, use $T_m = 283K$ for which,

$$h_r = C_4 \left(1 + \sqrt{1 + (\frac{d}{b})^2} - \frac{d}{b} \right)$$

Where,

C_4 a constant, 2.11 W/(m²·K)

For the purposes of the calculations above, non-rectangular cavities are transformed into rectangular cavities with the same dimensions, as shown in Figure H.1.

The transformation is carried out using the following formulas:

$$b = \sqrt{A' \times \frac{b'}{d'}} \qquad \qquad d = \sqrt{A' \times \frac{d}{b'}}$$

Example Calculation:

Assuming,

d = 0.01m

b = 0.06m

e_1= 0.9

e_2 = 0.85

Step 1

$$\lambda_{eq} = \frac{d}{R_s}$$

$$\lambda_{eq} = \frac{0.01}{R_s}$$

Step 2

$$R_s = \frac{1}{h_a + h_r}$$

Step 2.1. Because b < 0.05m,

$$h_a = \frac{C_1}{d}$$

$$h_a = \frac{0.025}{0.01}$$

$$h_a = 2.5$$

Step 2.2

$$h_r = 4 \times \sigma \times T_m^3 \times E \times F$$

Where,

$$E = (\frac{1}{e_1} + \frac{1}{e_2} - 1)^{-1}$$

$$E = (\frac{1}{0.9} + \frac{1}{0.85} - 1)^{-1}$$

$$E = (1.111 + 1.176 - 1)^{-1}$$

$$E = 0.777$$

And,

$$F = \frac{1}{2}(1 + \sqrt{1 + (\frac{d}{b})^2} - \frac{d}{b})$$

$$F = \frac{1}{2}(1 + \sqrt{1 + (\frac{0.01}{0.006})^2} - \frac{0.01}{0.006})$$

$$F = \frac{1}{2}(1 + \sqrt{1 + 2.778} - 1.667)$$

$$F = \frac{1}{2}(1 + 1.944 - 1.667)$$

$$F = 0.6385$$

Carrying these results back to the equation for h$_r$,

$$h_r = 4 \times \sigma \times 283^3 \times 0.777 \times 0.6385$$

$$h_r = 2.5503$$

So,

$$R_s = \frac{1}{h_a + h_r}$$

$$R_s = \frac{1}{2.5 + 2.5503}$$

$$R_s = 0.198$$

Carrying this result back to the equation for λ_{eq},

$$\lambda_{eq} = \frac{0.01}{R_s}$$

$$\lambda_{eq} = \frac{0.01}{0.198}$$

$$\lambda_{eq} = 0.05051 \text{ W·m/K}$$

Appendix I – IGU Air Gap Thermal Conductivity Example

The following is an example of how to calculate the equivalent thermal conductivity for the fictitious gas layers. Assuming the window is being modelled for the cool-temperate climate zone, the target center of glass U-value is 0.70 W/m·K and the calculation follows.

Figure I.1 Example of a 6.3 mm / 12.7 mm / 6.3 mm / 12.7 mm / 6.3 mm triple-glazed IGU
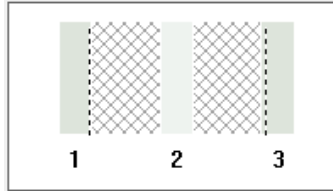
$$U = \frac{1}{h_i + \Sigma \frac{d_g}{\lambda_g} + \Sigma \frac{d_a}{\lambda_a} + h_e}$$

$$0.70\,Wm^2K = \frac{1}{0.04\frac{m^2K}{W} + \frac{0.0063\,m}{1.0\frac{W}{mK}} + \frac{0.0063\,m}{1.0\frac{W}{mK}} + \frac{0.0063\,m}{1.0\frac{W}{mK}} + \frac{0.0127\,m}{\lambda_a\frac{W}{mK}} + \frac{0.0127\,m}{\lambda_a\frac{W}{mK}} + 0.13\frac{m^2K}{W}}$$

$$0.70\,Wm^2K = \frac{1}{0.04\frac{m^2K}{W} + 0.0063\frac{m^2K}{W} + 0.0063\frac{m^2K}{W} + 0.0063\frac{m^2K}{W} + \frac{0.0254\,m}{\lambda_a\frac{W}{mK}} + 0.13\frac{m^2K}{W}}$$

$$\frac{\lambda_a\frac{W}{mK}}{0.0254\,m} = \frac{1}{0.70\frac{W}{m^2K}} - 0.04\frac{m^2K}{W} - 0.0063\frac{m^2K}{W} - 0.0063\frac{m^2K}{W} - 0.0063\frac{m^2K}{W} - 0.13\frac{m^2K}{W}$$

$$\lambda_a\frac{W}{mK} = \frac{1.23967\frac{m^2K}{W}}{0.0254\,m}$$

$$\lambda_a = 0.02049\frac{W}{mK}$$

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Appendix J – ISO 10077 Validation of THERM 7.4

This Appendix summarizes the results of a validation exercise conducted by Peel Passive House Consulting to demonstrate that THERM 7.4 can be used to simulate window energy performance within the tolerances specified in Section 4.2 of ISO 10077-2, following the *B.C. Reference Procedure for Using THERM to Determine Window Performance Values for Use with the Passive House Planning Package Version 1.1* (BC Reference Procedure).

To determine the thermal performance of windows and doors, the Passive House Institute (PHI) follows ISO 10077-2, *Thermal performance of windows, doors, and shutters – Calculation of thermal transmittance – Part 2: Numerical methods for frames*, (ISO 10077). ISO 10077-2 provides a method for determining the thermal performance of fenestration products using two-dimensional (2D) simulation.

PHI requires the 2D calculations to be carried out using a software program validated according to Section 4.2 of ISO 10077-2. Validated software must be able to calculate the two-dimensional thermal conductance, L^{2D}, of the examples provided in Annex D within ±3% of the tabulated values.

Several commercially available software programs exist that have been independently validated against ISO 10077-2 Annex D, including HEAT2 by BLOCON, and flixo by infomind. These programs are not widely used in North America.

THERM is a 2D thermal simulation program for fenestration products developed by the Lawrence Berkeley National Laboratory. THERM has been extensively validated for use with NFRC 100 and is widely used across North America. A previous study had confirmed that earlier versions of THERM, including version 7.1, had been validated to ISO 10077-2. To support the use of THERM for PHPP window simulations in North America, it was deemed necessary to also validate the current version of THERM.

J.1   Summary of Validation Results

To validate THERM 7.4 to ISO 10077-2:2017 Annex I (Single Equivalent Thermal Conductivity Method), eight out of ten of the validation examples provided in Annex D were simulated. Table J.1 presents a summary of the thermal performance results. According to Section 4.2 of ISO 10077-2, validated software must be able to calculate the two-dimensional thermal conductance, L^{2D}, of the examples provided in Annex D within ±3% of the tabulated values. The simulated L^{2D} for all modelled examples were within 3% of the accepted value. Although not a validation criterion, the simulated U_f for all modelled examples were within 5% of the expected value. Two of these examples, D.4 and D.10, are discussed in detail.

Note, examples D.8 *Roller shutter box,* and D.9 *PVC shutter profile* were not simulated as part of this work as they do not directly pertain to the reference procedure. However, separate validation has shown similar results for these examples using THERM.

TABLE J.1: SUMMARY OF THE VALIDATION SIMULATION RESULTS COMPARED TO THE TABULATED VALUES FROM ISO 10077-2 ANNEX D, TABLE D.3 AND TABLE D.4

Example	L^{2D} (W/m·K)			U_f (W/m²·K)		
	ISO10077: 2017	THERM 7.4	%	ISO10077: 2017	THERM 7.4	%
D.1	0.550	0.554	0.7%	3.22	3.25	1%
D.2	0.263	0.262	-0.4%	1.44	1.43	-1%
D.3	0.424	0.429	1.2%	2.07	2.12	2%
D.4	0.346	0.347	0.3%	1.36	1.36	1%
D.5	0.408	0.402	-1.5%	2.08	2.02	-3%
D.6	0.659	0.647	-1.8%	4.67	4.55	-3%
D.7	0.285	0.284	-0.4%	1.31	1.28	-2%
D.8	0.181	Not modelled		1.05	Not modelled	
D.9	0.207	Not modelled		3.64	Not modelled	
D.10[1]	0.481	0.482	0.7%	0.084[1]	0.083[1]	-1%

[1] Example D.10 is for the determination of a linear thermal transmittance value, Ψ_{spacer} (W/m·K)

J.2   Validation Examples

ISO 10077-2 Annex D provides all the necessary geometric and thermophysical properties to enable precise modelling of the validation cases. TABLE J.2 presents the boundary conditions and TABLE J.3 presents the material conductivities required for the validation modelling.

TABLE J.2: ISO 10077-2 VALIDATION BOUNDARY CONDITIONS (ADAPTED FROM TABLE I.1)

Key	Surface Resistance (m²·K/W)	Temperature (˚C)
(A) Adiabatic	∞	-
(B) External	0.04	0
(C) Internal (Normal/Reduced)[1]	0.13 / 0.20	20

[1]See ISO 10077-2 Annex I

TABLE J.3: ISO 10077-2 VALIDATION MATERIALS (ADAPTED FROM TABLE I.2)

| Key	Material	Conductivity (W/m·K)
a	insulation panel	0.035
B	soft wood	0.13
c	PVC	0.17
d	EPDM	0.25
e	polyamide 6.6 with 25 % glass fibre	0.3
f	Glass	1.0
g	steel	50
h	aluminum[a]	160
i	Pile weather stripping (polyester mohair)	0.14
k	polyamide	0.25
l	PU (polyurethane), rigid	0.25
m	polysulfide	0.40
n	silica gel (desiccant)	0.13
o	gas filling	0.034[b]
p	Polyisobutylene	0.20

[a] All surfaces have an emissivity of 0.9

[b] Equivalent thermal conductivity of the gas filling

J.3   I.4 Wood Frame Window

Example I.4. is a wood frame window, shown in Figure J.1. Consistent with the standard, an insulation panel extending 190 mm was modelled in place of glazing following the BC Reference Procedure.

> *Figure J.1: Example I.4, wood frame window section (ISO 10077-2)*
>
>
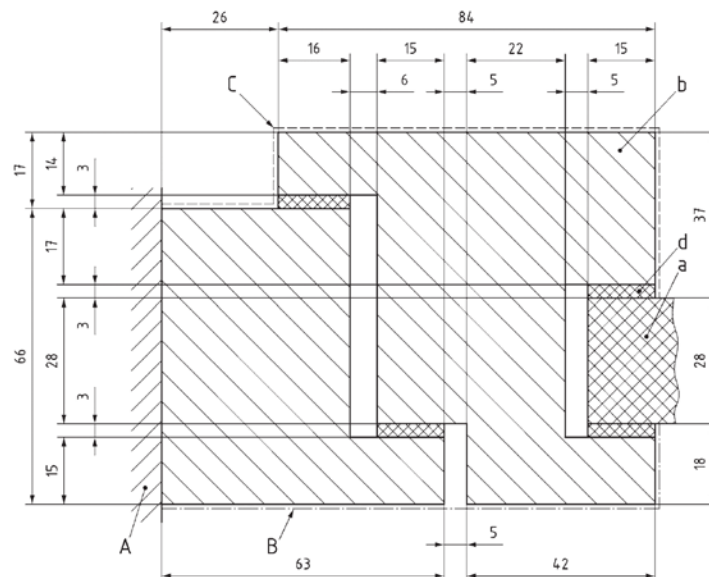
To ensure that the boundary conditions were correctly applied, the total heat flow through interior and exterior surfaces were checked and found to be equal, as expected, (Figure J.2).

Figure J.2: THERM Results for example I.4, heat flow in equals heat flow out
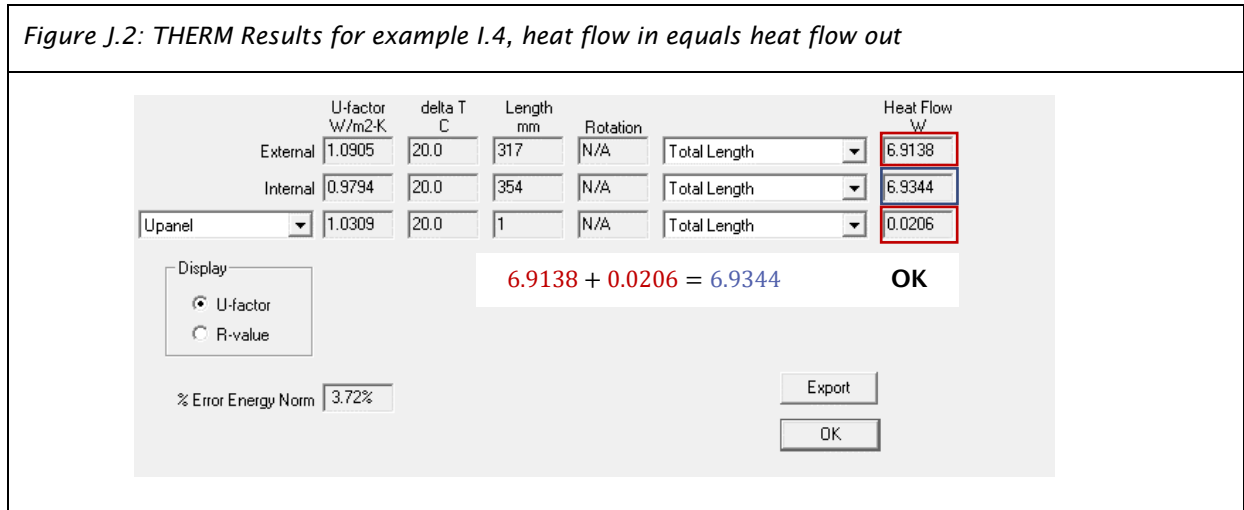
As a second check, the isotherms were inspected. The isotherms at the edge of the glazing furthest away from the frame were observed to be parallel, as expected, (Figure J.3).

Figure J.4: THERM model of example I.4 with isotherms

Parallel Isotherms
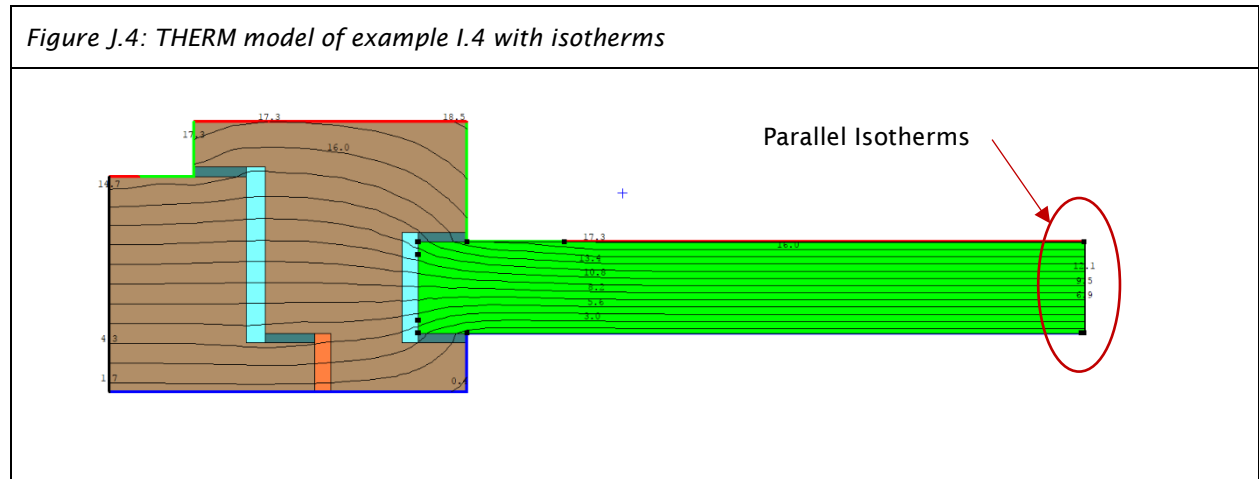
J.3.1 U_f Calculation

Following the methodology outlined in the BC Reference Procedure, the thermal conductance of the model (L_f^{2D}) was calculated and shown to be within ±3% values given in BS EN ISO 10077-2:2017. (TABLE J.4)

TABLE J.4: COMPARISON BETWEEN THERM AND ISO 10077-2 FOR EXAMPLE I.4

|	ISO 10077-2:2017	THERM 7.4	% Difference
L_f^{2D} (W/mK)	0.346 (0.001)	0.347	0.3%
U_f (W/m²K)	1.36 (0.01)	1.37	0.7%

J.4   I.10 Psi-Spacer Model

The wood frame spacer example in Figure I.10 in BS EN ISO 10077-2:2012 was simulated using the steps outlined in the BC Reference Procedure. Figure J.4 shows the glazing unit with spacer in the wood frame. The glazing unit was modelled as described in BS ISO 10077-2:2017 with a Ug of 1.3 W/m²K (gas conductivity of 0.034 W/m·K) and a glazing length of 190 mm.

Figure J.4: Example I.10, wood frame window, with a conventional spacer (ISO 10077-2)
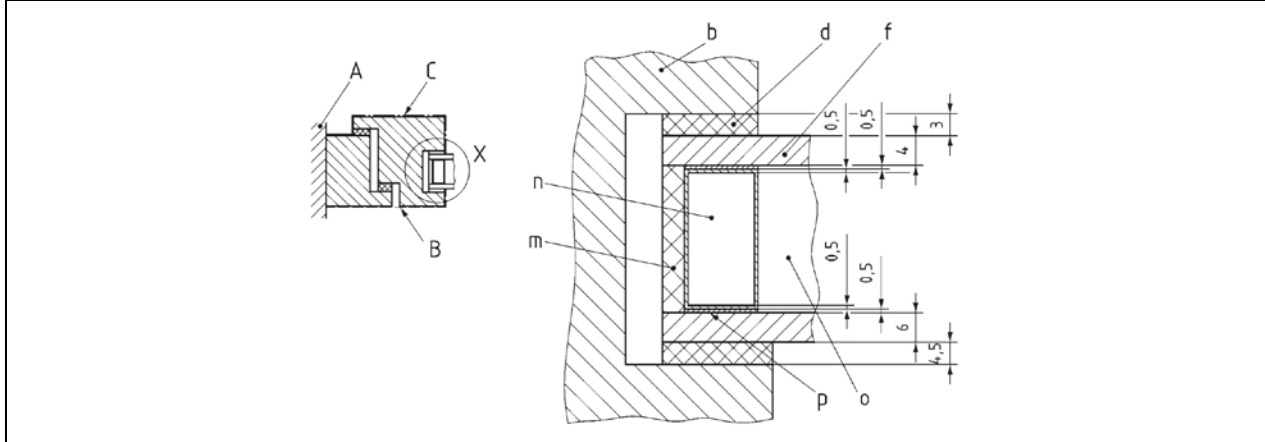

To ensure that the boundary conditions were correctly applied, the total heat flow through interior and exterior surfaces were checked and found to be equal, as expected (Figure J.5).

Figure J.5: THERM Results for example I.10, heat flow in equals heat flow out
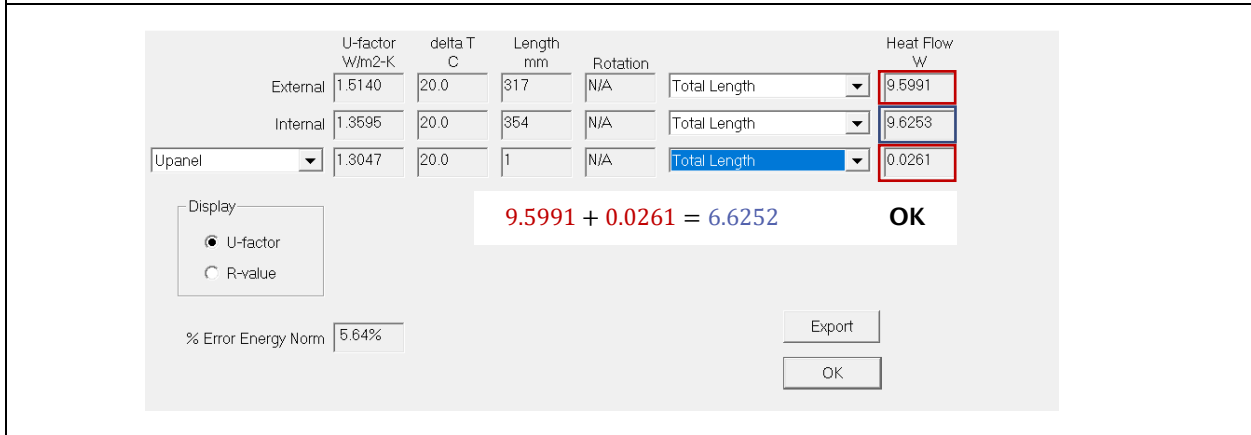
The isotherms at the outside edge of the glazing are shown to be parallel as expected (Figure J.6)

Figure J.6: THERM model of example I.10 with isotherms
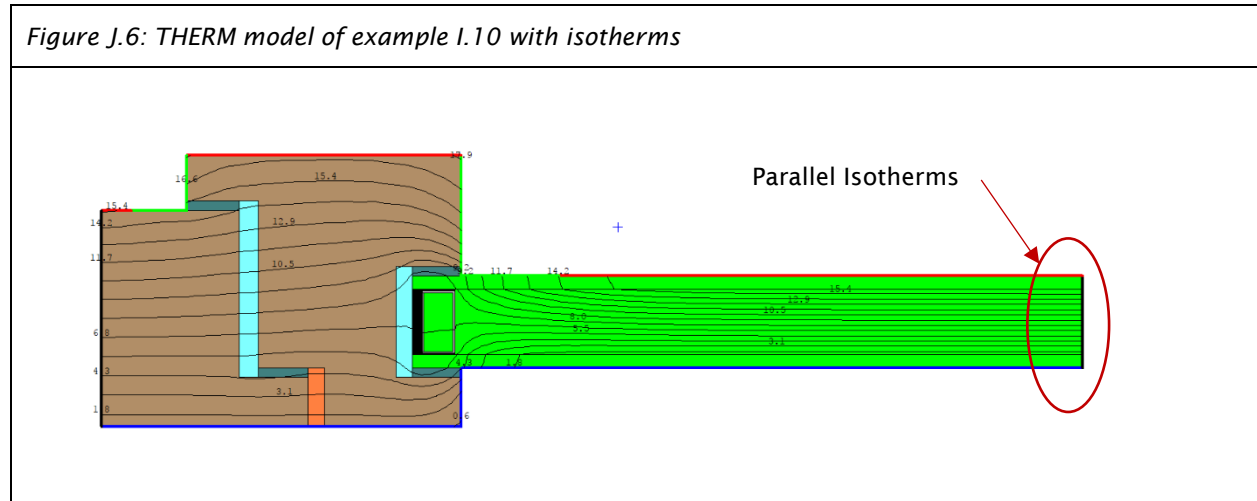
J.4.1 Ψ_{spacer} Calculation

Following the methodology outlined in the BC Reference Procedure, the thermal conductance of the model (L_Ψ^{2D}) was calculated and shown to be within ±3% values given in EN ISO 10077-2:2017 (TABLE J.5). Ψ_{spacer} differed by less than 5%.

TABLE J.5: COMPARISON BETWEEN THERM AND ISO 10077-2 FOR EXAMPLE I.10.

	ISO 10077-2:2017	Therm 7.4	% Difference
L_Ψ^{2D}	0.481 (0.004)	0.482	0.2%
Ψ_{spacer}	0.084 (0.004)	0.083	-1.2%

J.5   Additional References

At least one other group has independently validated previous versions of THERM against ISO 10077-2 (Nammi, et al. 2014). The authors of that technical report similarly found that THERM 7.1 could model the examples in ISO 10077-2 Annex D within 3% of the tabulated values. TABLE J.6 reproduces the relevant results from (Nammi, et al. 2014).

TABLE J.6: SUMMARY OF THE VALIDATION SIMULATION RESULTS COMPARED TO THE TABULATED VALUES FROM ISO 10077-2 ANNEX D, (NAMMI, ET AL. 2014).

Example	L^{2D} (W/m·K)		
	ISO10077:2012	THERM 7.1	% Difference
D.1	0.550	0.560	1.8%
D.2	0.263	0.263	<1%
D.3	0.424	0.426	0.8%
D.4	0.346	0.347	0.3%
D.5	0.408	0.412	1.0%
D.6	0.659	0.659	<1%
D.7	0.285	0.285	<1%
D.8	0.186	0.184	-1.1%
D.9	0.207	0.208	0.5%
D.10	0.481	0.484	0.6%

J.6   Conclusion

Based on the results of thermal simulations conducted using the BC Reference Procedure, THERM version 7.4 meets the validation criteria of ISO 10077-2:2017 when the Equivalent Thermal Conductivity method is used for frame cavities.