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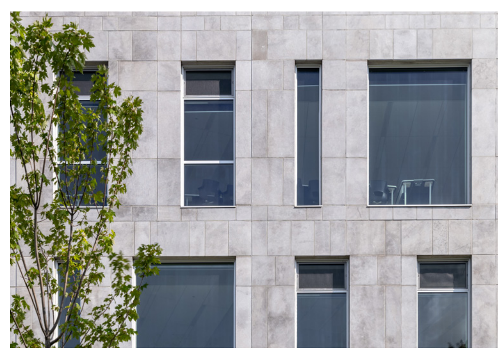
THERMAL PERFORMANCE OF PRECAST ENCLOSURES



Meeting NECB 2025 Requirements

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1 Introduction

Energy and thermal performance requirements are growing and playing an increasingly significant role in building codes throughout North America. However, understanding and meeting the requirements has also become increasingly complex for building designers. At the same time, it has become clear that important decisions regarding basic enclosure assembly design and window area need to be made early in the design process to achieve the most cost-effective, energy-efficient, and comfortable building.

This guide provides designers, builders, and building owners with an introduction to compliance options for modern building codes, and suitable methods for quickly estimating the thermal performance of precast concrete enclosure wall systems at an early design stage.

1.1 Background

Current Canadian and US building codes are heavily influenced by energy considerations but this wasn't always the case. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) published one of the first building energy standards, ASHRAE Standard 90.1, in 1975. The earliest national standard for building energy performance in Canada, the National Energy Code for Buildings (NECB), was first introduced in Canada in 1997[1]. Energy consumption of a representative new code-compliant commercial building has been predicted to have dropped by about 50% since the early 1970s (Figure 1).

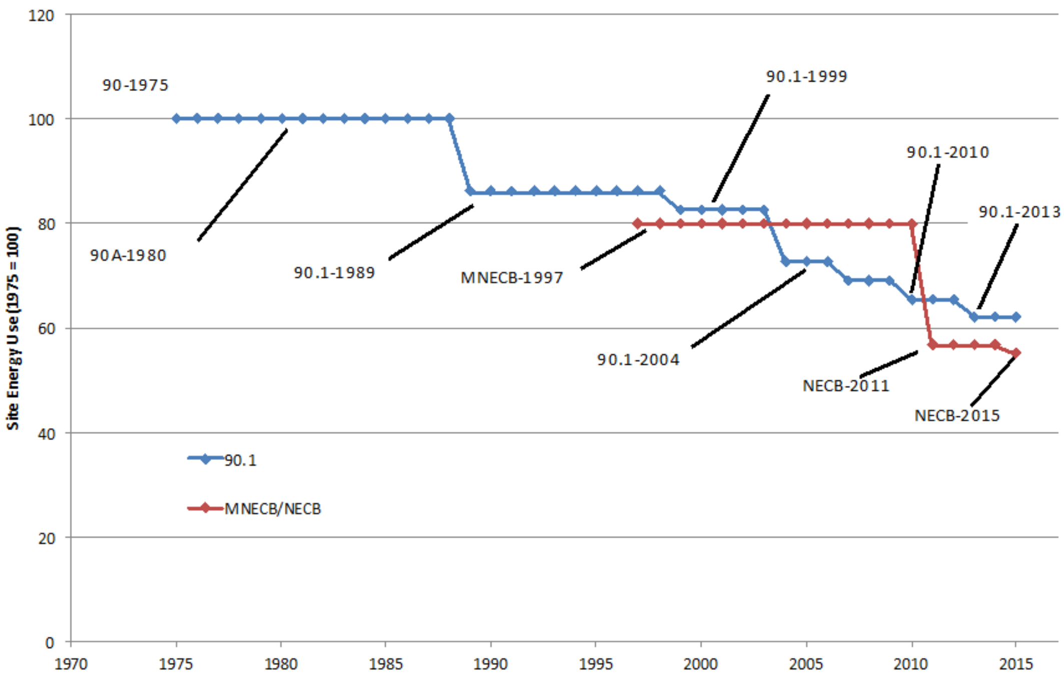


Figure 1: History of energy code performance[2] (approximate and varies with building type and climate)

[1] The 1997 version of NECB was dubbed the Model National Energy Code for Buildings, or MNECB.
[2] These benchmarks are approximate and have not been calculated for the NECB 2017, 2020, 2025.

In the early days, neither ASHRAE Standard 90.1 nor the NECB were widely adopted. However, in Canada, some provincial and municipal governments used the NECB as the basis for design and construction of new public buildings. Institutions such as universities or large public companies also made compliance with the NECB or ASHRAE Standard 90.1 a requirement for the design and construction of an increasing number of high-profile buildings.

As public awareness and concern grew over global warming, greenhouse gas emissions, and other environmental issues, so did the prevalence of energy and environmental rating systems such as LEED (Leadership in Energy and Environmental Design). Over time building rating systems, energy standards, and model energy codes encouraged the evolution of building codes. Today's building codes integrate many of the energy and thermal performance requirements from earlier standards and model codes.

The NECB was released in 2011, with updates in 2015, 2017, 2020, and 2025. This guide focuses on the 2025 version, and any reference to NECB throughout this document refers to the 2025 version, unless stated otherwise. Some of the provinces have multiple levels of energy performance, with Tier 1 representing the minimum standard for building energy efficiency and Tier 4 representing a net-zero energy ready project. In the following list of provinces, the noted tier represents the requirements of the 2020 NECB. As of the date of publication, British Columbia, Alberta (Tier 1), Saskatchewan, Manitoba, New Brunswick (Tier 2), PEI (Tier 1), and Nova Scotia (Tier 1) have adopted the 2020 NECB, although sometimes with provincial variations. Ontario has adopted the 2020 version with significant variations—this is a far less stringent standard, particularly with respect to thermal bridging.

The variation of the NECB 2020 adopted by Quebec has excluded the significant and impactful effects of thermal bridging added in the 2017 and 2020 versions. Thus, the enclosure requirements, while procedurally the same, are far less stringent than the unmodified version of the NECB. The minimum enclosure thermal resistance values for components such as walls, roofs, and windows are also lower, especially for colder climate zones.

Dependence on traditional materials and enclosure systems has also changed. The building industry has adopted and continues to develop new and improved ways of building to respond to changing code requirements and increasing performance expectations. Many different types of building systems are now being used throughout North America, prompting the development of more accurate methods for comparing and assessing their actual in-service thermal performance. The focus on better methods of predicting heat flow has, or will soon, enter mainstream building codes across North America. These new and more refined methods of accounting for heat flow also impact precast concrete enclosures.

1.2 Scope and Approach

The scope of this guide is limited to early-stage design estimates of the thermal resistance of precast concrete enclosure wall systems. The purpose is to allow design and energy modeling to proceed by estimating what thickness of insulation, or changes in construction details, would be required for specific R-value targets. The information is also intended to assist designers and owners make better comparisons between systems in the early stages of design (when many irrevocable decisions are made). Due to the specifics of the overall building design, the results may not be sufficient to demonstrate code compliance: additional energy modeling or trade-off analysis may be required.

The guide summarizes various compliance paths for meeting building energy codes. As these paths include “trade-off” options, different levels of thermal insulation can be used in walls for different projects. To accommodate this reality and simplify the document, thermal performance is provided for a range of insulation options.

The thermal performance of select details that are repeated throughout a building is considered. Other details that increase thermal bridging, such as parapets, base transitions, window installation, and project-specific conditions, are also important and need to be considered but are not covered in this guide as they are addressed later in the design process. The influence of dynamic thermal mass, which can only be properly assessed using computer programs for a specific building location, design, and occupancy schedule, has also been excluded. Most modern codes that specify high levels of thermal insulation do not consider the benefits for thermal mass because of this complexity.

The approach taken in this guide is to:

1. begin with an overview of the current thermal performance requirements in the NECB (Chapter 2),
2. explain approximate methods to predict the thermal performance of common precast concrete systems for use during early design stages, along with examples (Chapter 3),
3. present examples of precast enclosure system solutions, and the calculation of their R-value, to meet the thermal performance requirements (Chapter 4), and
4. develop a detailed worked example to explain the NECB approach for whole building R-value.

Appendices provide more detailed supporting information that may be useful for more technical readers.

2 The NECB

This chapter provides a brief overview of the NECB compliance paths and highlights requirements specific to precast enclosures. The reader should gain access to the freely available 2025 NECB and the guide document for the 2020 code: *User's Guide – National Energy Code of Canada for Buildings 2020,* as this guide draws on these documents as its primary source.

Adoption of building codes, acts, and standards, often with modifications, is a provincial mandate. Provinces update their building codes every few years, and hence, designers should check their current building codes and any related amendments.

It should also be noted that variances exist in how local jurisdictions may interpret building code requirements and these variances tend to evolve over time in unpredictable ways. Hence, this guide is intended for early design stage decisions. Professionals with knowledge of local interpretations should perform actual project compliance calculations as the project nears permit application.

NECB compliance requires the designer to consider the building enclosure (Part 3), Lighting (Part 4), Heating, Ventilating and Air-conditioning Systems (Part 5), Service Water Systems (Part 6) and Electrical Power Systems and Motors (Part 7). This guide only considers the building enclosure, and in particular, how Part 3 of the NECB impacts the design of precast concrete enclosures.

Predicting the energy consumption of a building is challenging as buildings are incredibly complex. All building codes make simplifying assumptions to make the level of effort manageable. The NECB makes fewer simplifying assumptions than previous codes, and hence its predictions are more likely to better represent actual performance. In particular, the NECB requires the consideration of thermal bridging – this is a major change for building designers and will be a focus of this guide. The impact of including thermal bridging on the predicted performance of the building can be significant: the enclosure R-value used in calculation by the NECB 2025 (which is relatively accurate) may be half the value calculated using previous codes (such as Ontario's SB-10). At the same time, the minimum enclosure R-value targets are essentially the same.

Building codes across North America define the minimum performance that designers are legally allowed to provide, although owners or various green building standards often set higher performance targets. Part 10 of the 2025 NECB defines four Energy Performance Tiers: Tier 1 is the code minimum performance, whereas Tiers 2 through 4 set progressively higher performance requirements and lower allowable energy consumption. Use of Part 10 requires whole building energy modeling to demonstrate compliance. To conduct whole building energy models, the actual thermal performance of all parts of the enclosure must first be quantified.

The enclosure thermal performance calculation methods in the NECB are sufficiently accurate to predict the performance of enclosures that may be intended for other codes and standards. Hence, the information in this guide can be useful in the design stage of standards such as Passive House or Energy Star. However, by definition, compliance with other standards requires careful review and use of the accepted calculation methodologies in those standards.

2.1 NECB Compliance Paths

Designers are quite familiar with enclosure requirements that vary according to climate zone and enclosure component (e.g., wall, roof, window, etc.). In past codes, occupancy (e.g., residential versus commercial) and construction methodology (e.g., wood framing versus steel framing) also impacted the minimum required thermal performance. The NECB 2025 enclosure requirements vary only with climate zone and by enclosure component.

It is not possible to answer the question “what R-value do I have to meet” in the design of enclosures because the NECB defines three primary compliance paths: (1) prescriptive, (2) simple trade-off, and (3) whole building energy modeling. As a result, NECB-compliant buildings can be constructed with a wide range of windows, roofs, floor slabs, and wall R-values. Thus, it is necessary to understand the different compliance pathways.

These three pathways are briefly discussed in the sections below. Figure 2 provides a summary of these compliance paths, which are broadly similar to other modern buildings and energy codes. Figure 3 is an overview of the three pathways.

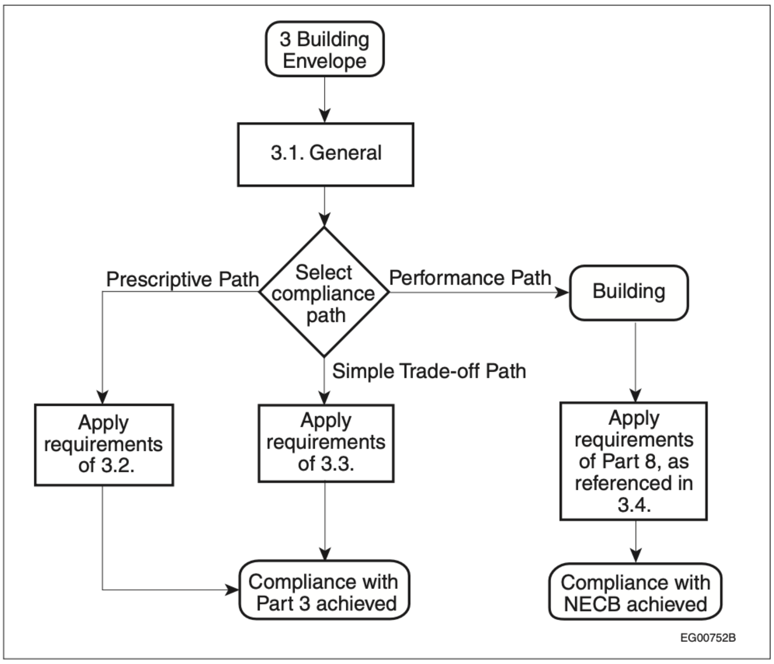


Figure 2: Compliance pathway choices for enclosures in NECB 2025

Prescriptive	**Trade-Off**	**Whole Building**
Use when all building enclosures and HVAC components meet minimum requirements and the window area does not exceed the maximum limits. Each enclosure component has a minimum thermal performance. Comparison to Section 3.2.2 shows compliance.	Overall average performance of entire enclosure (windows, walls, roofs, below-grade) is mandated Area-weighted thermal values compared to a notional building with the minimum prescriptive requirements.	Fewest mandated minimum requirements. Hourly energy modeling of the whole building, including lighting and HVAC compared to a notional building with the minimum prescriptive requirements. Requires specialist energy modeling personnel.
Precast Enclosure Design Approach		
Calculate component U-value, including thermal bridging. Adjust insulation type and thickness and thermal bridging details to meet the component target. Confirm the window area is less than the maximum limit. Ensure minimum HVAC & lighting requirements are met.	Calculate component U-value, including thermal bridging. Adjust performance of each component, along with window area, to meet overall target. Ensure minimum HVAC & lighting requirements are met.	Calculate overall U-value including thermal bridging for components. Adjust along with component R-/U-values, HVAC performance, and lighting.

Figure 3: Summary comparison of the three enclosure compliance pathways in NECB 2025

2.2 Climate

The climate in which the building is to be located plays an important role in understanding what energy-saving measures are required. The climate categories in the NECB use a similar zone numbering system as recent Canadian and US codes. A map of Canada showing the approximate range of zones is provided in Figure 4. These climate zones are exclusively based on Heating Degree Days (HDD) below 18˚C, which is tabulated in Table C-1 of the NECB (and is also provided in the NBCC).

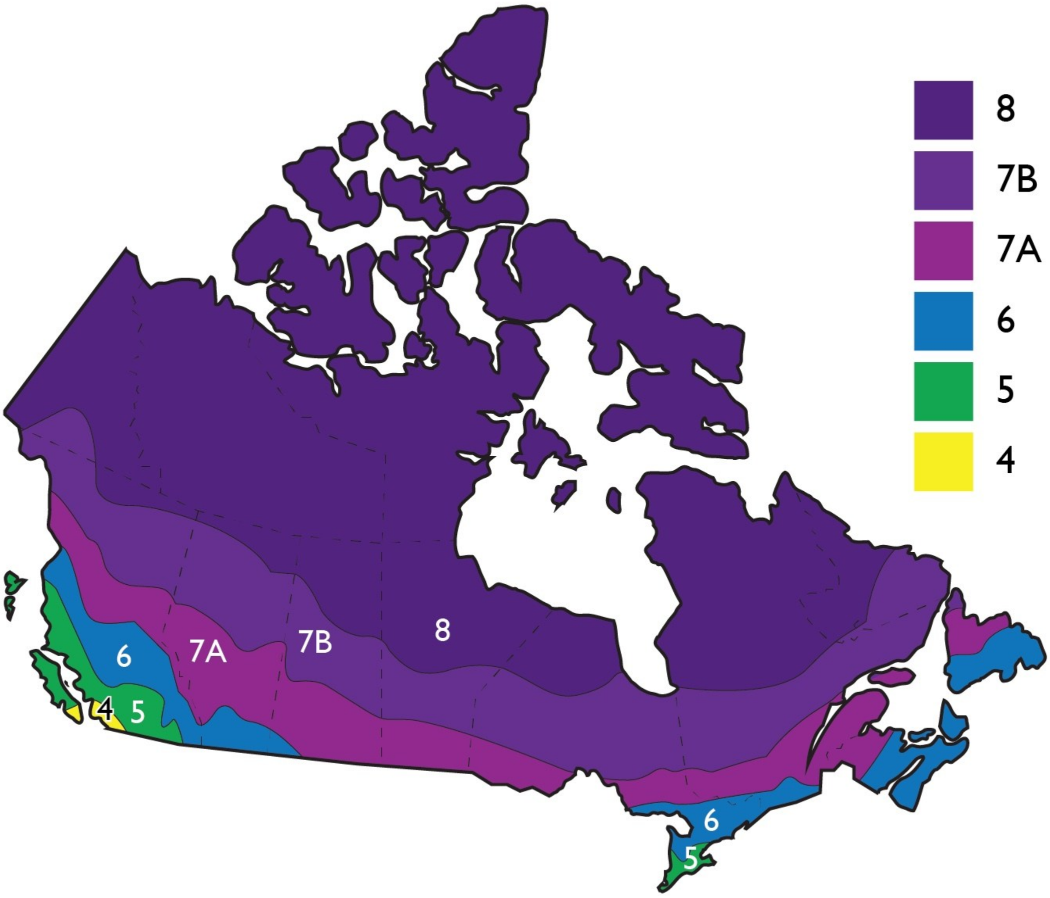


Figure 4: NECB climate zones for energy compliance

As codes have moved closer to more accurately describing R-values, the need to define categories for different assembly types (such as wood frame, light-gauge steel framing, masonry, etc.) has diminished. The NECB also no longer has a category for mass walls.

Although specific characteristics (R-value, airtightness, SHGC[3]) of building enclosures can reduce the demand for space heating and cooling, improvements to heating and cooling system efficiencies, lighting design, and mechanical ventilation systems can also have a major impact on large commercial and institutional buildings. Thus, the NECB prescribes minimum performance levels for a wide range of mechanical equipment, lighting, and control systems.

2.3 Prescriptive Approach

The simplest and oldest method of prescribing building energy performance is to specify the minimum required performance for each enclosure component (in either U-value or R- value), including opaque walls, fenestration, roofs, below-grade components, etc.

The NECB requires that assemblies meet a minimum tabulated performance level described by a U-value (or overall R-value). The advantage of this approach is that a wide range of materials, in a very

[3] Solar Heat Gain Coefficient is an important measure of a fenestration systems ability to control solar heat gain.

wide range of designs, can be used to meet the code. The major disadvantage is that some calculations are required: the focus of this guide is to make such calculations easier to perform.

Table 1 summarizes the maximum allowed assembly U-value (and minimum R-value) as a function of climate zone for the National Energy Code for Buildings 2025.

Table 1: NECB 2025 Enclosure Performance Requirements

Enclosure Component	Climate Zone					
	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
	Maximum SI U-value (W/m²·℃)					
Walls	0.290	0.265	0.240	0.215	0.190	0.165
Roof	0.164	0.156	0.138	0.121	0.117	0.110
Floors	0.193	0.175	0.156	0.138	0.121	0.117
Windows	1.90	1.90	1.73	1.73	1.44	1.44
Skylights	2.69	2.69	2.41	2.41	2.01	2.01
Doors	2.12	1.90	1.90	1.90	1.90	1.44
Basement	0.568	0.379	0.284	0.284	0.284	0.210
Slabs (on Grade)	0.757 (for 1.2m)	0.757 (for 1.2m)	0.757 (for 1.2m)	0.757 (for 1.2m)	0.757 (for 1.2m)	0.379 (full area)

Enclosure Component	Climate Zone					
	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
	Minimum IP R-value (ft²·˚F·h/BTU)					
Walls	19.6	21.4	23.7	26.4	29.9	34.4
Roof	34.6	36.4	41.1	46.9	48.5	51.6
Floors	29.4	32.4	36.4	41.1	46.9	48.5
Windows	3.0	3.0	3.3	3.3	3.9	3.9
Skylights	2.1	2.1	2.4	2.4	2.8	2.8
Doors	2.7	3.0	3.0	3.0	3.0	3.9
Basement	10.0	15.0	20.0	20.0	20.0	27.0
Slabs Grade	7.5 (for 4 ft)	7.5 (for 4 ft)	7.5 (for 4 ft)	7.5 (for 4 ft)	7.5 (for 4 ft)	15 (full area)

The NECB also specifies a maximum fenestration-and-door-to-wall ratio (FDWR) that varies with climate zone. FDWR is defined as the area of fenestration and doors divided by the gross above-grade enclosure wall area. The maximum is 40% in Climate Zones 4 and 5 and drops linearly to 20% for Climate Zone 8 (Figure 5). Clause 3.2.1.4 provides an equation that allows the FDWR to vary *within* a climate zone:

Max Allow FDWR = (2000 – 0.2 * HDD)/3000, but FDWR= 0.2 for HDD ≤7000

For example, although both Timmins, ON (HDD=5940) and Calgary, AB (HDD=5000) are in Climate Zone 7A, the maximum FDWR will be 27% (i.e., 0.27 in Figure 5) for Timmins and 33% for Calgary. Given the important impact of fenestration, this seemingly small variation is sometimes significant.

The limits on fenestration and door area have been imposed because of the many scientific studies demonstrating that window areas greater than these maximums neither reduce lighting energy nor offset winter heating losses with useful solar gains (Carmody et al 2004, Johnson et al 1984, Love et al 2008, Poirazis et al 2008).

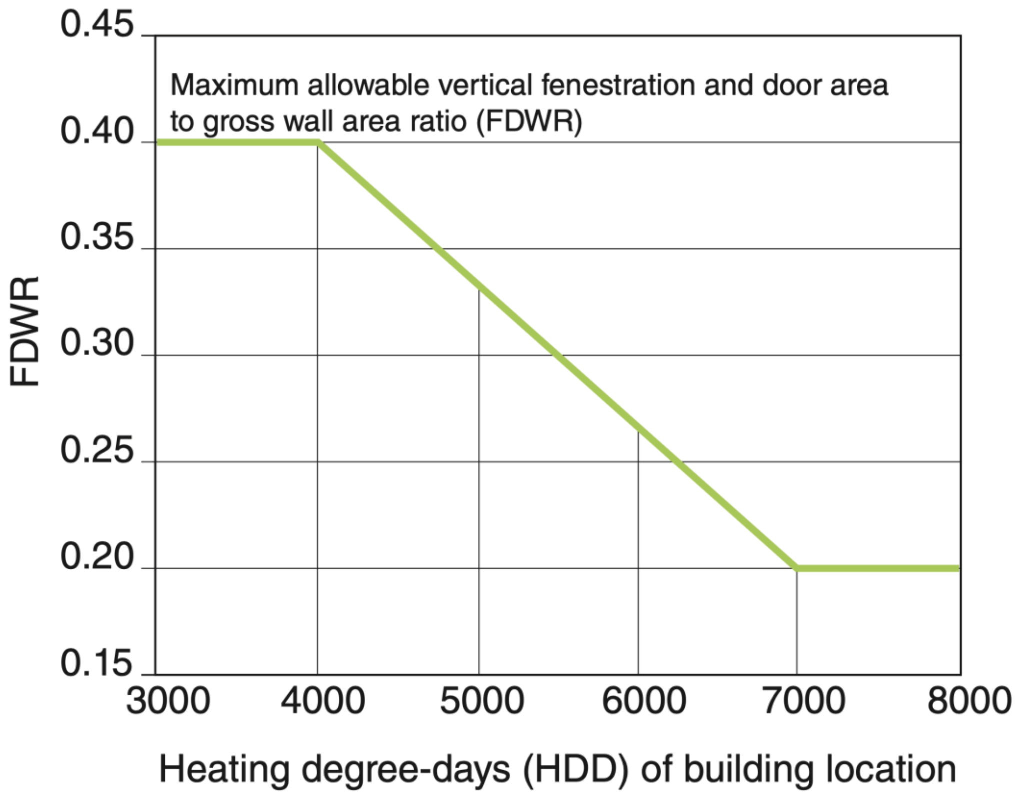


Figure 5: Maximum Fenestration-and-Door-to-Wall Ratio (FDWR) under the NECB prescriptive approach

Even though higher window-to-wall ratios cost more to build and increase energy consumption (and often result in comfort and glare problems), designers often choose to increase window area beyond the tabulated prescriptive maximum. The trade-off or whole building approach must be used to demonstrate compliance for projects that exceed the maximum FDWR.

2.4 Trade-off Analysis

To provide designers with more flexibility, most modern codes, including the NECB, allow for the trade-off between enclosure components. Some of the tabulated prescriptive enclosure R-values may be reduced and/or the FDWR may be increased, if the performance of other parts is increased sufficiently to offset the energy impact of these reductions. However, trade-offs are limited to being within categories of vertical or horizontal components, meaning trade-offs are allowed between:

1. above-grade walls, doors, and windows, including adjustment to allowable FDWR, and
2. roofs, floors, and skylights.

Only the above-grade parts of the enclosure can be traded-off with other components; below-grade elements cannot be traded-off. Also, one cannot use the simple method to trade off lower R-value enclosures with higher performance heating, cooling, ventilation, or lighting equipment. If HVAC trade-offs are desired, the whole building modeling approach must be used.

If the trade-off approach is used, there are no prescribed minimum R-values; however, it is difficult to conceive a compliant building with significant enclosure areas that are much less than the prescribed values in the prescriptive approach.

2.5 Whole Building Energy Modeling

For buildings with very high Window to Wall Ratio's (WWR), trade-off analysis rarely provides sufficient flexibility, and whole building energy modeling is used to take advantage of highly efficient lighting, and high-performance HVAC systems (including lighting and domestic hot water) to offset the low thermal performance of the glazing.

The energy consumption of the entire building can be estimated through the use of hourly building energy simulation programs. Such modeling must include details of occupancy density, usage schedule, heating, cooling, and ventilating equipment, pumps, fans, and lights, as well as accurate estimates of enclosure component performance. The cost and effort of whole building modeling usually means this approach is chosen only for larger projects. However, it allows for a very wide range of building enclosure performance levels. By specifying highly efficient mechanical equipment and making specific assumptions about occupant behaviour, it may be possible to build enclosures with effective overall wall R-values as little as half those required by prescriptive limits.

2.6 Calculating Enclosure U- and R-values

All three pathways of compliance require the estimation of an enclosure U-value (or its inverse, the R-value). There are numerous methods of estimating the thermal resistance of enclosure assemblies, which differ primarily by the simplifications they use. Historically, it was common to calculate the R-value of an assembly by adding the thermal resistance of each layer in an assembly. This ignored two- and three-dimensional impacts. An important feature of the 2025 NECB is that it requires estimates of essentially all two- and three-dimensional impacts.

In Clause 3.1.1.5 (5) a) the NECB explicitly defines the allowable calculation methods for use in predicting the thermal characteristics of building assemblies. These include:

a) i) the "ASHRAE Handbook– Fundamentals," or
ii) ISO 14683, "Thermal bridges in building construction – Linear thermal transmittance – Simplified methods and default values," or

iii) CSA Z5010, “Thermal bridging calculation methodology”.

In lieu of calculations, laboratory tests can be performed in accordance with ASTM C1363.

The NECB Appendix A-3.1.1.5(5)(a) describes the BC Hydro “Building Envelope Thermal Bridging Guide” (BETG) as an acceptable source of information. The National Building Code of Canada (NBCC) also provides information (especially about assumed material properties and framing factors). Although a small point, the NBCC Appendix A-9.36.2.4(1) defines a combined Isothermal-planes / parallel path method for assessing wood framing impacts that is not strictly compliant with NECB sub-clause a) of 3.1.1.5. This code appendix also describes a unique method of calculating heat flow through steel studs not referenced by the NECB. Hence, although the NBCC will likely be considered an authoritative source, its methods are not strictly aligned with the NECB and the standard methods referenced.

2.6.1 Insulation Installation

The NECB also has requirements about how to install insulation. In general, the insulation must be installed in a manner (Clause 3.2.1) that will not compromise its thermal performance because of air leakage, wetting, or water penetration. Good precast concrete enclosure design practice ensures this clause is met.

Clause 3.2.1.2 of the NECB has the most relevance to precast concrete. It states:

> *“Joints between components of the building envelope, such as expansion or construction joints or joints between walls and doors or fenestration, shall be insulated in a manner that provides continuity across such joints.”*

This means that the thermal resistance of two-stage joints between panels should be considered. A joint filled with air will provide some thermal resistance, although convection and radiation will limit the insulation value. Hence, installing multiple foam backer rods, fibrous insulation, or flexible spray foam[4] coincident with the insulation layer of the enclosure wall can be used to “provide continuity across such joints” as required by the NECB (Figure 6). As joints between precast panels do not have conductive concrete in them, the air gaps and backer rods can actually result in *higher* R-values than in the body of the precast panel if the insulation layer’s R-value is maintained at the joint.

[4] Two-pound density closed-cell spray foam insulation widely used for wall insulation is usually too stiff for joint filling and foam intended for the purpose – often sold specifically for joint filling and application around windows – should be specified.

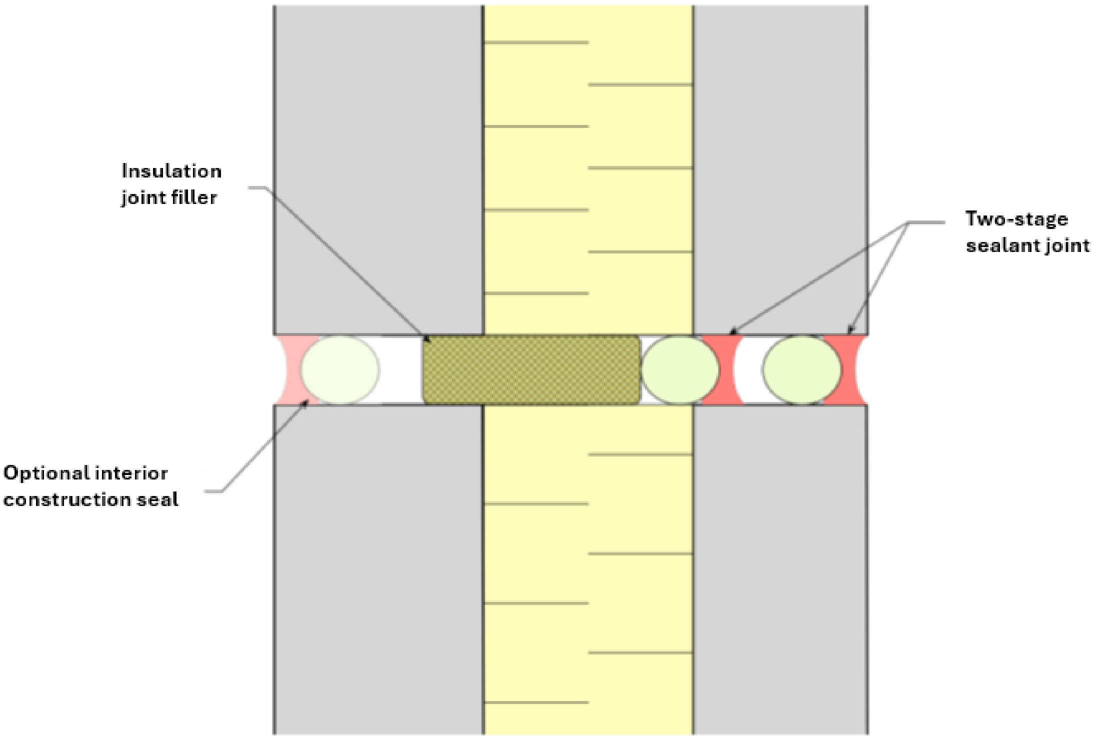


Figure 6: Example of a well-insulated joint detail in a double wythe insulated precast wall panel

2.6.2 Thermal Bridging

Based on research conducted by numerous organizations nationally and internationally, thermal bridging is now understood to contribute significantly to overall heat flow, especially in well-insulated enclosures. Floor slabs, intersecting walls, parapets, balconies, etc., can result in significant heat loss (Figure 7) and should be covered with insulation.

"Continuous Insulation" or "c.i." is a common terminology encountered in modern prescriptive codes. This was added to code language to minimize thermal bridging, primarily in steel- and wood-framed enclosures. Continuous insulation (ci) is defined[5] as:

> *"Insulation that is uncompressed and continuous across all structural members without thermal bridges other than fasteners and service openings. It is installed on the interior or exterior or is integral to any opaque surface of the building envelope".*

It should be noted that the NECB does not prescriptively require continuous insulation; instead it sets performance targets for components of the enclosure and requires that most thermal bridging be accounted for. However, because continuous insulation remains a powerful strategy for managing thermal bridging, it will likely continue to be a major part of most designs. Nevertheless, any design that meets the performance requirements is acceptable.

[5] This definition is taken from ASHRAE 90.1-2022, Section 3.

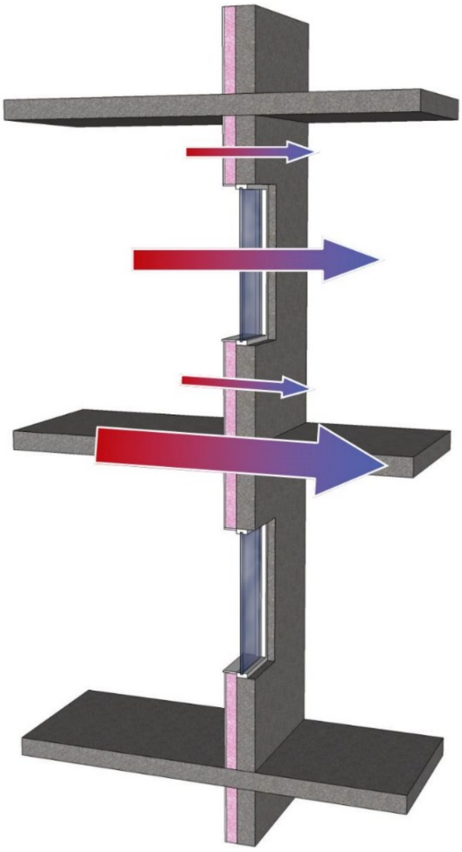


Figure 7: Heat flow paths through centre of wall, floor slab, and windows (arrow size is relative to magnitude of heat flow).

NECB Clause 3.1.1.7 mandates that thermal bridging should be considered and itemizes the following categories to be addressed:

> *"the calculated overall thermal transmittance of opaque assemblies shall include the effect of thermal bridging for all elements of the assembly, including:*
>
> *a) point thermal bridges,*
>
> *b) linear thermal bridges, and*
>
> *c) thermal bridges at junctions between building envelope materials, components, and assemblies."*

Reference to the Appendix A-3.1.1.7.(1) notes:

> *"Point elements include fasteners, ties, anchors, attachments and connectors."*
>
> *"Linear elements include studs, joists, ancillary members, lintels, plates, sills, flashings, angles, shelf angles, purlins, girts, sub-girts, hat channels, U-channels and furring."*
>
> *"Junctions between building envelope materials, components and assemblies occur at balconies, canopies, slab edges, fenestration perimeters (including the installation design details between the rough opening and the fenestration), spandrels, parapets, roof-to-wall junctions, corners, and edges of walls or floors. Junctions also occur at the intersection of interior walls with exterior walls, roofs or ceilings".*

Other codes and standards are also expected to require the same consideration of thermal bridging over time. ASHRAE 90.1-2022 is currently almost as demanding as the NECB. The recent Energy Modeling Guidelines of the Canadian Green Building Council [2024] requires essentially the same methodology as the current NECB, as does the Toronto Green Building Standard, Version 3.

The relatively new Canadian standard CSA Z5010:21 *Thermal bridging calculation methodology*, is recommended as guidance for any detailed calculations of complex assemblies.

2.7 Closure

Because the NECB offers several compliance paths, there is no single R-value that is required for a specific building in a specific location. The prescriptive path does not provide sufficient flexibility for some types of buildings. The trade-off path can provide a simple method of accommodating specific project needs, such as higher window-wall ratios or thermal bridging at balconies. Better than minimum window performance and enhanced wall R-values can be traded-off to demonstrate compliance.

Precast concrete systems are well placed to respond to the demand for higher thermal performance, as a broad range of R-values can be provided by relatively modest changes to design details. The thermal performance of precast concrete enclosure systems is considered in more detail in the remainder of this guide.

3 Calculating Enclosure Thermal Performance

Many owners do not wish to provide more performance than the minimum code requirement, and hence designers need to design buildings that "just meet" these codes. This requires both an understanding of the code minimum performance and how to calculate the performance of their building enclosure. Other projects have different goals or have a longer-term perspective. In this case, designers are driven to make the best choices between many competing alternative enclosure design systems and materials. In either case, being able to understand and predict enclosure thermal performance is necessary.

3.1 Background

Heat can flow across an enclosure by three modes: convection (air leakage), conduction, and radiation. Air leakage (bulk convection) is limited by the airtightness of the assembly. For opaque assemblies, the conduction and radiation modes are grouped together. The common measure of a building assembly's ability to control heat flow is its U-value, and the inverse, R-value. These metrics assume that the assembly is airtight[6], and hence building airtightness is measured and regulated separately.

Although R-value often uses traditional inch-pound (IP or I-P) units, it remains the most common means of communicating thermal resistance. Canadian codes and standards usually employ metric (SI) units and the NECB lists metric U-values. To differentiate the metric (SI) from the traditional (IP) units, metric thermal resistance is reported as RSI and the two units can be easily converted.

R-value = RSI * 5.67 RSI

RSI = R-value / 5.67.

The R-value (or RSI) of products and material layers is often tabulated in handbooks or provided by manufacturer's literature. In some cases, a material's thermal conductivity is provided. For a solid, homogenous layer made of a single material, thermal resistance can be simply calculated from the thickness of the material and its thermal conductivity by using:

$$R = \text{thickness} / \text{thermal conductivity} = t / k \qquad \text{(Eq. 1)}$$

where,

k is the thermal conductivity, in BTU/(hr·in·°F) or W/(m K), and

t is the thickness of the layer in inches or metres.

Table 1, Chapter 26, of the 2021 *ASHRAE Handbook of Fundamentals* (ASHRAE 2021) and Table A-9.36.2.4.(1)-D in Appendix A of the 2025 *National Building Code of Canada* (NBCC 2025) provide authoritative thermal conductivity (k) and R-values for a range of building materials.

[6] Precast concrete is an excellent material for use as part of an air barrier system: it is strong, stiff and air impermeable. CPCI has tested precast concrete to ASTM E2357, and the full report is available from CPCI.

The thermal resistance of a multi-layer assembly of flat materials (many types of building enclosures) can be calculated from (Straube & Burnett 2025):

$$R_T = R_1 + R_2 + \ldots + R_n \qquad \text{(Eq. 2)}$$

where,

R_T is the total one-dimensional thermal resistance of an assembly, and

R_1 to R_n is the resistance of each of the assembly's layers, including air films, air gaps, and solid materials.

For a multi-layered assembly formed of different materials, air spaces, and even complex framing, the thermal performance can be estimated provided that the thermal resistance of each of these layers can be found from tables or calculations (Figure 8). There are inherent simplifications in this approach. For example, the thermal resistance of air layers and air films is a complex combination of radiative and convective heat transfer modes that are reduced to a single approximate values. Because the thermal resistances of air films and air spaces are each relatively small, the simplification has little impact. Layer 5 is a simplification of a complex three-dimensional assembly with significant variations and the potential to meaningfully impact the overall results. Hence, determining the thermal resistance requires more advanced calculations, or tabulation of common variations. It is the latter approach that is taken in the guide.

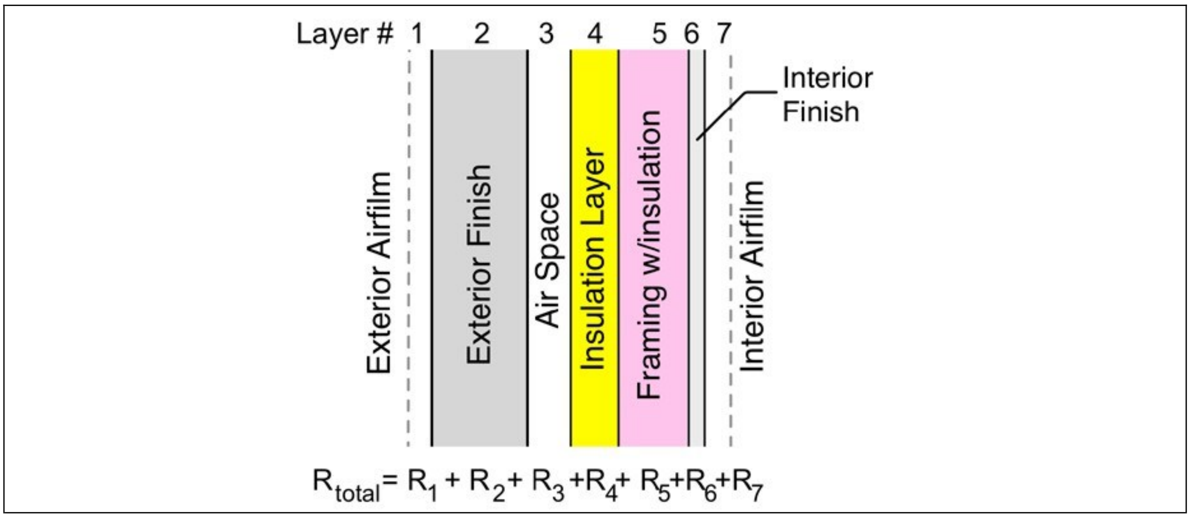


Figure 8: Example calculation of multi-layer assembly thermal resistance.

The U-value is used to describe the overall thermal transmittance of an assembly and is defined as:

$$U = 1 / R_T \qquad \text{(Eq. 3)}$$

The prescriptive tables of building codes in the past listed the R-value of the insulation layer that must be installed assuming a specific type of construction. As assemblies have become more varied and the industry more sophisticated, codes like the NECB now specify required maximum U-values for entire assemblies, including finishing materials, air films, and air gaps. Using this approach requires users to calculate the overall thermal performance of an enclosure assembly to demonstrate compliance, but offers much more flexibility.

3.2 Definitions of R-value

There are many different definitions of R-value. The definition applied depends on the code, standard, code official, and the different needs of energy modelers and designers. The most important distinction between different definitions is how thermal bridging is considered.

When heat moves through an enclosure element, it flows through more than just the centre of the enclosure: additional heat will flow through areas of steel or concrete that penetrate the insulation layer. Such penetrations, termed *thermal bridges*, are inevitable and codes increasingly require designers to account for them when judging compliance with codes and standards. Many of these definitions were developed over thirty years ago (e.g. Christian & Kosny, 1995).

There are several types of R-values reported in the industry or demanded by codes. These include:

→ the ***Installed R-value***, or nominal R-value which is simply the rated R-value of the insulation products in their installed condition (e.g. compressed batt insulation or nothing). The contribution of other materials is ignored.

→ the ***Assembly R-value*** or ***Centre-of-Wall*** is calculated by assuming the assembly is one-dimensional and simply adding the thermal resistance of all layers (e.g. in a double-wythe precast concrete insulated wall panel, also known as "sandwich" panel, the outer concrete, insulation, inner concrete, air films).

→ the ***Clear-wall R-value*** (R_{cw}) or "clear field "accounts for the thermal resistance of the layers (assembly R- value) but *also* includes the two-dimensional effect of standard repetitive framing (e.g. steel studs and tracks) and repeating conductive penetrations (optionally including cladding attachments).

→ the ***Whole-wall R-value***, (R_{ww}) includes the clear-wall R-value (R_{cw}) *plus* the thermal impact of any additional framing or fasteners at transitions (parapets, corners, foundation-to-above-grade-wall, wall-to-roof, balconies, etc.) and transitions (windows and door openings), canopy attachments, fall-arrest anchors, but *excludes* window area. For simplicity, sometimes the clear-wall R-value is used instead of the whole-wall R-value (i.e., thermal bridging is ignored), but this approach can significantly overestimate the thermal performance of many commercial enclosure systems.

→ the ***Overall R-value*** ($R_{overall}$) measures the performance of an entire enclosure type (such as wall or roof) and includes the combined effect of whole-wall R-value (R_{ww}) plus the heat loss through windows, doors, and curtainwalls. It is important for understanding overall building performance and is an implicit part of the simple trade-off methods used to demonstrate compliance (see Section 3.5).

→ **Effective R-value** is not a universal term but rather is used to describe an R-value that may include some or all thermal bridging, air leakage, or even thermal mass. There is no one definition, and it is not consistently used by major energy standards, but it is often the clear-wall R-value that is implied. Hence, the meaning of effective R-value varies depending on both the user of the term and the context.

Any of these R-values might also be reported as a U-value (U = 1/R, Equation 3). However, to add to the complexity, U-values almost always include the resistance of surface films (discussed later in the guide), whereas R-values may or may not. It is for these reasons that those in the building industry must be quite careful when interpreting requirements and be specific and precise when communicating required thermal performance.

For opaque walls, it is common for designers to specify thermal resistance, R_{cw}, as an RSI (˚C m²/W) or R-value (˚F ft²/BTUh), while U-value (W/m² ˚C or BTUh/ft² ˚F) is used to describe the thermal transmittance, U_V, of vision glazing. Building codes of the past used an installed R-value/RSI requirement which only accounted for the insulation, while window U-values included both surface films and the thermal bridging effects of framing and edge-of-glass construction.

3.3 Calculating R-values for Common Components

As described in Section 3.1, the thermal resistance of simple assemblies can be calculated by adding the resistance of individual layers as described in countless references, including the ASHRAE *Handbook of Fundamentals* and the Appendix to the *National Building Code of Canada*. A practical and simple method of predicting the thermal performance of enclosure assemblies is to reduce complex and common assemblies to equivalent layers with tabulated R-values. Then the designer can simply add the R-values to generate an accurate and NECB-compliant component R-value.

The thermal contribution of interior finishes, continuous layers of insulation, and interior light-gauge framing are common options for many commercial systems and will therefore be considered first.

3.3.1 Interior Finishes and Light-gauge Framing

Many enclosure systems employ gypsum wallboard (GWB) and light-gauge steel framing on the interior to provide a familiar finish, additional fire resistance, or to provide a space to easily run services such as power and communications. In many cases, the space between the studs is also insulated.

To calculate the thermal performance provided by a layer of 3-5/8" (92 mm), 4" (102 mm) or 6" (152 mm) steel studs, the significant thermal bridging caused by the heat flow through the studs and tracks must be considered. Studs that resist wind load tend to be thicker (18- or 20-gauge), whereas studs that support interior gypsum may only be 25-gauge. The thicker gauge steel does transmit more heat, but both drastically reduce the nominal R-value of any insulation (fibrous or foam) installed within the system. Hence, prescriptive tables in energy codes recommend a certain amount of insulation on the exterior of the studs to provide continuous insulation ("ci" in code short form).

For practical applications, steel stud framing, and any insulation installed in the stud cavity can be simplified as a monolithic layer with an equivalent R-value (Table 2), to which the R-value of the gypsum board interior finish (Table 3) can be added.

When surface coefficients are combined with standard air film values (see 3.3.3 Air Films and Surface Coefficients), a very practical summary table can be produced (

Table 4). It can be seen that for the common R-13 (RSI 2.1) and R-19 (RSI 3.35) batt between steel framing scenarios, an effective R-value of only 6.0 and 7.1, respectively, can be expected (a 54% and 63% reduction, respectively). If the details of double-studs at windows, and closer stud spacing than nominal and floor slabs are accounted for, the actual R-values provided are closer to R-4 to R-5.

Table 2: Effective R-value for Light-gauge Steel Framing without Sheathing Acting as a Single Layer[7]

Cavity Depth		Rated Cavity R-value	Layer R_{cw}-value	Layer RSI_{cw}
In	mm	(Installed R-value)	@ 16 inch centres	@ 405 mm centres
2.5	64	Empty	0.75	0.13
3.5	89	Empty	0.79	0.14
		R-13	6.0	1.06
		R-15	6.4	1.13
6.0	152	Empty	0.84	0.15
		R-19	7.1	1.25
		R-21	7.4	1.31
		R-24	7.6	1.34

Table 3: Thermal Resistance of Gypsum Wallboard Finish

Gypsum Wallboard (GWB) Thickness		Thermal Resistance	
in	mm	R-value	RSI
1/2	13	0.45	0.08
5/8	16	0.56	0.10

Table 4: Clear-Wall R-value for Light-gauge Steel Framing including both Air Films (Table 6) and 5/8" Gypsum Wallboard Interior Finish

Cavity Depth		Rated Cavity R-value	Layer R_{cw}-value	Layer RSI_{cw}
in	mm	(Installed R-value)	@ 16 inch centres	@ 405 mm centres
2.5	64	Empty	2.15	0.37
3.5	89	Empty	2.19	0.39
		R-13	7.4	1.31
		R-15	7.8	1.38
6.0	152	Empty	2.24	0.39
		R-19	8.5	1.50
		R-21	8.8	1.55
		R-24	9	1.59

[7] Data primarily assembled from ASHRAE 90.1-2022 Appendices, eg. Table A9.2B, A3.1A, A3.1D, A3.3

3.3.2 Continuous Insulation

The nominal R-value of continuous layers of insulation (ci) can simply be added to the R-value of other layers at the stated value, provided that only fasteners and insulation attachments penetrate the layer[8]. The approximate R-value per inch (or, in metric, thermal conductivity) of common product categories are provided in Table 5. If a specific product and brand of insulation has been selected, the R-value from the producer's data sheet can be used. Note that concrete does not provide a meaningful contribution to R-value (although dynamic thermal mass effects do help reduce energy use in complex and difficult-to-predict ways).

Table 5: Recommended Approximate R-values for Continuous Insulation Layers and Concrete[9]

Material	Conductivity (R/inch)	R-value at 2"	R-value at 2.5"	R-value at 3"	R-value at 3.5"	R-value at 4"
Open-cell foam	3.8	7.6	9.5	11.4	13.3	15.2
Spray cellulose	3.8	7.6	9.5	11.4	13.3	15.2
Mineral wool semi-rigid	4.0	8.0	10.0	12.0	14.0	16.0
Expanded polystyrene Type 2	4.0	8.0	10.0	12.0	14.0	16.0
Extruded polystyrene	5.0	10.0	12.5	15.0	17.5	20.0
Polyisocyanurate (approx.)	5.5	11.0	13.8	16.5	19.3	22.0
ccSPF	6.0	12.0	15.0	18.0	21.0	24.0
Concrete	0.06	0.12	0.15	0.18	0.21	0.24

Material	Conductivity (W/mK)	RSI for 50 mm	RSI for 63 mm	RSI for 75 mm	RSI for 90 mm	RSI for 100 mm
Open-cell foam	0.038	1.3	1.7	2.0	2.3	2.7
Spray cellulose	0.038	1.3	1.7	2.0	2.3	2.7
Mineral wool semi-rigid	0.036	1.4	1.8	2.1	2.5	2.8
Expanded polystyrene Type 2	0.036	1.4	1.8	2.1	2.5	2.8
Extruded polystyrene	0.029	1.8	2.2	2.6	3.1	3.5
Polyisocyanurate (approx.)	0.026	1.9	2.4	2.9	3.4	3.9
ccSPF	0.024	2.1	2.6	3.2	3.7	4.2
Concrete	2.4	0.02	0.03	0.03	0.04	0.04

3.3.3 Air Films and Surface Coefficients

All assemblies also have an internal and external resistance to heat flow, often referred to as an "air film" or "surface coefficient". Standard design values are tabulated in Table 6.

Although these provide only a modest amount of R-value (R-0.84) to every assembly, they are included as part of tabulated code minimum U-values for assemblies and as part of the rated U-value of windows.

[8] Z-girts should never completely penetrate an insulation layer or a significant (i.e., more than 50%) reduction in performance of the layer will result.
[9] These values are based on NBCC 2025 Table A-9.36.2.4(1) D *Thermal Resistance Values of Common Building Materials* supported and extended by RDH's extensive laboratory testing of samples. Specific products may have performance 10% more or less than these values.

Table 6: R-value of Interior and Exterior Surface Films (ASHRAE 2021)

Condition	RSI-Value	R-value
Interior Surfaces	0.120	0.68
Exterior Surfaces	0.029	0.16

3.4 Calculating Thermal Bridging Impacts

The clear-wall performance (R_{cw}) includes thermal bridging of regularly spaced framing elements, such as light-gauge steel framing, but does not include heat flow through floor slabs, window installation details, cladding attachment, etc. Thermal bridging effects not accounted for in the clear-wall performance (R_{cw}) can be captured by several different calculation methods. Computer-based finite-element thermal models of two- and three-dimensional systems are preferred, but the cost of project-specific analysis cannot usually be justified for early-stage design or small projects.

Simpler hand calculation methods, such as the parallel path and zone method, can and have been used for years to assess thermal bridging. Precast concrete systems can often use simpler approaches such as the parallel path method for many applications. The parallel path method uses an area-weighted U-value based on different possible heat flow paths (Figure 9). Heat flow paths with significantly different thermal performance, such as a stud and cavity insulation or a wall and a penetrating balcony, are calculated separately and their U-values weighted in proportion to their relative area. If there are two flow paths, 1 and 2, the following equation would be used:

$$U_{avg} = U_1 \bullet \frac{A_1}{A_1 + A_2} + U_2 \bullet \frac{A_2}{A_1 + A_2} \quad \text{(Eq. 4)}$$

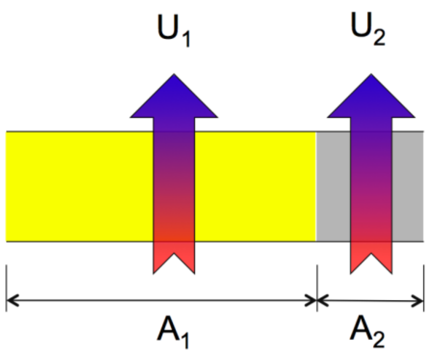


Figure 9: Parallel Path Heat Flow

Of course, the U-value is simply the inverse of R-value, and the actual areas can be replaced with percentage area (if path 1 covers 5% of enclosure area, A_1 / (A_1+A_2) becomes 0.05/ 1.0 =5%) then the parallel path method for two different areas can be written as:

$$R_{avg} = \frac{1}{R_1} \bullet \%A_1 + \frac{1}{R_2} \bullet \%A_2 \quad \text{(Eq. 5)}$$

The application of this simple approximate method will be presented for several different scenarios in Chapter 4.

A more recent methodology (based on the ISO 10211 Standard) of calculating thermal bridging is to use linear and point-based thermal bridging factors. This approach divides thermal bridges into two types: linear details that predominately exhibit two-dimensional heat flow and point details whose heat flow is primarily three-dimensional (Figure 10).

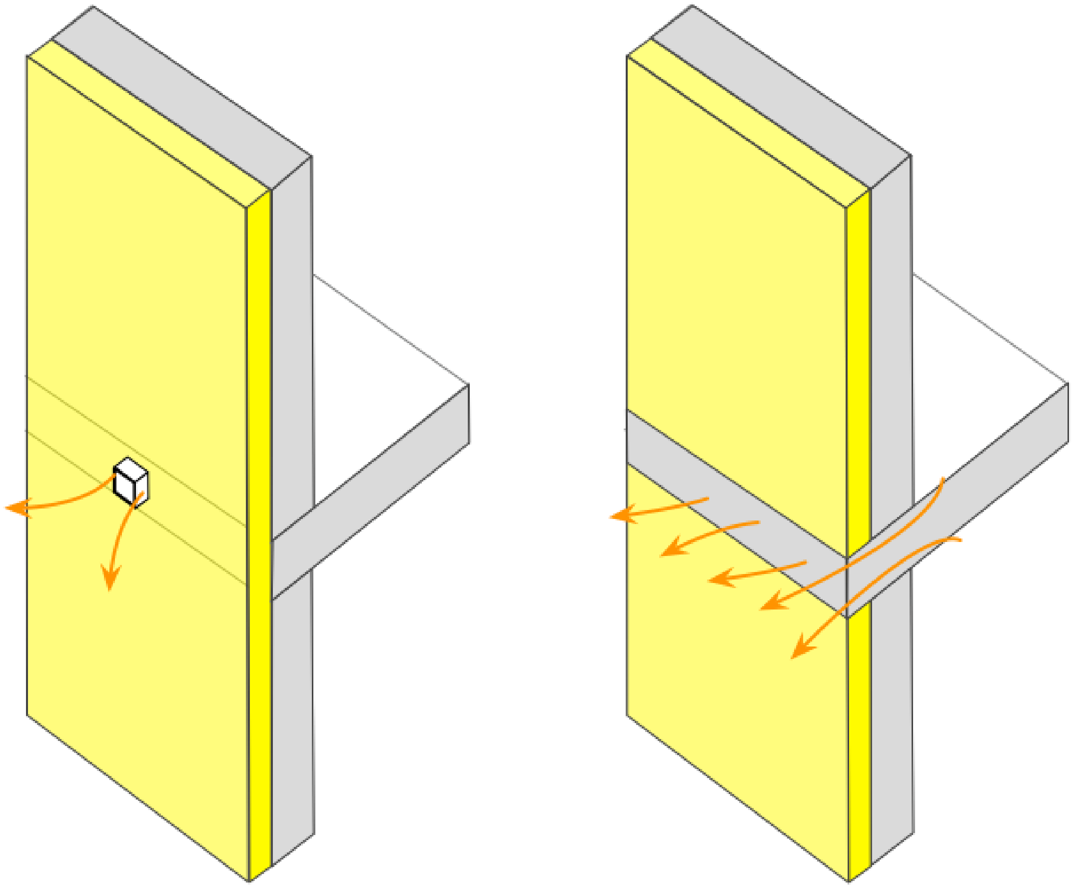


Figure 10: Three-dimensional (left, χ) and two-dimensional (right, Ψ_i) thermal bridges

Assigning the symbol psi (Ψ) to the transmittance of heat in two-dimensional details and the symbol chi (χ) to the transmittance of a point thermal bridge results in a heat loss equation that accounts for thermal bridging for a given building enclosure component:

$$Q = [U_{cw} \bullet A + \Sigma(\Psi_i \bullet L_i) + \Sigma(\chi_j \bullet n_j)] \bullet \Delta T \qquad \text{(Eq. 6)}$$

where,

Q is the overall heat flow, including thermal bridging,

U_{cw} is the clear-wall heat transmittance ($1 / R_{cw}$),

A is the area of the assembly, including all details in the analysis area,

Ψ_i is the linear heat transmittance value of detail "i",

L_i is the total length of the linear detail "i" in the analysis area,

χ_j is the point heat transmittance value of detail "j",

n is the number of point thermal bridges of type "j" in the analysis area, and

ΔT is the temperature difference across the wall.

This calculation can be applied to all enclosure systems but requires the development of specific thermal bridging factors. These detail-specific factors have been published for hundreds of assemblies (RDH 2013, Higgins et. al. 2014, BC Hydro 2021, https://thermalenvelope.ca/) or can be derived from two- and three-dimensional thermal computer models. Currently, the BC Hydro Thermal Bridging Guide contains 29 precast concrete details and a total of 743 details. CPCI has generated a number of Ψ (linear) and χ (point) heat transfer factors specific to precast enclosures (Appendix B and E).

This method allows the average whole-wall U-value to be calculated using:

$$U_{ww} = \frac{\frac{A_{wall}}{R_{CW}} + \Sigma\,(\Psi \cdot L_i) + \Sigma\left(X_j \cdot n_j\right)}{A_{wall}} \qquad \text{(Eq. 7)}$$

where,

A_{wall} is the total area of the opaque components

Ψ_i is the linear heat transmittance value of detail "i"

L_i is the total length of the linear detail "i" in the analysis area

χ_j is the point heat transmittance value of detail "j", and

n is the number of point thermal bridges of type "j" in the analysis area

As many prefer to use R-value in their communications, R_{ww} can simply be calculated from $U_{ww}=1/R_{ww}$, similar to Equation 3.

3.5 Windows and Overall R-value

True thermal performance and code compliance requires the design to consider the influence of windows, doors, and curtainwalls on heat flow through the entire vertical enclosure. Window, door, and curtainwall R-values are much lower than that required of opaque walls. Because heat flows preferentially through low-thermal resistance components, much more heat flows through fenestration systems in most buildings, even those buildings with limited glazing area.

Designers of a high-performance building will generally consider the Overall Wall R-value as a measure of the enclosure thermal performance. The NECB infers an Overall Wall R-value in its prescriptive paths by imposing a maximum Fenestration-and-Door-to-wall area (FDWR) (Clause 3.2.14) and minimum component R-values (Table 1), both of which vary by climate zone.

The overall R-value of an enclosure wall assembly can be drastically changed by modifying the Window-to-Wall Ratio (WWR) (Ross and Straube 2014) and window performance. To compare the impact of WWR, glazing performance, and opaque wall performance, an equivalent overall R-value, which combines the influence of the Whole-Wall R-value with the Window U-value, can be used as a single metric.

The simple trade-off compliance path in most codes is designed to ensure that this Overall R-value is more than some minimum value.[10]

Overall equivalent transmittance, $U_{overall}$, (and $R_{overall} = 1/ U_{overall}$) can be calculated using the parallel path method as:

$$U_{overall} = (1\text{-}WWR) / R_{ww} + WWR \cdot U_V \qquad \text{(Eq. 8)}$$

where,

WWR is the Window-to-Wall Ratio,

R_{ww} is the whole-wall R-value of the opaque assembly (or 1/U), and

U_V is the U-value of vision areas.

Overall R-value is of course:

$$R_{overall} = 1 / U_{overall} \qquad \text{(Eq. 3)}$$

Figure 11 demonstrates the large impact of window-to-wall ratio for a system with a clear-wall R-value of 20 and high-performance double-glazed aluminum windows. The overall enclosure R-value drops from R-9.4 to R-4.5 as the WWR increases from 20% to 60%. This example emphasizes that window area can be reduced to significantly increase overall performance. It can also be used to reduce the thermal performance of the opaque wall well below that required in the prescriptive tables.

[10] Currently the overall R-value is in the range of R-6 to R-9 for CZ4 through 7A in NECB 2025.

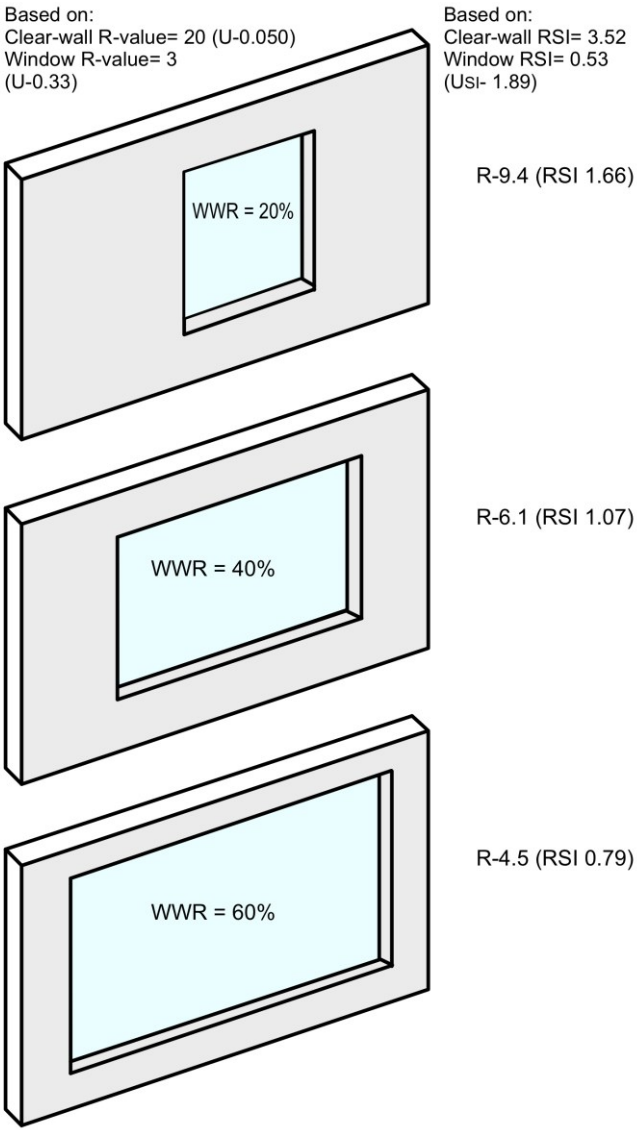


Figure 11: Impact of windows on overall enclosure R-value

Figure 12 explores the influence of window selection in another way. It plots the overall R-value for good-quality triple-glazed aluminum, double-glazed fiberglass, and good-quality double-glazed aluminum windows (U=0.20, 0.30, and 0.35, respectively, as opposed to code minimum) and R-12, R-24, and R-30 opaque walls. The overall R-value (the value used for the simple trade-off compliance path) for several climate zones are shown on the plot.

Figure 12 uses Fenestration-door-to-wall ratio (FDWR) instead of Window-to-wall ratio (WWR) but they are the same thing for this analysis[11]. For larger FDWR (i.e., above about 40% or 0.40) it can be seen how little performance is gained by increasing wall insulation (i.e., the R-10 and R-20 lines approach each other). The combination of high-thermal performance windows and lower window-to-wall ratios is almost always the lowest cost approach to energy efficiency and thermal comfort.

As an example, the graph can be used to show that an opaque R_{ww}-12 (RSI2.11) wall with U_f=0.3 (USI-1.70) windows (the solid green line) exceeds the minimum requirement for a HDD3900 climate (Zone

[11] Note: Only the NECB uses the FDWR term whereas all other codes and extensive literature on the subject uses WWR.

5) provided the fenestration-door-to-wall (FDWR) ratio is about 35% or lower. Note that the prescriptive maximum FDWR for a HDD3900 climate would be 0.40 (see Figure 5). This arrangement would also be compliant with a more demanding HDD4900 climate (Zone 6) if the FDWR was reduced to 21% (see the yellow circle at the intersection of the solid green line with the horizontal CZ6 line). The prescriptive maximum FDWR would be 0.34 in this climate. Doubling the wall R-value from R_{ww}-12 to R_{ww}-24 (RSI4.23) (dashed green line), but using the same windows (i.e., U_f=0.3 (USI-1.70)), would allow up to 34% FDWR in a HDD4900 climate (Zone 6). This is shown by the intersection of the green dashed line and the CZ6 line (purple circle). The dashed red line shows that the FDWR could be increased to 54% by selecting very high-performance windows (U_f=0.20) using the trade-off method (red circle).

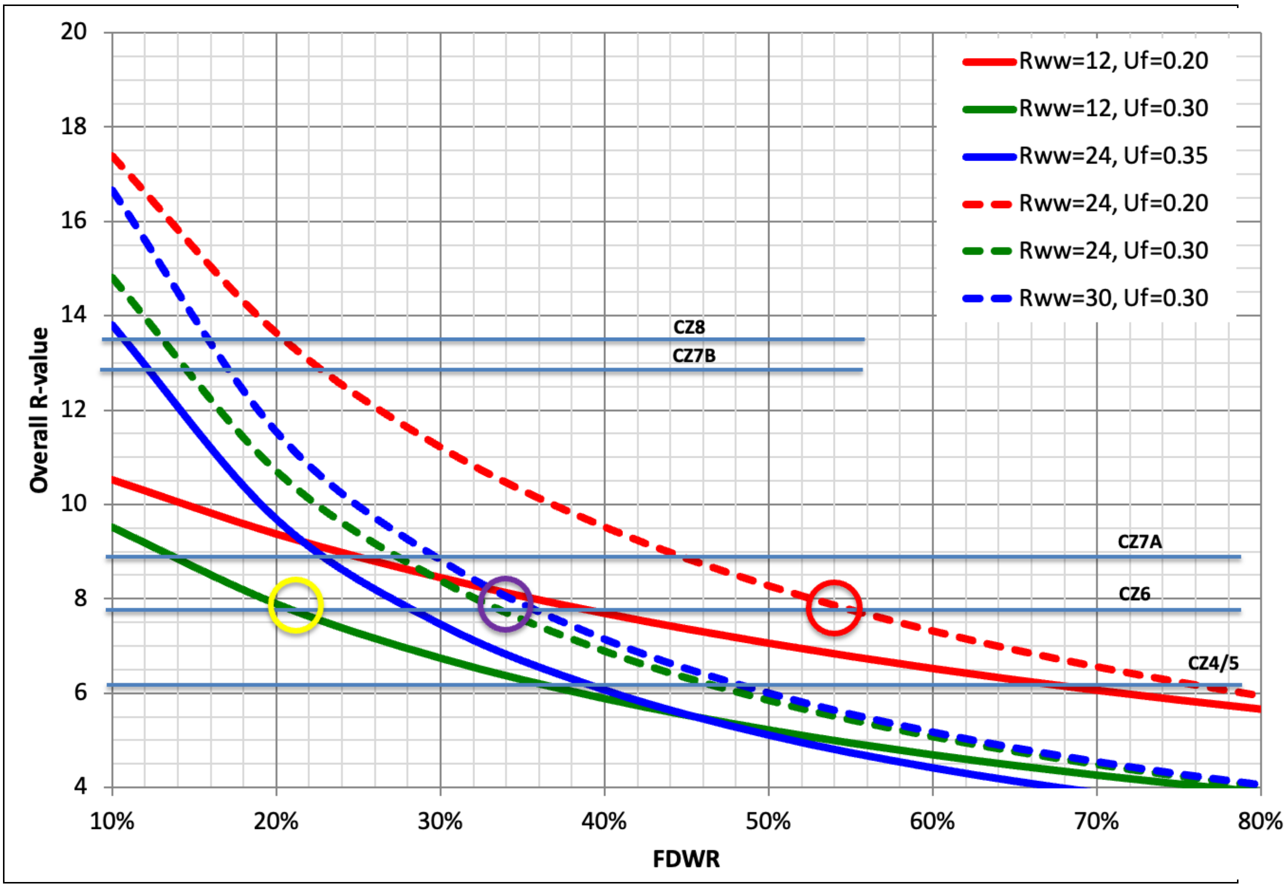


Figure 12: Combined impact of walls and windows and FDWR (Note: CZ= Climate Zone, R_{ww} is Whole-Wall R-value, and U_f is fenestration U-value)

In practice, when the FDWR is over 40% (or some climate-dependent lower value for the NECB) and poor thermally performing windows/curtainwall are specified, whole building energy modeling must be undertaken to demonstrate code compliance. In this common case, higher efficiency mechanical systems, more efficient system layouts, and more efficient lighting are combined with higher (than prescriptive) performance window and opaque wall systems to achieve compliance.

4 Calculating the Thermal Performance of Precast Concrete Systems

This chapter reviews the primary types of precast concrete enclosures and provides worked examples and tabular data to allow for the calculation of enclosure U-value and R-value. To account for thermal bridging, each precast system requires special approximations. Each of the common precast enclosure wall systems are then covered in the following sections.

The U-value/R-value calculated can also be used to demonstrate compliance with the prescriptive requirements, if the prescriptive or enclosure trade-off path is selected. A competent energy modeler can also use the information presented to conduct whole building energy modeling or more detailed trade-off analysis. For more complex details, or higher performance designs, it is likely that more detailed 2-D or 3-D computer heat flow models will be justified.

4.1 Types of Precast Enclosures

Precast concrete walls are comprised of several broad types. Further information can be found at www.cpci.ca.

Single Wythe Wall Panels ("Conventional" or Architectural Precast) are used as exterior panels providing the primary air-control, and the rainwater management. The concrete panel also provides the enclosure structural support function (that is, it collects wind and self-load and transfers it to the primary structure). Thermal control is provided by insulation installed on the interior side of the panel.

Double Wythe Insulated Panels ("Sandwich" or "Integrally Insulated Wall Panels") incorporate thermal insulation between the exterior finish wythe and the interior wythe. The exterior and interior wythes are connected with ties (often low-conductivity stainless wire or composite polymers) that maintain the structural integrity of the panel and provide the degree of composite action desired. These systems provide a complete enclosure, with integral fire resistance and air, water, vapor, and thermal control planes.

Precast Concrete Roof slabs are often used and are most commonly comprised of hollow core planks or double-T slabs. Floors over exterior space are another common enclosure made up of this type of precast concrete element. The thermal, air. water, and vapor-control planes are added to the precast component, almost always to the exterior[12]. Interior insulated roofs are possible but require additional water control layers on the exterior of the concrete element, as well as additional care with the interior airtightness.

Although many precast enclosures are formed from wall panels that transfer lateral loads and self-weight to the primary building structure, another type of precast concrete system is also used, often termed Total Precast, as it provides both the enclosure and the primary building structural support system.

Total Precast Concrete is a system that employs precast concrete enclosure walls (either single or

[12] Although it is possible to insulate on the interior of concrete roofs, there are numerous building science reasons why this is not desirable (primarily due to condensation risk) and hence why it is rarely done in Canada.

double-wythe insulated panels), partitions, floors and the roof as part of a total structural system, carrying all lateral and gravity loads. The enclosure walls of this system also collect enclosure loads such as wind and seismic loads.

4.2 Single Wythe Precast Concrete Wall Panels

Single wythe precast concrete enclosure wall systems are common, especially for taller buildings. They have the potential to economically provide very high thermal performance as they can provide excellent airtightness and good control of thermal bridging. An example of a proven modern design that can deliver high performance is shown in Figure 13.

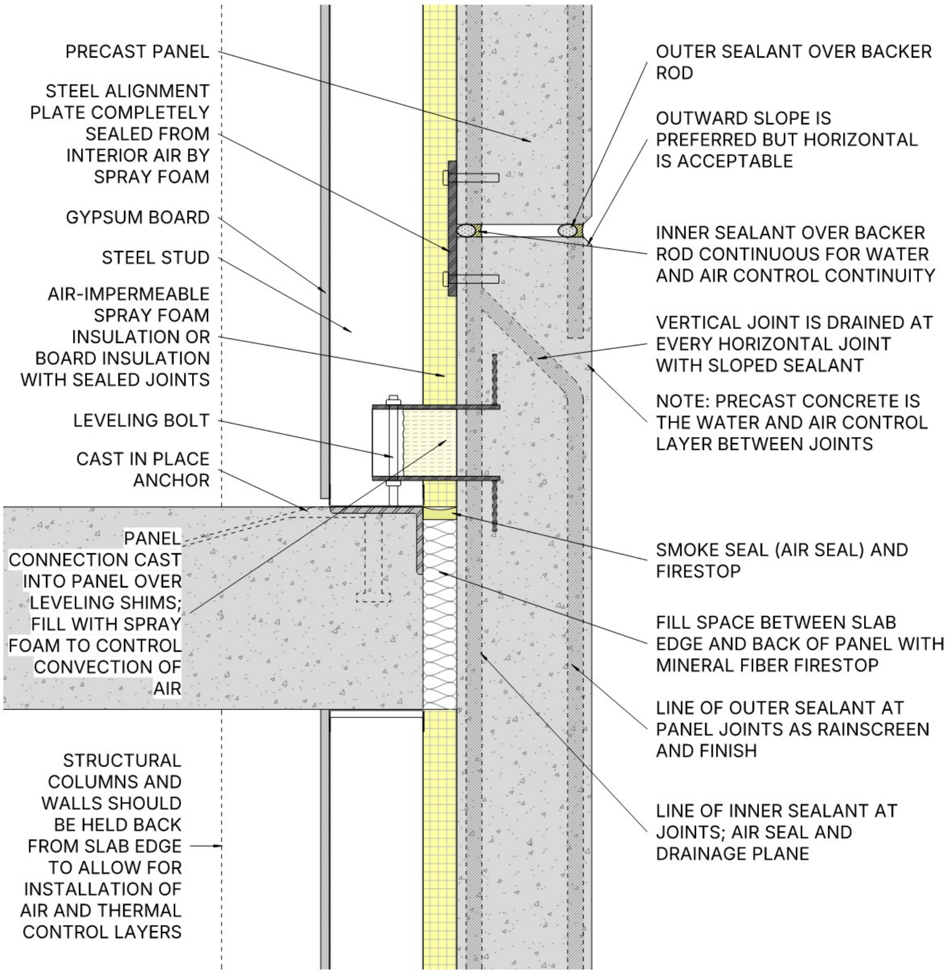
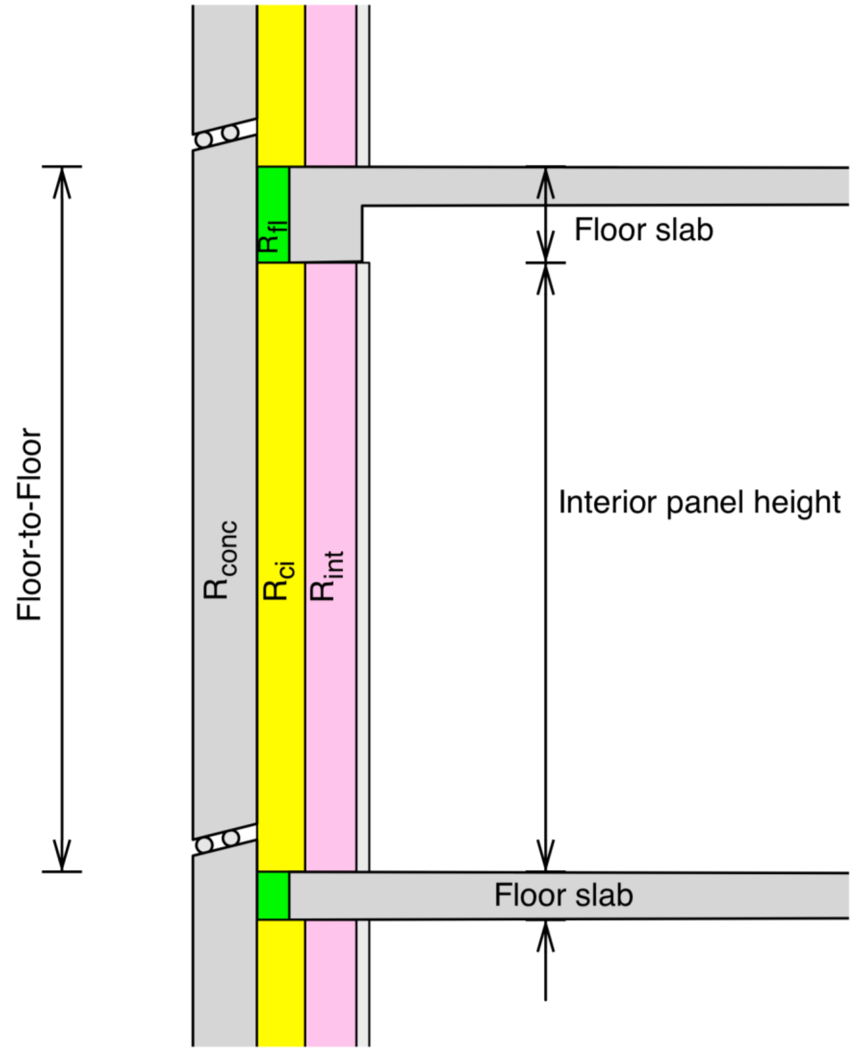


Figure 13: Floor intersection detail of a high-performance single wythe precast panel

To achieve good thermal performance, two aspects of the design must be given attention: the interior insulation, and the method of attachment to the primary structure.

Insulation is always added to the interior of the single wythe precast concrete panel, often in the field. To ensure good thermal performance, it is important to provide continuous interior insulation, rather than insulation between the steel stud framing. To avoid cold-weather condensation, it is critical that the insulation be in tight contact with the back of the concrete, and that the insulation (or an adhered facer) provide continuous airtightness and an appropriate amount of vapour diffusion resistance. The insulation can be semi-rigid mineral fiber (with airtight facer), rigid board foam (XPS, EPS, GPS or polyiso), or spray polyurethane foam. Light-gauge steel stud framing should be installed inboard of this continuous insulation layer and can be left un-insulated or insulated with fibrous or spray insulation[13].

The heat flow through the opaque portions of a single wythe precast wall can be calculated with only a few key inputs. The dimensions and layers required to calculate the thermal resistance are defined in Figure 14.



R_{conc}- Concrete panel thermal resistance (assumed to be zero)
R_{ci} – continuous insulation layer thermal resistance, ignoring small fasteners
R_{int} – thermal resistance of interior finishes, framing, and any insulation
R_{fl} – thermal resistance of fire stopping insulation and floor slab
Note: the floor slab height includes the depth of perimeter beams, if any

Figure 14: Definition of terms for single-wythe precast thermal calculation

[13] Due to thermal bridging through the steel studs, the addition of insulation to the studspace increases the effective R-value by only about R-5 to R-7, even if filled with closed cell Spray Polyurethane Foam insulation (ccSPF). Adding studspace insulation always increases the risk of cold weather condensation. For buildings with low or moderate relative humidity levels in the winter, the increased risk of condensation is often acceptable: high humidity buildings will require special consideration.

4.2.1 Clear-Wall R-value

To calculate the clear-wall R-value, the R-value of the continuous insulation is merely added to the R-value of the interior finishes, framing, and films. Tables 4 through 6 provide lists of the thermal properties of these common materials and elements.

> **Example**: A single wythe precast concrete system is comprised of a 127 mm (5”) reinforced concrete panel, 76 mm (3”) of closed cell Spray Polyurethane Foam (ccSPF) continuous insulation with an 89 mm (3.5”) steel stud framing at 406 mm (16”) on center with RSI2.1 (R-13) batt and 16 mm (5/8”) GWB on the interior (Figure 15).

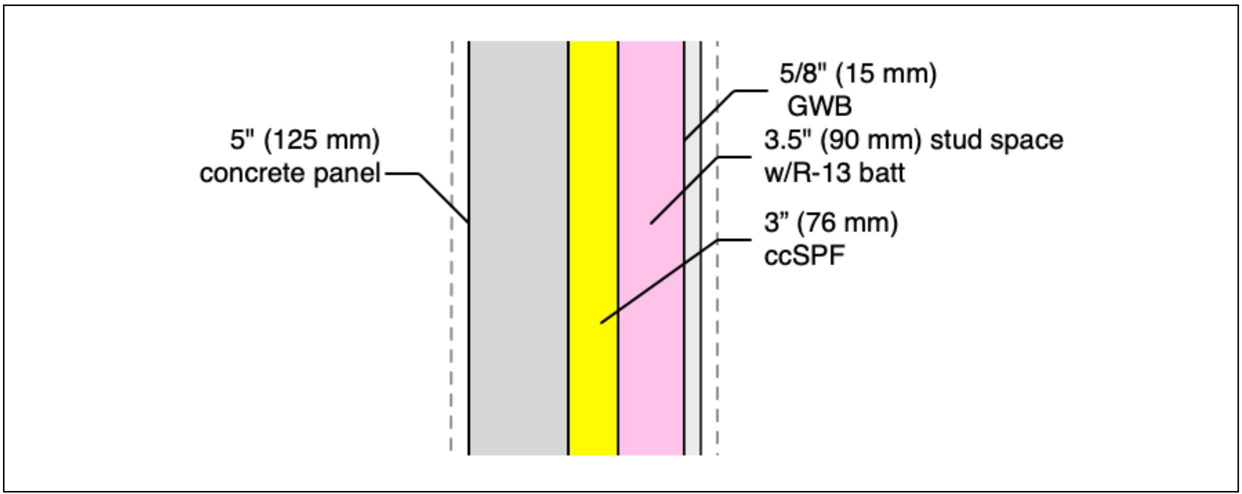


Figure 15: Example of an Architectural Precast Assembly

> The R-value of all interior finish components and framing is listed in
>
> Table 4 as R-2.2 with no batt, and R-7.4 with R-13 batt. The 3” of ccSPF is 3 times R-6/inch=R-18 (Table 5). Hence, the clear-wall R-value of this system is the sum of R-7.4 and R-18 = R-25.4. The R-value provided by the concrete (5” times 0.06/inch = R0.3 from Table 5) can also be included to reach R-25.7.
>
> If the stud space is left uninsulated, the R-value will be R-5.2 less, or R-20.5.

Incidentally, a clear-wall value of R-25.7 (U=0.0389, RSI =4.53) is very respectable performance for a system with a thickness of around 12” (305 mm). By comparison, a steel stud system would need to use 6” (152 mm) deep studs to resist wind loads in most commercial use and would provide only R-7.4 with an R-21 batt (see Table 2). To achieve about R-25.7, continuous insulation plus 1/2” (13 mm) of exterior gypsum sheathing with an R-value of over R-16 would be required to reach the same thermal performance. If mineral wool insulation was provided, this would require a 4” layer of mineral wool or about 3” of polyiso. Thus, the steel stud wall thickness would need to be 9.5” to 10.5” (240 to 267 mm) before any finish is applied to the exterior. Even assuming a thin (1/2” or 13 mm) panel cladding system over a 1.5” (38 mm) air gap and cladding attachment system, the resulting enclosure would be 11.5 to 12.5” (267 to 315 mm) thick.

4.2.2 Whole-Wall R-value: Accounting for Floor Slabs

While the above is sufficient for a clear-wall R-value calculation, the most recent versions of the NECB require that a whole-wall R-value must include the floor slab intersection and the precast concrete anchors. The approach for accounting for these potential thermal bridges is relatively new and the degree to which they are accounted for still depends somewhat on local guidance and the authority having jurisdiction.

The most important potential thermal bridge for a single-wythe precast enclosure wall system is the precast floor slab intersection. A gap between the back of the precast panel and the floor slab has always been provided in the past to allow for dimensional tolerances. However, today the gap should also be sized to provide a reasonable amount of thermal insulation continuity. The gap is almost always filled with mineral wool insulation to provide fire stopping between floors, and ranges from a practical minimum of just under 1" (25.4 mm) to as much as 4" (102 mm) and more. To calculate the whole-wall R-value for a single wythe precast enclosure, including the impact of the floor system, the following equation can be used[14]:

$$R_{ww} = 1 / \{ [(FF-T_{fl}) / FF] / R_{cw} + (T_{fl} / FF) / R_{fl} \} \quad \text{(Eq. 9)}$$

where,

R_{ww} is the whole-wall R-value of the precast panel (R-value or RSI) from above,

FF is the floor-to-floor height (feet or meters),

T_{fl} is the floor slab thickness (feet or meters), and

R_{fl} is R-value of the floor-precast assembly (R-value or RSI).

The R-value of the floor slab interface with the panel is almost wholly dependent on the thickness and effectiveness of the firestop insulation. In almost all cases, the firestop insulation is medium-density mineral wool, and thus an R-value of R-4 per inch can be assumed. If the interior and exterior surface films are added to typical concrete thicknesses, the R-value of the precast floor slab intersection can be estimated. Common values for use in early-stage design calculations are provided in Table 7.

Table 7: Total R-value of Precast Panel Floor-Slab (R_{fl}) Intersections

Stone Wool Firestopping Thickness, in (mm)	Effective Slab R-value	Effective Slab RSI
1 (25)	4.75	0.84
1.5 (38)	6.83	1.2
2 (51)	8.90	1.57
2.5 (64)	11.00	1.94
3 (76)	13.10	2.31
3.5 (89)	15.15	2.67
4 (102)	17.20	3.03
t>4"	4.0*t+1.2	0.704*t+0.21

[14] This equation assumes the parallel-path method which has been shown via 2-D modeling to be sufficiently accurate for the typical precast concrete building dimensions shown here.

Example: The single wythe precast system from the previous example (R_{cw}=25.7) spans 3861 mm (12'8") from floor-to-floor. The floors are comprised of a 178 mm (7") deep reinforced concrete slab with a 10" (254 mm) deep perimeter beam. If a 51 mm (2") gap is specified to be filled with mineral wool firestopping insulation, what is the whole-wall R-value and U-value?

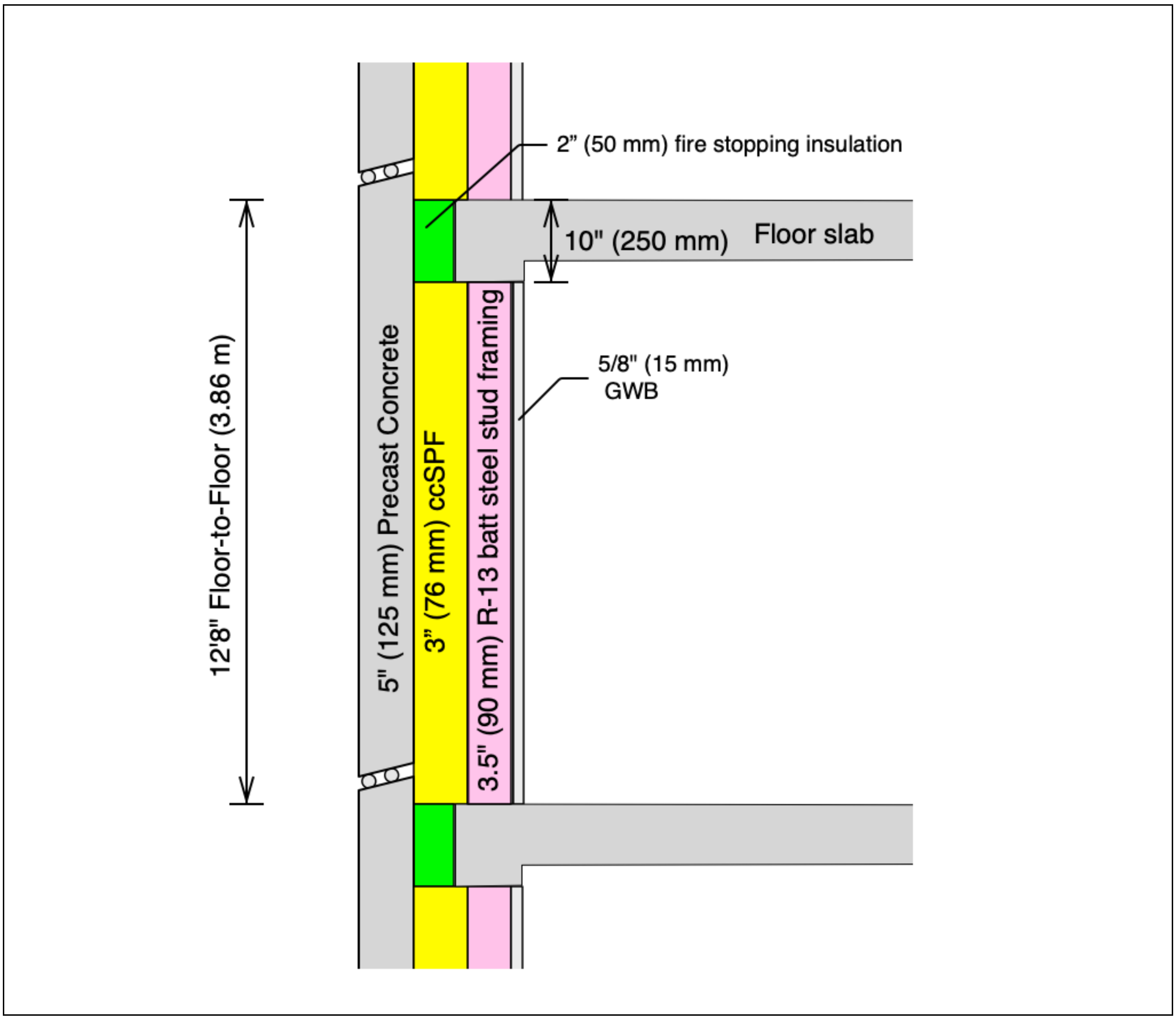


Figure 16: Example Single Wythe Precast System

The whole-wall R-value can be estimated by entering values into Equation 9:

$$R_{ww} = 1/\{ [(FF-T_{fl}) / FF] /R_{cw} + (T_{fl} / FF) / R_{fl}\}$$

where FF=12.66 feet, T_{fl} is 10/12=0.83 ft (note that the slab thickness is not used if a perimeter beam system is deeper), and floor R-value is 8.90 (from Table 7).

$$R_{ww} = 1/(((12.66-.83)/12.66)/25.7) + ((0.83/12.66)/8.9) = 22.9$$

The whole-wall R-value estimate is R-22.9 (RSI=4.03, U=0.044). This does not include the impact of precast anchors. Note that the clear-wall R-value calculated earlier was 25.7.

Hence, this system would meet the prescriptive wall requirement for NECB CZ5, but not CZ6. Increasing the firestop insulation thickness to 4” (R_{fl}=17.2) would change the whole-wall R-value to 24.9, which would meet the prescriptive wall requirements for CZ6.

To exceed the minimum prescriptive requirement in Climate Zone 7B (R29.9), one solution would be:

- 5” (125 mm) of precast concrete (R-0.3),
- 5” (125 mm) of continuous polyiso insulation (R-30),
- 3.5” (89 mm) stud space filled with R-13 batt,
- 5/8” (16 mm) GWB interior finish, and
- a fire stopping gap of 2” (51 mm) (R-13.1).

This assembly yields a clear-wall R-value of 31.1(R_{SI} 5.48). If the fire stopping gap were increased to 76 mm (3”) the whole-wall performance would rise to R_{SI}=5.91 (R_{ww}=33.6).

Of course, modest improvements in window performance and/or reductions in window area below the maximum FDWR allowed can also meet the code through the simple enclosure trade-off method.

Higher R-value enclosures are increasingly being demanded for higher Tier (e.g., Tier 2 and higher) targets, Net-Zero Energy buildings, and Passive House projects. To achieve this level of performance, more than 4” (102 mm) of continuous insulation and at least a 2” (51 mm) fire stopping gap will usually be needed, even in CZ5 and CZ6.

Using the same simple calculations, Table 8 provides the whole-wall R-value for a range of floor-to-floor heights, clear-wall R-values, and slab edge insulation thicknesses for an 8” thick (200 mm) floor slab. Appendix C contains tables for 12” (305 mm) thick floor slabs and metric units.

Table 8: Whole-Wall R-value (R_{ww}) for Single Wythe Precast Panels (I-P)

For 8" thick floor slab edge		Floor-to-floor height (ft)						
R_{cw}	Slab edge insulation (in)	9	10	12	14	16	20	24
7.4	1	7.1	7.1	7.2	7.2	7.2	7.3	7.3
	2	7.5	7.5	7.5	7.5	7.5	7.4	7.4
8.8	1	8.3	8.3	8.4	8.5	8.5	8.6	8.6
	2	8.8	8.8	8.8	8.8	8.8	8.8	8.8
12	1	10.8	10.9	11.1	11.2	11.3	11.4	11.5
	2	11.7	11.7	11.8	11.8	11.8	11.9	11.9
16	1	13.6	13.8	14.1	14.4	14.6	14.8	15.0
	2	15.1	15.2	15.3	15.4	15.5	15.6	15.7
20	1	16.2	16.5	17.0	17.3	17.6	18.1	18.4
	2	18.3	18.5	18.7	18.9	19.0	19.2	19.3
24	1	18.5	18.9	19.6	20.1	20.5	21.1	21.6
	2	21.3	21.6	21.9	22.2	22.4	22.7	22.9
	3	22.6	22.7	22.9	23.1	23.2	23.4	23.5
28	1	20.5	21.1	22.0	22.7	23.3	24.1	24.6
	2	24.2	24.5	25.0	25.4	25.7	26.1	26.4
	3	25.8	26.0	26.3	26.6	26.7	27.0	27.1
32	1	22.5	23.1	24.3	25.1	25.8	26.9	27.6
	2	26.8	27.3	28.0	28.5	28.9	29.5	29.8
	3	28.9	29.2	29.6	29.9	30.2	30.5	30.8
36	2	29.4	29.9	30.8	31.4	31.9	32.7	33.2
	3	31.9	32.2	32.8	33.2	33.6	34.0	34.3
	4	33.3	33.6	33.9	34.2	34.4	34.7	34.9
40	2	31.8	32.4	33.5	34.3	34.9	35.8	36.5
	3	34.7	35.2	35.9	36.4	36.8	37.4	37.8
	4	36.4	36.8	37.3	37.6	37.9	38.3	38.6
44	2	34.0	34.8	36.1	37.0	37.8	38.9	39.7
	3	37.5	38.0	38.9	39.6	40.1	40.8	41.3
	4	39.4	39.9	40.5	41.0	41.3	41.8	42.2
48	2	36.2	37.1	38.6	39.7	40.6	41.9	42.8
	3	40.1	40.8	41.8	42.6	43.2	44.1	44.7
	4	42.4	42.9	43.7	44.2	44.7	45.3	45.7

Table 9: Whole-Wall RSI-value (RSI_{ww}) for Single Wythe Precast Panels (SI)

For 203.2 mm thick floor slab edge		Floor-to-floor height (mm)						
RSI_{cw}	**Slab edge insulation (mm)**	**2743**	**3048**	**3657**	**4267**	**4876**	**6096**	**7315**
1.30	25.4	1.25	1.25	1.27	1.27	1.27	1.29	1.29
	50.8	1.32	1.32	1.32	1.32	1.32	1.30	1.30
1.55	25.4	1.46	1.46	1.48	1.50	1.50	1.51	1.51
	50.8	1.55	1.55	1.55	1.55	1.55	1.55	1.55
2.11	25.4	1.90	1.92	1.95	1.97	1.99	2.01	2.03
	50.8	2.06	2.06	2.08	2.08	2.08	2.10	2.10
2.82	25.4	2.40	2.43	2.48	2.54	2.57	2.61	2.64
	50.8	2.66	2.68	2.69	2.71	2.73	2.75	2.77
3.52	25.4	2.85	2.91	2.99	3.05	3.10	3.19	3.24
	50.8	3.22	3.26	3.29	3.33	3.35	3.38	3.40
4.23	25.4	3.26	3.33	3.45	3.54	3.61	3.72	3.80
	50.8	3.75	3.80	3.86	3.91	3.95	4.00	4.03
	76.2	3.98	4.00	4.03	4.07	4.09	4.12	4.14
4.93	25.4	3.61	3.72	3.87	4.00	4.10	4.24	4.33
	50.8	4.26	4.31	4.40	4.47	4.53	4.60	4.65
	76.2	4.54	4.58	4.63	4.68	4.70	4.76	4.77
5.64	25.4	3.96	4.07	4.28	4.42	4.54	4.74	4.86
	50.8	4.72	4.81	4.93	5.02	5.09	5.20	5.25
	76.2	5.09	5.14	5.21	5.27	5.32	5.37	5.42
6.34	50.8	5.18	5.27	5.42	5.53	5.62	5.76	5.85
	76.2	5.62	5.67	5.78	5.85	5.92	5.99	6.04
	101.6	5.86	5.92	5.97	6.02	6.06	6.11	6.15
7.04	50.8	5.60	5.71	5.90	6.04	6.15	6.31	6.43
	76.2	6.11	6.20	6.32	6.41	6.48	6.59	6.66
	101.6	6.41	6.48	6.57	6.62	6.67	6.75	6.80
7.75	50.8	5.99	6.13	6.36	6.52	6.66	6.85	6.99
	76.2	6.60	6.69	6.85	6.97	7.06	7.19	7.27
	101.6	6.94	7.03	7.13	7.22	7.27	7.36	7.43
8.45	50.8	6.38	6.53	6.80	6.99	7.15	7.38	7.54
	76.2	7.06	7.19	7.36	7.50	7.61	7.77	7.87
	101.6	7.47	7.56	7.70	7.78	7.87	7.98	8.05

4.2.3 Accounting for Anchors

Most single wythe precast concrete panels are connected to the primary building structure by two gravity loadbearing connections and usually four additional tie-back (wind) connections. The NECB requires the heat flow through these to be considered. Although the functions of the lateral tie-back connectors can be combined with the function of the gravity load-bearing connections (thereby limiting the number and total size of connections penetrating the insulation), typical tie-back connectors result in only a small increase in thermal bridging as they commonly comprise a single threaded rod. Other connectors are used to attach each panel to the neighbouring panels. Only the connections that pass through the continuous insulation need to be considered because panel-to-panel connections do not increase heat loss.

The most practical and sufficiently accurate method of accounting for the impact of steel connections passing through precast concrete panels on overall thermal performance is to add the heat loss coefficient (that is the heat loss per degree temperature difference) from each anchor. A chi-factor (χ) (see Section 3.4) for a single anchor can be generated using a 3D computer model. The total heat flow coefficient of the system can then be calculated by adding the product of the heat flow through each anchor and the total number of anchors divided by the panel area to the previously calculated whole-wall R-value:

$$U_{ww} = 1/R_{ww} + \chi \cdot n / A \qquad \text{(Eq. 10)}$$

where,

A is the total panel area,

χ is the "chi" heat loss factor of a single anchor, and

n is the number of load-bearing anchors (typically 2).

The overall thermal resistance can then be calculated by inverting the U-value. A 3-D computer model of a generic single wythe precast anchor was generated for this guide (see Appendix B). The results are summarized in Table 10. It can be seen that the chi-factor varies with firestopping thickness.

Table 10: Chi-factor (χ) for a single generic precast anchor

Mineral Wool Firestopping Thickness		Anchor Chi (χ)	
in	**mm**	**W/K**	**Btu/F**
1	25.4	0.16	0.31
1.5	38	0.17	0.33
2	51	0.18	0.35
2.5	64	0.19	0.35
3	76	0.19	0.36
3.5	89	0.19	0.36
4	102	0.20	0.37
t > 4"	t > 102 mm	0.20	0.38

Example: The single wythe panel system described in the previous example, that is a panel with a whole-wall RSI-value of 4.03 (R-22.9, U=0.044), is hung from two steel knife-edge connections. The average panel is 12 feet (3658 mm) wide and thus a full panel has an area of 12 x 12.66 = 151.9 square feet (14.11 square metres).

The chi-factor for a knife-edge anchor with a 2" (51 mm) firestopping gap is given in Table 10 as 0.35 Btu/F (0.18 W/K). Hence, the whole-wall U-value of the panel, including two anchors is:

$$U_{ww} = 1/R_{ww} + \chi \cdot n / A$$

$$U_{ww} = 1/22.9 + 0.35 \cdot 2 / 151.9 = 0.0437 + 0.0046 = 0.0483$$

$$R_{ww} = 1/ U_{ww} = 20.7$$

Thus, in this scenario, including the anchors in the calculation would lower the R- value from 22.9 to R-20.7 (U=0.0483, RSI=3.65). This value would not quite meet the CZ5 minimum requirement (R-21.4); even a small change in window area or window performance would allow for compliance using the Trade-off Method.

There are numerous techniques that can be used to reduce the thermal impact of anchors such as encasing them in sprayed-on insulation (which may also protect them from condensation). If spray foam is used on the walls, it is common to also spray insulation over the anchor; even 1" (25 mm) of foam would reduce the heat loss through the anchor by more than half. While thermally effective, these methods must be balanced against the potential need to inspect the anchor in the future and the benefit of condensation risk reduction. Another option is the use of stainless steel for the anchors; the thermal conductivity of stainless steel is about one quarter of carbon steel and this can often have a meaningful impact on thermal performance.

A thermally problematic connection can occur if the concrete panel is supported directly on a concrete foundation wall that is not insulated on the interior. The NECB would require the thermal bridging to be accounted for at this scenario. For low-rise buildings, such as warehouses and big box stores, heat loss through this detail can comprise a significant proportion of the heat loss through the entire enclosure wall. It should be managed to avoid having to significantly increase the wall's R-value to compensate for the heat loss.

Thermal bridging can be minimized in the design at the grade transition by using precast connections similar to the anchors used at the suspended floors of high-rise buildings described above. This approach will allow the insulation to continue below grade in an unbroken manner outboard of the foundation structure. If the concrete panel must bear on the foundation wall, a 2D heat flow analysis should be conducted to quantify the impact of the particular arrangement chosen.

4.3 Double-Wythe Insulated (Sandwich) Panels

Double-wythe insulated panels provide a continuous layer of insulation encapsulated during the production process between two layers of concrete. The panels are connected to the primary building structure via the inner structural wythe. This precast component requires no additional on-site finishing work that is typically required for other enclosure systems to provide a complete building enclosure; no additional fire resistance, insulation, or airtightness is needed. A high-performance double-wythe insulated panel section is shown in Figure 17.

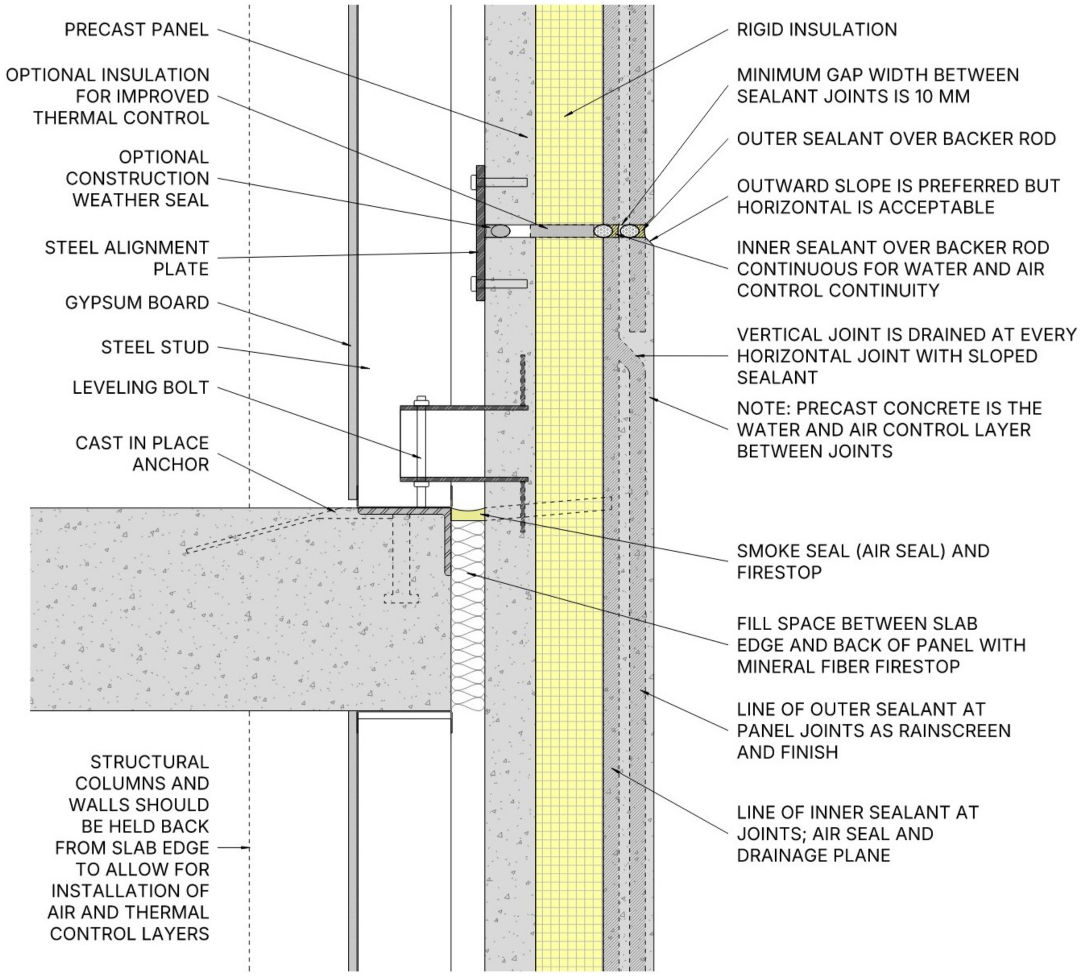


Figure 17: Section of a high-performance double-wythe insulated precast concrete panel at the floor level.

The thermal performance of modern insulated panels can be excellent, provided that the insulation layer is kept continuous and not penetrated by thickened concrete at the panel edges, cast-ins, or significant carbon steel connectors that penetrate or disrupt the continuous insulation layer. Connectors have been developed to connect the exterior layer through the insulation with a limited amount of thermal bridging over the last 30 years. Stainless-steel wire, fibreglass and carbon-fiber reinforced plastic provide a wide range of proven structural solutions with reduced impact on thermal performance.

Codes will accept the full R-value of the continuous insulation layer in most cases. However, some code officials may require evidence from the manufacturer that the connection system used does not impair the thermal performance[15].

[15] A three-dimensional computer model or full-scale test of one tie and its associated tributary area should typically be sufficient evidence

4.3.1 Clear-Wall R-value

The clear-wall R-value of a double-wythe precast panel can be calculated in the same manner as described previously for single wythe precast systems.

The clear-wall R-value of a double-wythe panel is approximately that of the insulation installed between the two layers of concrete. The concrete itself and air films only contribute a modest amount of thermal resistance, and the wire/composite connectors only reduce the performance by a little. The addition of interior framing, either hat channels or steel studs, adds little unless filled with insulation. A summary of approximate insulation values for double wythe panels using small stainless wire connectors or composite polymer connectors (two technologies with limited thermal impact) is summarized in Table 11 below as a function of insulation type and thickness.

Table 11: Approximate Whole-Wall Thermal Resistance of Double-wythe Insulated Precast Panels

	Insulation Type		
Insulation Thickness (in)	R4/in (MW/EPS)	R5/in (XPS)	R6/in (PIC)
2	9.4	11.4	13.4
2.5	11.4	13.9	16.4
3	13.4	16.4	19.4
3.5	15.4	18.9	22.4
4	17.4	21.4	25.4
4.5	19.4	23.9	28.4
5	21.4	26.4	31.4
6	25.4	31.4	37.4
8	33.4	41.4	49.4

Note: Insulation values include air films and 7" (178 mm) of concrete, but do not include interior finishes and assume inter-wythe connections have negligible impact

Insulation Thickness (mm)	k=0.036 W/mK (MW/EPS)	k=0.029 W/mK (XPS)	k=0.024 W/mK (PIC)
51	1.65	2.00	2.35
64	2.00	2.44	2.88
76	2.35	2.88	3.41
89	2.70	3.32	3.94
102	3.06	3.76	4.46
114	3.41	4.20	4.99
127	3.76	4.64	5.52
152	4.46	5.52	6.58
203	5.87	7.28	8.69

4.3.2 Whole-Wall R-value: Accounting for Anchors & Floor Slabs

The anchors and the floor slabs connecting the precast panel system to the primary building structure are entirely contained on the inside of the continuous insulation layer for double wythe insulated precast panel systems. Hence, neither condition impacts the thermal performance.

Example: What is the whole-wall R-value and U-value for a double-wythe insulated precast wall system (Figure 18) comprising a 76 mm (3") concrete outer wythe, 127 mm (5") of XPS insulation, and a 127 mm (5") concrete inner wythe. The system will span 4.42 m (14'6") from floor-to-floor. The floors are comprised of a 200 (8") deep reinforced concrete slab with 305 mm (12") deep drop-panels. A 25.4 mm (1") slab edge gap is specified as filled with mineral wool firestopping insulation.

As the double-wythe panel passes in front of the primary structural system, the details of precast to floor slab intersection, the floor-to-floor height, the firestop thickness, and attachment have no effect on the thermal performance of the enclosure.

A simple estimate, using Table 11, would be R-26.4 (RSI 4.64), for 127 mm (5") of XPS, including the benefit of air films and concrete. In practice, many such systems will have slightly lower R-values because of inter-wythe ties, and slightly higher R-values because of interior finishes (if installed).

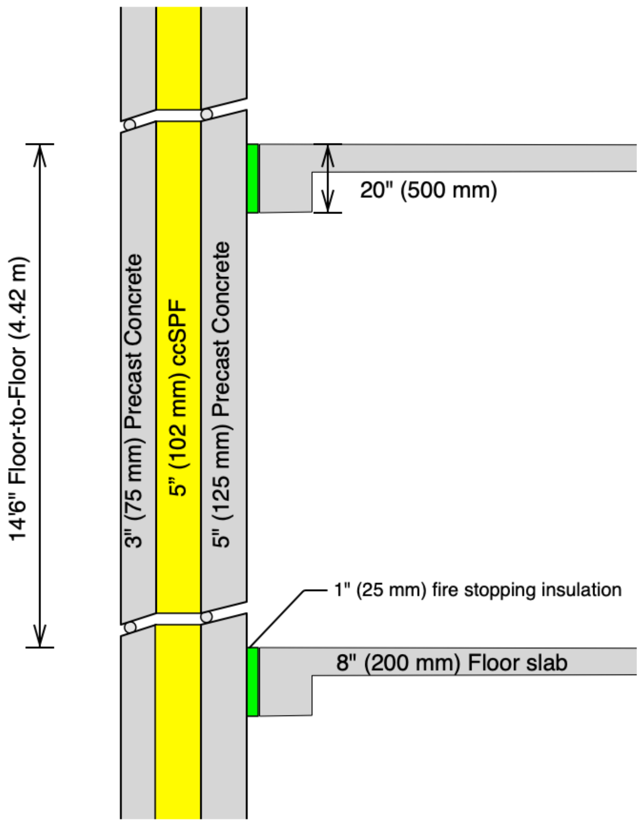


Figure 18: Example double-wythe insulated precast concrete wall panel

Such a system would meet the *prescriptive* requirements of NECB Climate Zones 4 through 7A. To achieve higher performance, thicker insulation would be needed (6" of XPS would meet up to NECB Zones 7B, and 6" of PIC would meet NECB Zone 8 requirements).

Using trade-off analysis, better windows can be used to target a true overall R-value for the vertical enclosure (see Section 3.5). For example, enclosure walls with higher FDWR ratios than prescriptively permitted in cold climate zones, such as Edmonton (HDD5120, CZ=7A, FDWR<0.33), could use the same panel design with 40% window-to-wall ratio provided the window U-value was lower than about 0.25 (U_{SI} < 1.45). Various other combinations are also possible (Figure 12).

4.4 Total Precast

Total precast systems either use the single wythe precast panel or the inner wythe of a double-wythe insulated wall panel as a vertical load-bearing element in a total system of precast floors, walls, and core elements.

Total precast double-wythe insulated wall panel systems (Figure 19) perform thermally in essentially the same manner as non-gravity-load bearing panels (Section 4.3). No additional calculations are needed as essentially all the insulation value is provided by continuous insulation outboard of the interior concrete structural support layer.

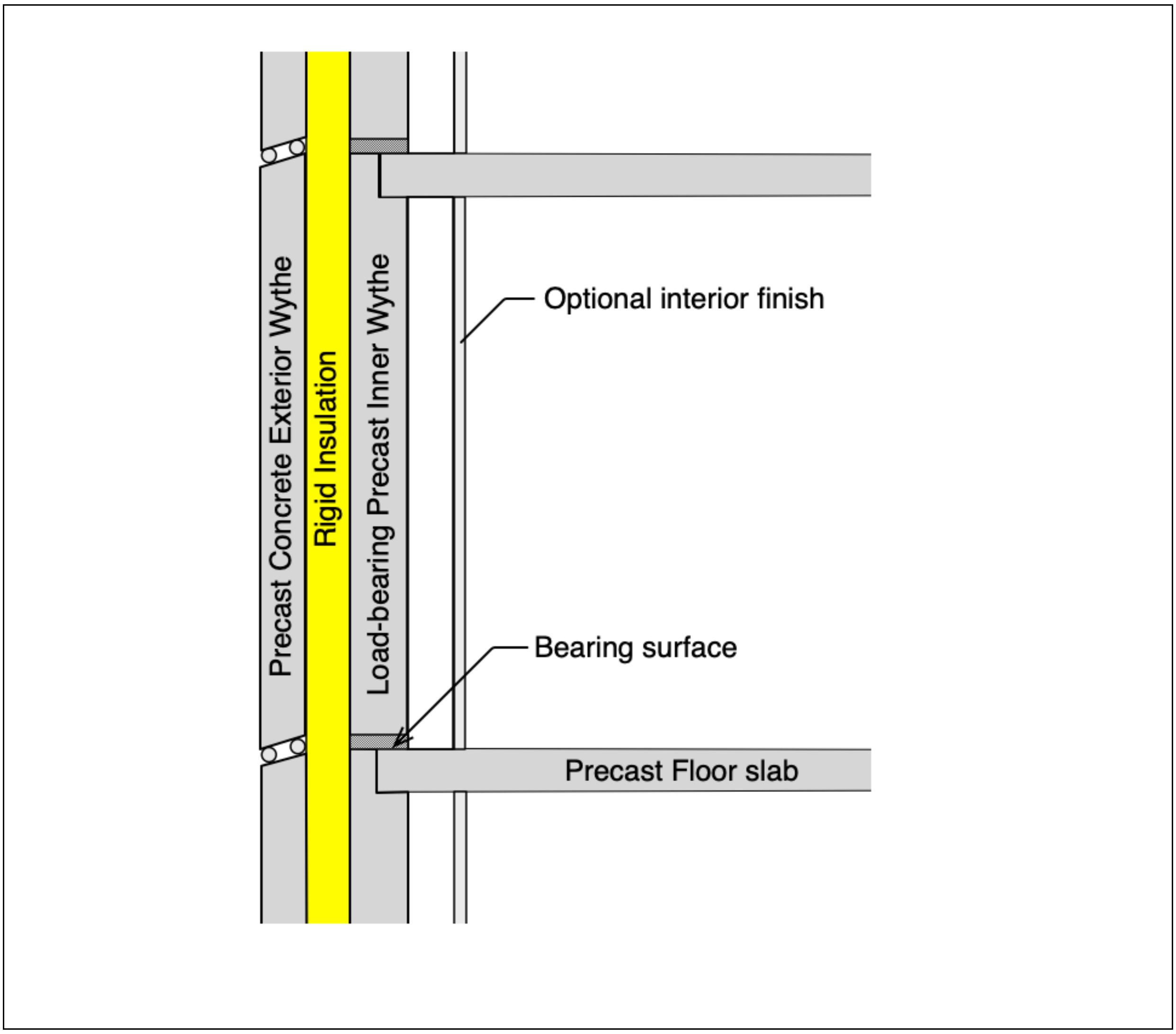


Figure 19: Double-wythe insulated total precast wall system

4.4.1 Clear-Wall R-value

The clear-wall R-value of single-wythe total precast system wall panels (Figure 20) is calculated in the same way described in Section 4.2.1 for architectural precast panels.

4.4.2 Whole-Wall R-value: Accounting for Floor Slabs

The key thermal distinction between single-wythe total precast and other precast systems lies in how heat moves through the floor-to-wall connection. Heat loss through the floor slab-wall panel load-bearing structural connection is a major thermal bridge and must be accounted for[16]. The following section describes approximate calculation methods for this condition.

[16] Floor slabs do not always bear on exterior wall panels in total precast systems: if the slab spans parallel to an exterior wall, it is practical, and thermally desirable, to provide a thermally broken joint in this location filled with fire-resistant mineral fiber insulation. There will often need to be lateral structural connections between the floor and wall, but these can resemble small discrete wall anchors similar to those that attach architectural precast panels. At this condition, the thermal performance can be evaluated using the methods outlined in Sections 4.2.2 and 4.2.3.

The whole-wall R-value for a total precast wall system including the impact of a floor system penetrating the insulation layer can be calculated in a similar manner to single wythe precast but recognizing that the floor slab is not thermally broken by the slab edge insulation. The parallel path method can be used to approximate heat flow:

$$R_{ww} = 1/\{ [(FF-T_{fl}) / FF] / R_{cw} + (T_{fl} / FF) / R_{fl} \} \quad \text{(Eq. 9)}$$

where,

R_{ww} is the whole-wall R-value of the wall panel (R-value or RSI),

FF is the floor-to-floor height (feet or metres),

T_{fl} is the floor slab thickness (feet or metres),

R_{CW} is the clear-wall R-value, and

R_{fl} is R-value of the concrete floor-to-wall assembly (R-value or RSI).

The R-value of a typical concrete slab in this application is approximately R-1.2 (RSI 0.21). This is based on two-dimensional thermal calculations for a range of concrete slabs.

Example: A total precast system (Figure 20) with a floor-to-floor height of 2.95 m (9'8") comprises an 200 mm (8") concrete wall, 75 mm (3") of mineral wool, a 90 mm (3.5") steel stud with RSI2.1 (R-13) batt, 16 (5/8") gypsum supporting a 200 mm (8") thick precast concrete hollow core slab. Calculate the clear-wall R-value and the whole-wall R-value.

Using Table 4, the interior layers can be seen to have an R-value of R-7.4, the 3" (76 mm) of mineral wool provide 3 x R-4/inch (from Table 7) = R-12 and the 8" (203 mm) of concrete provide 8 x R-0.072/inch = R-0.56 for a total clear-wall R-value of 7.4 + 12+ 0.56 = R-20.

The impact of the floor slab on the whole-wall R-value can be estimated, using Equation 10 and R-1.2 for the slab:

$$R_{ww} = 1/\{ [(FF-T_{fl}) / FF] / R_{cw} + (T_{fl} / FF) / R_{fl} \}$$

$$= 1/\{ [(9.66-0.66) / 9.66] /20 + (0.66/ 9.66) / 1.2\} = R\text{-}9.6$$

Thus, the whole-wall R-value drops from R-20 to R-9.6 because of the floor slab penetration. The floor slab can be seen to have a significant impact on the overall performance.

This system would not be compliant with any NECB prescriptive climate zone, and it is physically impossible to make up for the additional heat loss at the floor slab with any window U-value or area. Of course, the whole building approach can use an energy model to support compliance by enabling mechanical and electrical system trade-offs, potentially making the wall meet NECB requirements.

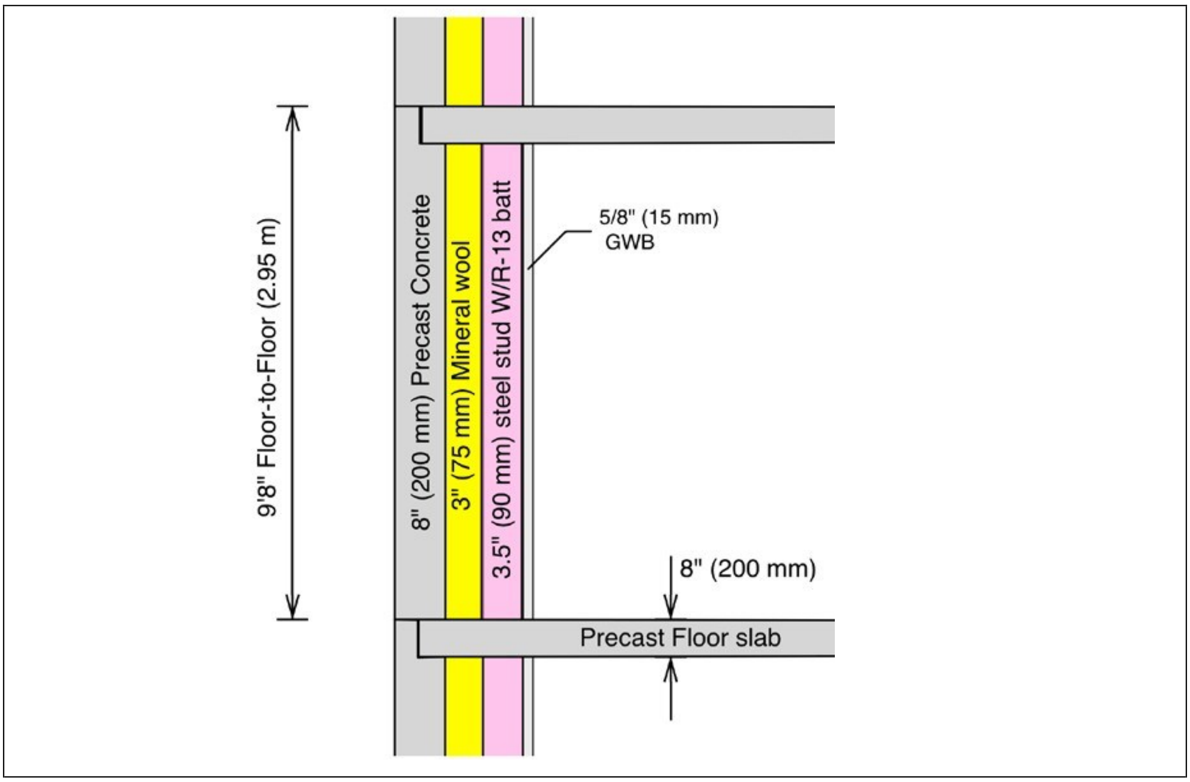


Figure 20: Example generic total precast whole-wall

The whole-wall R-value for a generic total precast system has been calculated using the principles described for systems with an 8" (203 mm) concrete floor slab, an 8" (203 mm) thick concrete wall panel, and a range of different of floor-to-floor heights and clear-wall R-values. The results are shown in Table 12.

Table 12: Approximate Generic Total Precast Whole-Wall R- and RSI-values with no slab edge insulation

	Floor-to-Floor (ft)				
***R**$_{ww}$*	**9**	**9.66**	**11**	**12**	**16**
5	4.0	4.1	4.2	4.3	4.4
7.5	5.4	5.5	5.7	5.8	6.2
10	6.5	6.6	6.9	7.1	7.7
12.5	7.4	7.6	8.0	8.2	9.0
15	8.1	8.4	8.8	9.2	10.1
17.5	8.7	9.0	9.6	10.0	11.2
20	9.3	9.6	10.3	10.7	12.1
25	10.1	10.6	11.4	11.9	13.7
30	10.8	11.3	12.2	12.9	15.0
35	11.3	11.9	12.9	13.6	16.1
40	11.8	12.4	13.5	14.3	17.0
	Floor-to-Floor (m)				
***RSI**$_{ww}$*	**2.74**	**2.94**	**3.35**	**3.66**	**4.88**
0.88	0.71	0.72	0.74	0.75	0.78
1.32	0.95	0.97	1.00	1.02	1.08
1.76	1.1	1.2	1.2	1.3	1.3
2.20	1.3	1.3	1.4	1.4	1.6
2.64	1.4	1.5	1.6	1.6	1.8
3.08	1.5	1.6	1.7	1.8	2.0
3.52	1.6	1.7	1.8	1.9	2.1
4.40	1.8	1.9	2.0	2.1	2.4
5.28	1.9	2.0	2.2	2.3	2.6
6.16	2.0	2.1	2.3	2.4	2.8
7.04	2.1	2.2	2.4	2.5	3.0

Relatively simple changes to the design of the slab edge can improve the thermal performance. For example, the slab edge that penetrates through the interior insulation layer can be insulated, as shown in Figure 21. The bearing area, assumed to be 3” (76 mm), still contributes to heat flow, but the edge of slab heat flow path can be severely reduced using this detail.

A series of 2-D finite-element thermal modeling runs were undertaken to develop the psi-factor (refer to Section 3.4 Calculating Thermal Bridging Impacts) for this more complex heat flow path. The psi-factor was found to be approximately 0.775 W/K for the range of typical enclosure wall insulation thicknesses. The results for this approach (Table 13) show that the thermal performance is modestly better than the detail with no slab edge insulation.

> **Example**. A single-wythe total precast wall system with 50 mm (2”) of XPS insulation, a floor-to-floor height of 3.048m (10’), and RSI4.40 (R-25) clear-wall insulation is proposed for a residential building. What is the whole-wall R-value of this system?
>
> The edge insulation has an R-value of 10 (RSI 1.76), hence Table 13 can be used. The results show an estimated whole-wall R-value of 11.8 (RSI 2.08). Again, this design would not meet

the NECB prescriptive or trade-off methods, even if a true R-40 of interior insulation were to be installed.

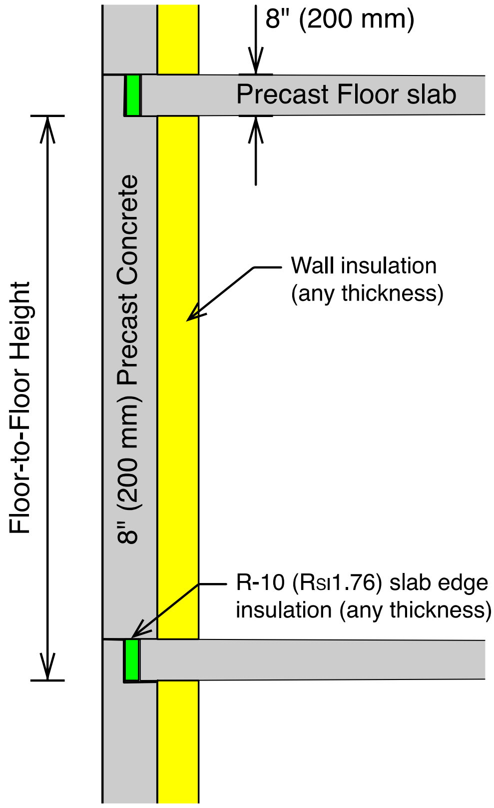


Figure 21: Single-wythe total precast system with slab edge insulation assumed for calculations in Table 13.

An alternate insulated corbel system was also calculated which showed somewhat better performance but none of the scenarios, even those with clear-wall performance of R-40, met the lowest prescriptive requirement of the NECB. This system and the results are described in more detail in Appendix D.

Table 13: Approximate Generic Total Precast Whole-Wall R- and RSI-values for Insulated Slab Edge Design with R10 slab edge insulation.

			Floor-to-floor (ft)		
R_{ww}	**9**	**9.66**	**11**	**12**	**16**
5	4.0	4.1	4.2	4.2	4.4
7.5	5.5	5.6	5.7	5.9	6.2
10	6.7	6.8	7.1	7.3	7.8
12.5	7.7	7.9	8.3	8.5	9.3
15	8.6	8.8	9.3	9.6	10.6
17.5	9.4	9.7	10.2	10.6	11.7
20	10.0	10.4	11.0	11.5	12.8
25	11.1	11.6	12.4	12.9	14.7
30	12.0	12.5	13.5	14.2	16.3
35	12.8	13.3	14.4	15.2	17.7
40	13.4	14.0	15.2	16.0	18.9
			Floor-to-Floor (m)		
RSI_{ww}	**2.74**	**2.94**	**3.35**	**3.66**	**4.88**
0.88	0.71	0.71	0.73	0.74	0.77
1.32	0.96	0.98	1.01	1.03	1.09
1.76	1.2	1.2	1.3	1.3	1.4
2.20	1.4	1.4	1.5	1.5	1.6
2.64	1.5	1.6	1.6	1.7	1.9
3.08	1.6	1.7	1.8	1.9	2.1
3.52	1.8	1.8	1.9	2.0	2.3
4.40	2.0	2.0	2.2	2.3	2.6
5.28	2.1	2.2	2.4	2.5	2.9
6.16	2.2	2.4	2.5	2.7	3.1
7.04	2.4	2.5	2.7	2.8	3.3

5 Worked Examples of Precast Systems

The NECB requires almost all thermal bridging to be considered. For a typical building project (Figure 22) the details that must be considered (i.e., the heat loss quantified) include the window and door head, jamb, sill, parapet, at-grade transition, and soffit and balcony (if any). The relative impact of these details depends not only on their design, but also on the relative proportion of each. For example, the parapet and at-grade transitions will be much more important for low-rise buildings than high-rise, whereas the window details will often be the most important detail for multi-storey residential buildings, while having little effect on a warehouse.

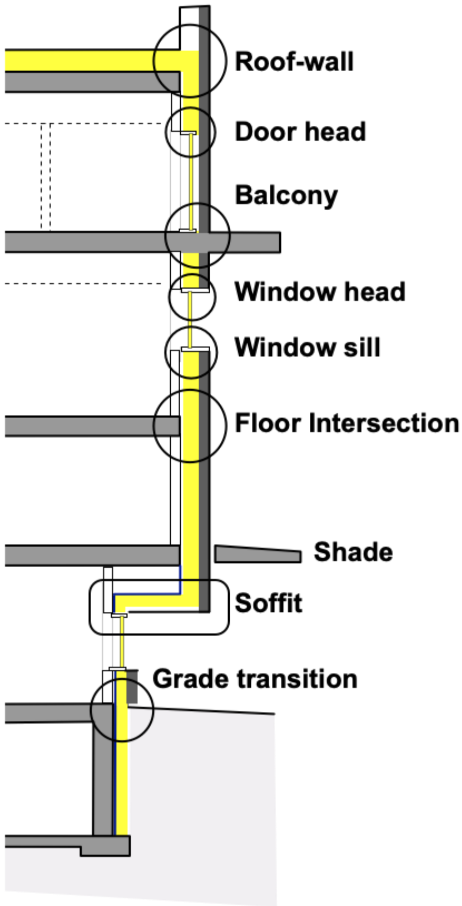


Figure 22: Common details in building projects

The information presented in Chapters 3 and 4 allow for an estimate of the whole-wall R-value of a precast enclosure wall system. However, only the thermal bridges at floor slabs and panel anchors have been accounted for. The NECB requires all thermal bridging be accounted for. There is a growing body of knowledge that can aid in the prediction of the other thermal bridging. The *BC Hydro Thermal Bridging Guide* (conveniently available at www.thermalenvelope.ca) is recommended and will be used as a primary reference.

> **Example**. A 6.1m (20 ft) by 2.95 m (9'8") tall double wythe insulated precast wall panel with a clear-wall R-value of 20 has two aluminum windows installed as shown in Figure 23. Calculate the thermal bridging impact of the installation details using the *BC Hydro Thermal Bridging Guide.*

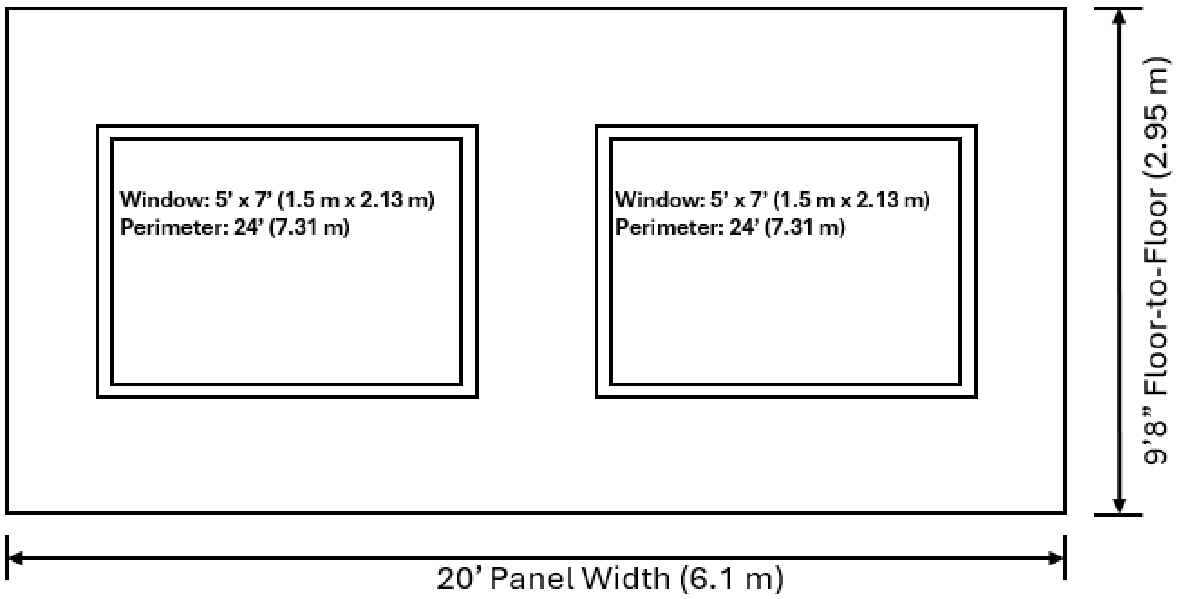


Figure 23: Example Precast Panel with punched window openings

An example of the type of data available is shown in Figure 24 for an aluminum window installed in a precast panel. The window installation can be a significant source of thermal bridging if care is not considered in design.

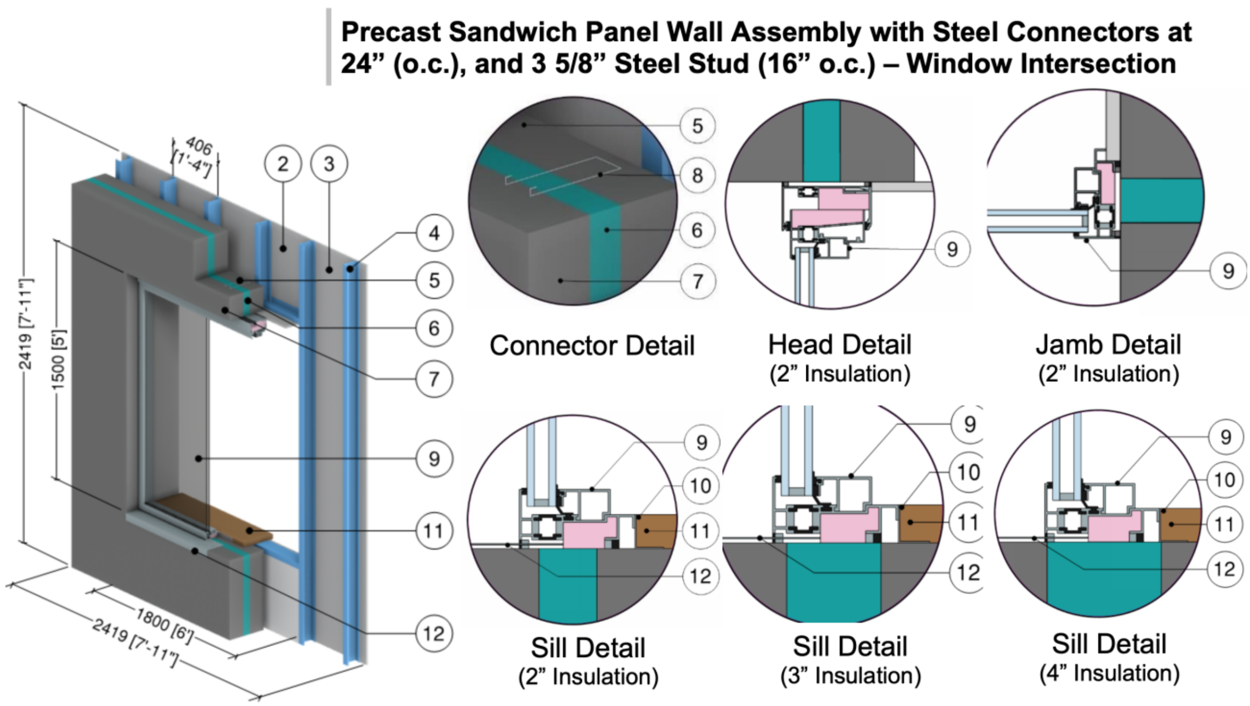


Figure 24: Window installation details for a double wythe precast wall panel (from thermalenvelope.ca)

This panel has a calculated Fenestration-and-Door-to-Wall Ratio (FDWR) of 36%. The data summarized in the table provides linear transmittance values for the heat loss through the head, jamb and sill.

Table 14: Thermal results for window details (from thermalenvelope.ca)

Sandwich Panel Insulation 1D R-Value (RSI)	R_t ft²·hr·°F / Btu (m² K / W)	U_t Btu/ft² ·hr ·°F (W/m² K)	ψ_h Btu/ft ·hr ·°F (W/m K)	ψ_l Btu/ft ·hr ·°F (W/m K)	ψ_j Btu/ft ·hr ·°F (W/m K)	ψ_g Btu/ft ·hr ·°F (W/m K)
R-10 (1.76)	5.2 (0.92)	0.192 (1.09)	0.051 (0.089)	0.024 (0.042)	0.021 (0.036)	0.031 (0.054)
R-15 (2.64)	5.7 (1.00)	0.176 (1.00)	0.048 (0.082)	0.025 (0.042)	0.015 (0.025)	0.026 (0.044)
R-20 (3.52)	6.1 (1.07)	0.164 (0.93)	0.033 (0.057)	0.024 (0.043)	0.013 (0.022)	0.017 (0.029)

In general, Equation 7 (see Chapter 3 of this report), with tabulated coefficients, is used to produce whole-building estimates:

$$U_{ww} = \frac{\frac{A_{wall}}{R_{CW}} + \Sigma\,(\Psi \cdot L_i) + \Sigma(X_j \cdot n_j)}{A_{wall}} \qquad \text{(Eq. 7)}$$

where,

A_{wall} is the total area of the opaque components,

Ψ_i is the linear heat transmittance value of detail “i”,

L_i is the total length of the linear detail “i” in the analysis area,

χ_j is the point heat transmittance value of detail “j”, and

n is the number of point thermal bridges of type “j” in the analysis area.

In this example, the panel area is 193.2 ft² (17.96 m²), the opaque area is 123.2 ft² (11.45 m²), and the clear-wall R-value is given as R-20 (RSI 3.52). The only thermal bridges we are including here (assuming inter-wythe connectors have been included in the clear-wall R-value) are the window installation details. The window frame and glazing heat flow should be included in the window U-value. Hence, the additional heat flow due to the installation detail is the sum of the head, jamb and sill details.

From the dimensions given, the total length of the sill and the head are 14 feet (4.27 m) each, and the total jamb length is 20 ft (6.1 m). The whole-wall U-value can be found from:

$$U_{ww} = \frac{\frac{A_{wall}}{R_{CW}} + \Sigma\,(\Psi \cdot L_i) + \Sigma(X_j \cdot n_j)}{A_{wall}}$$

$$= \frac{\frac{123.2}{20} + (14*0.033 + 14*0.024 + 20*0.013)}{123.2}$$

= 6.16 + (0.462 + 0.336 + 0.26) / 123.2 = 7.214 / 123.2

= 0.0586

Thus, the whole-wall R-value can be estimated to be R-17.06 (RSI3.00).

The BC Hydro guide does not provide values for panels with higher clear-wall thermal resistance. However, it can be seen that the psi-factors given in Table 13 for this example decrease slightly with increasing panel R-value. Hence, it is reasonable and conservative to apply these same factors to a wall with higher thermal resistance. Thus, if the clear-wall R-value of a panel was assumed to be 26, the whole-wall U-value would be expected to be less than 0.047 or R-21.2.

The calculations show that these window frame installation details reduce the clear-wall R-value by over 15%.

Parapets are another common thermal bridge that must be considered in almost all projects. Parapets play an especially important role in low-rise building projects because the impact of the parapet is distributed over a small wall area.

> **Example**. A 24 ft tall (7.32 m) single wythe precast concrete panel covers the walls of a warehouse building with a 22 ft clear interior height. The clear-wall R-value of the panel is 20. Calculate the thermal bridging impact of the installation details using the *BC Hydro Thermal Bridging Guide.*
>
> The detail most similar to the example is taken from the BC Hydro Thermal Bridging Guide and reproduced below (Figure 25 and Table 15). The psi-factor is presented as 0.334 BTU/hr ft °F. To provide a more general answer that is useful in early-stage design, the results will be calculated for a linear length of one foot. The height of the insulated enclosure will vary and depends on details of the roof slab and parapet projection. In this case it is convenient to assume an enclosure height of 23 feet.

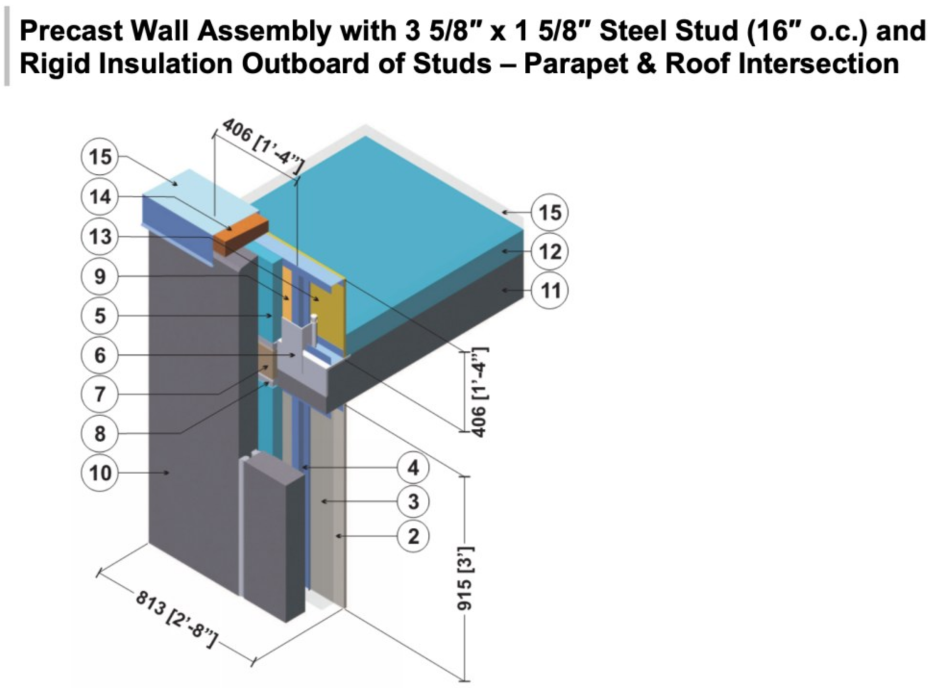
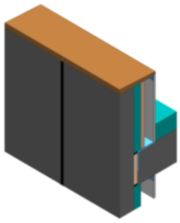


Figure 25: Parapet detail of single-wythe panel (Detail 7.5.6 from thermalenvelope.ca)

Table 15: Thermal results for parapet details (from thermalenvelope.ca)

Parapet Linear Transmittance

R ft²·hr·°F / Btu (m² K / W)	U Btu/ft² ·hr ·°F (W/m² K)	ψ Btu/ft hr °F (W/m K)
R-9.1 (1.60)	0.110 (0.63)	0.334 (0.579)



The whole-wall U-value can be found from:

$$U_{ww} = \frac{\frac{A_{wall}}{R_{cw}} + \Sigma\,(\Psi \cdot L_i) + \Sigma\left(X_j \cdot n_j\right)}{A_{wall}}$$

$$= \frac{\frac{23}{20} + (1 * 0.334)}{23}$$

= 1.15 + (0.334) / 23 = 1.484 / 23

= 0.0645

Hence, the windowless panel R-value would be R-15.5.

It is worth noting that the current BC Hydro Guide has 800 details, but no detail of a single-wythe precast wall panel meeting grade. Provided that the design of the at-grade transition ensures that the rigid insulation used on the inside of the precast panel is carried in a continuous manner down below-grade for 1.2 m or more (Figure 26), there would be little thermal bridging, hence, it could be ignored in early-stage design.

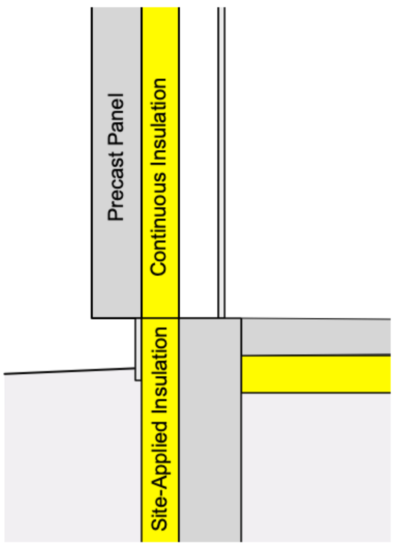


Figure 26: Conceptual design for continuous insulation at-grade transition

Provided the entire building has a modest FDWR of less than 10% (common and practical for warehouse, workshop, and big box stores), this precast panel could meet the prescriptive requirements in Climate Zones of up to CZ7A.

6 Summary

Building codes, standards, and building owners are increasing their demands for better performing buildings. Modern codes provide a number of different compliance paths, allowing for a wide range of enclosure R-values to meet and exceed the performance requirements.

To properly estimate the actual thermal resistance of enclosure wall systems requires a better understanding of and an avoidance of thermal bridging. This guide has presented the concepts at an introductory level for use in the early-stage design of precast concrete enclosure systems.

Users should approach the guide by first calculating the clear-wall R-value for the system and floor-to-floor height they are considering, including thermal bridging of light-gauge steel framing and floor slab intersections. The insulation thickness and type can be adjusted as needed so that the calculated value meets target design values or code minimums. For prescriptive design, these values are sufficient, but alternate code compliance paths may make use of the values calculated for the selected enclosure design.

The methods presented are not onerous to use, and sufficiently accurate for early-stage design decisions. More detailed computer-based modeling will often be justified for more complex systems, more accurate results, and final design values.

The examples presented throughout the guide demonstrate that there are many ways for precast concrete enclosure systems to deliver high levels of thermal performance, often more easily and more economically than other types of enclosure systems.

7 References & Guidance Documents

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Appendix A: Assumptions for Thermal Calculations

The choice of thermal conductivity of materials is of course critical to the results. Although ASHRAE, NBCC, Chartered Institute of Building Services Engineers, US National Institute of Science and Technology, and others provide tables of thermal conductivity for many materials, slight variations in manufacturer, moisture content, and age can make small differences in conductivity. Materials such as masonry and concrete have particularly large variations. Even steel, a common material that is important to thermal bridging, has a range of reported conductivity (k = 45 to 60 W/mK for carbon steel). Because of these variations, it is important that the values used in any analysis be well documented.

The R-value of standard concrete is low, so low that it can often be ignored. The value used in this guide will be the same as that used in recent ASHRAE work (ASHRAE 1365). Concrete weighs, *without* steel, about 140 pcf (2250 kg/m^3). The addition of steel reinforcing increases the density and the thermal conductivity along the length of the steel. The American Concrete Institute's ACI 122 suggests a thermal conductivity for standard density limestone aggregate concrete of 9.86 Btu/hr/ft^2/in F (k = 1.4 W/m K). This value is used by National Concrete Masonry Association (NCMA) Thermal Guide (NCMA 2012). This is lower than most design values, which assume the concrete contains steel and is damp. A value of k=2.4 W/mK was assumed in this guide, as it is closer to the value quoted in the National Building Code of Canada Appendix.

The properties of insulation, of course, have the largest impact on the overall results. It is recommended that material properties be taken at standard North American rating conditions of a mean of 24°C (75°F) as these are the most commonly available. The guide provides tables of common categories of insulation, but some products (particularly mineral wool and fiberglass) can vary significantly from one product to another.

The transfer of heat across airspaces and from surfaces to the surrounding environment is complex. Standard practice, accepted by codes, is to assign an equivalent conductance to a fictitious layer termed the "air film". The ASHRAE Handbook of Fundamentals provides recommended values (summarized in Table 2) intended for design conditions. For most practical cases, a value of R-0.85 or RSI 0.15 should be assumed for the combined effect of both interior and exterior films.

A detailed table of numerous factors affecting heat transfer across airspaces is provided in Table 3 of Chapter 26 of the ASHRAE Handbook (ASHRAE 2021). The value for heat transfer given for a mean temperature of 10°C with a temperature difference of 16.7°C is recommended for basic analysis. For more detailed work, enclosed air spaces within curtainwall and window framing can be calculated using ISO 10077 and ASHRAE recommendations.

Appendix B: Single Wythe Precast Concrete Panel - Thermal Model

The three-dimensional computer heat flow simulation program HEAT3 v7.0 was used to develop thermal conductance values for a number of thermal bridges, shown graphically in Figures B1 and B2. The resulting psi- and chi-factors are reported in Table B1 below.

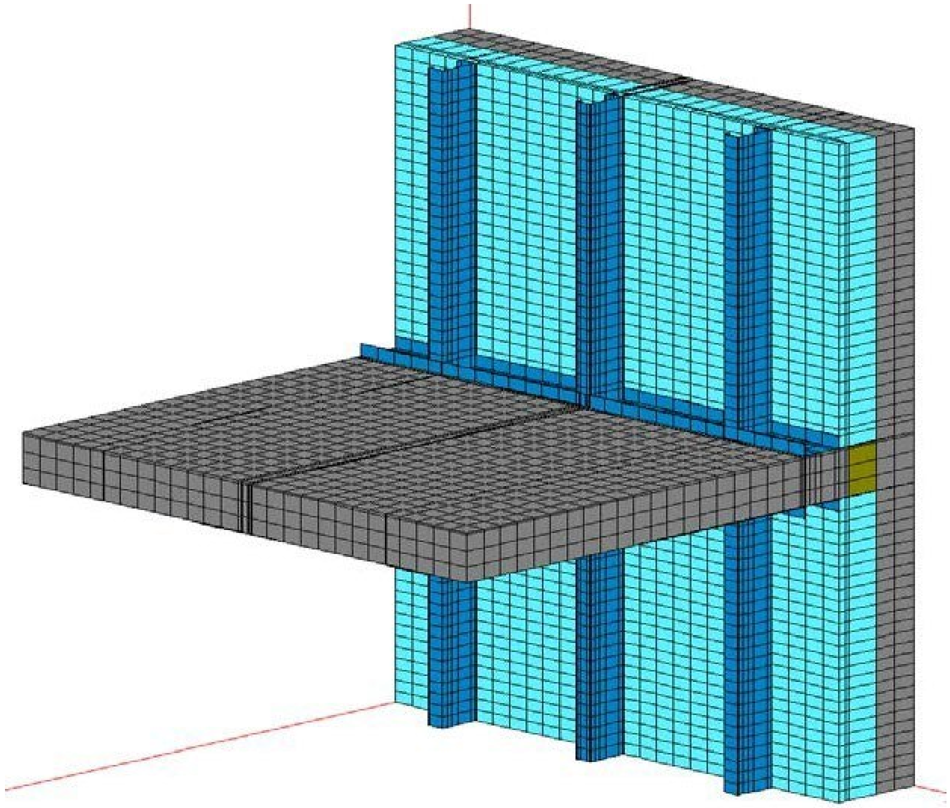
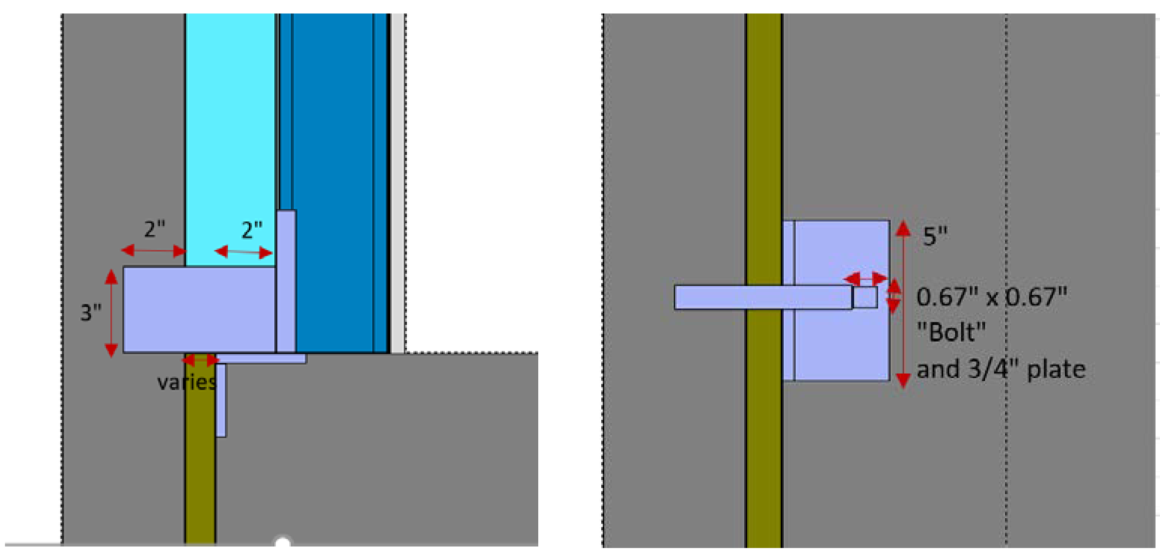


Figure B1: Finite volume model used to assess heat flow at anchors.



Note: 1" =25.4 mm

Figure B2: Vertical and horizontal section of generic precast anchor (extend precast anchor another 2" into the panel

Table B1: Summary of Single Wythe Precast Anchor and Floor Slab Thermal Bridge Results

	Insulation Thickness	Firestopping Gap Thickness	Clear-wall U (W/m²K)	Psi (Ψ) (W/mK) Slab	Chi(χ) (W/K) Anchor
Continuous Insulation ccSPF (k=0.024 W/mK) w/ Slab Edge Insulation (k=0.036 W/mK)	3" (76 mm)	1" (25 mm)	0.278	0.178	0.184
		2" (51 mm)		0.072	0.196
		3" (76 mm)		0.032	0.199
	4" (102 mm)	1" (25 mm)	0.214	0.195	0.168
		2" (51 mm)		0.089	0.198
		3" (76 mm)		0.047	0.199
		4" (102 mm)		0.024	0.200
	6" (152 mm)	1" (25 mm)	0.148	0.211	0.143
		2" (51 mm)		0.109	0.168
		3" (76 mm)		0.066	0.175
		4" (102 mm)		0.041	0.184
Continuous Insulation Stone Wool (k=0.036 W/mK) w/ Slab Edge Insulation (k=0.036 W/mK)	3" (76 mm)	1" (25 mm)	0.394	0.158	0.175
		2" (51 mm)		0.052	0.188
		3" (76 mm)		0.012	0.191
	4" (102 mm)	1" (25 mm)	0.307	0.181	0.162
		2" (51 mm)		0.074	0.191
		3" (76 mm)		0.030	0.193
		4" (102 mm)		0.007	0.194
	6" (152 mm)	1" (25 mm)	0.215	0.204	0.137
		2" (51 mm)		0.101	0.163
		3" (76 mm)		0.056	0.170
		4" (102 mm)		0.029	0.212

The thermal bridge factors can be used to calculate the whole-wall U-value using the following equation:

$$U_{ww} = [U_{cw} * A + \psi * w + \chi * n] \qquad \text{(Eq. 11)}$$

where,

U_{ww}= whole-wall thermal transmittance [W/m² °C],

n = number of anchors (2 in most cases),

w = width of the precast panel [m],

A = area of panel [m²],

ΔT = temperature difference from inside to outside,

U_{CW} = clear-wall thermal transmittance [W/m²K], and

A = width * height of the panel [m²].

Appendix C: Supplementary Tables

Table C1: Whole-Wall RSI Values for Single Wythe Precast Panels for 204 mm Deep Floor Slabs (SI)

203 mm floor slabs		**Floor-to-floor height (m)**						
RSI_{cw}	**Slab edge insulation (mm)**	**2.7**	**3.0**	**3.7**	**4.3**	**4.9**	**6.1**	**7.3**
0.37	25	0.39	0.38	0.38	0.38	0.38	0.38	0.38
	51	0.39	0.39	0.39	0.38	0.38	0.38	0.38
1.30	25	1.25	1.26	1.26	1.27	1.27	1.28	1.28
	51	1.32	1.32	1.32	1.31	1.31	1.31	1.31
1.50	25	1.41	1.42	1.43	1.44	1.45	1.46	1.46
	51	1.50	1.50	1.50	1.50	1.50	1.50	1.50
1.76	25	1.63	1.64	1.66	1.67	1.68	1.70	1.71
	51	1.75	1.75	1.75	1.75	1.75	1.75	1.76
2.11	25	1.90	1.92	1.95	1.97	1.99	2.01	2.03
	51	2.06	2.07	2.07	2.08	2.08	2.09	2.09
2.47	25	2.15	2.18	2.22	2.26	2.28	2.32	2.34
	51	2.37	2.37	2.39	2.40	2.41	2.42	2.43
2.82	25	2.40	2.43	2.49	2.53	2.56	2.61	2.64
	51	2.66	2.68	2.70	2.71	2.73	2.74	2.76
3.17	25	2.63	2.67	2.74	2.80	2.84	2.90	2.94
	51	2.95	2.97	3.00	3.02	3.04	3.07	3.08
3.52	25	2.85	2.90	2.99	3.06	3.11	3.18	3.23
	51	3.22	3.25	3.29	3.32	3.35	3.38	3.40
4.23	25	3.25	3.33	3.45	3.54	3.62	3.72	3.80
	51	3.75	3.80	3.86	3.91	3.95	4.00	4.04
4.93	25	3.62	3.72	3.88	4.00	4.10	4.24	4.34
	51	4.25	4.31	4.41	4.47	4.53	4.60	4.65
	76	4.55	4.58	4.64	4.68	4.71	4.75	4.78
5.64	25	3.96	4.08	4.27	4.43	4.55	4.73	4.86
	51	4.73	4.80	4.93	5.02	5.09	5.19	5.26
	76	5.09	5.14	5.22	5.27	5.32	5.38	5.42

Table C2: Whole-Wall RSI values for Single Wythe Precast Panels for 305 mm Deep Floor Slabs (SI)

305 mm floor slabs		Floor-to-floor height (m)						
RSI_{cw}	Slab edge insulation (mm)	2.7	3.0	3.7	4.3	4.9	6.1	7.3
0.37	25	0.39	0.39	0.39	0.39	0.38	0.38	0.38
	51	0.40	0.40	0.39	0.39	0.39	0.38	0.38
1.30	25	1.23	1.23	1.25	1.25	1.26	1.27	1.27
	51	1.33	1.33	1.32	1.32	1.32	1.31	1.31
1.50	25	1.38	1.39	1.40	1.42	1.43	1.44	1.45
	51	1.50	1.50	1.50	1.50	1.50	1.50	1.50
1.76	25	1.57	1.59	1.61	1.63	1.65	1.67	1.68
	51	1.74	1.74	1.74	1.75	1.75	1.75	1.75
2.11	25	1.81	1.83	1.87	1.91	1.93	1.96	1.99
	51	2.03	2.04	2.05	2.06	2.07	2.08	2.08
2.47	25	2.03	2.06	2.12	2.16	2.20	2.25	2.28
	51	2.32	2.33	2.35	2.37	2.38	2.40	2.41
2.82	25	2.23	2.28	2.35	2.41	2.45	2.52	2.56
	51	2.59	2.61	2.64	2.67	2.68	2.71	2.73
3.17	25	2.42	2.48	2.57	2.64	2.70	2.78	2.84
	51	2.85	2.88	2.92	2.95	2.98	3.02	3.04
3.52	25	2.60	2.67	2.78	2.87	2.93	3.04	3.11
	51	3.09	3.13	3.19	3.23	3.27	3.32	3.35
4.23	25	2.91	3.01	3.16	3.28	3.37	3.51	3.62
	51	3.56	3.61	3.70	3.77	3.82	3.90	3.95
4.93	25	3.19	3.31	3.50	3.65	3.78	3.96	4.10
	51	3.98	4.06	4.18	4.28	4.35	4.45	4.53
	76	4.38	4.43	4.50	4.56	4.60	4.67	4.71
5.64	25	3.44	3.58	3.81	4.00	4.15	4.38	4.55
	51	4.37	4.47	4.63	4.75	4.85	4.99	5.09
	76	4.86	4.93	5.03	5.11	5.17	5.26	5.32

Appendix D: Load-bearing Single Wythe Results

There are numerous emerging techniques to improve the thermal performance of loadbearing single-wythe precast systems. One insulated slab edge solution was presented in the main body of the guide. Another solution involving insulated corbels was investigated using thermal modeling.

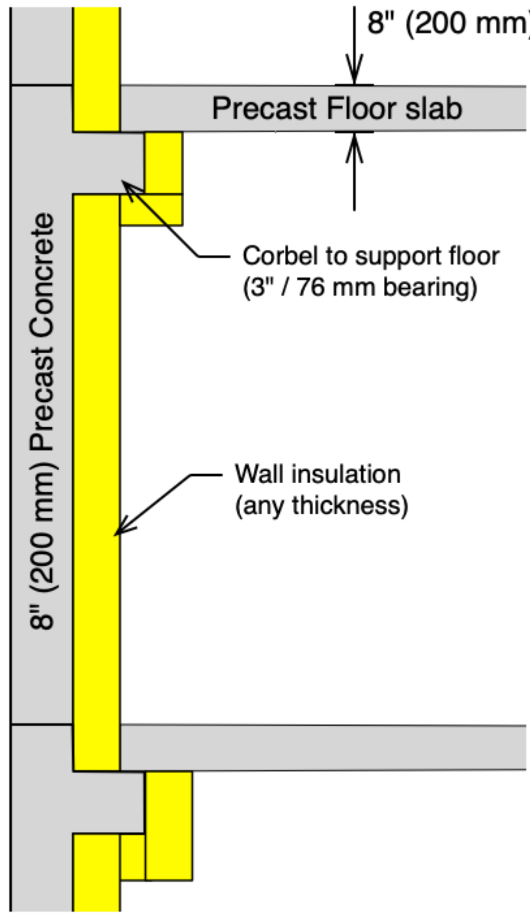


Figure D1: Alternate insulated slab edge solution.

The corbel was assumed to be 8" (200 mm) deep and insulated in the same manner as the wall. The same 8" (200 mm) hollowcore precast floor slabs were assumed as for other solutions. A critical detail for the thermal performance of the corbel is the nature of the bearing (assumed to be grout and thin fibreboard in this example) and the amount of steel connecting the floor to the wall. No steel has been considered in the results presented below, but even modest amounts of steel connecting the interior floor to the exterior wall may reduce the R-value. The use of fibre composite reinforcing bars and polymer-based bearing pads can be investigated as project-specific methods of reducing heat transfer.

An example of the thermal gradients and geometry modelled is shown in Figure D2.

The results suggest a psi-factor of about 0.480 W/mK. Of course, there are modest variations with insulation thickness and type, but this psi value approximated a range of realistic solutions between 50 and 125 mm of insulation. These results are presented in a tabular format below for interested users.

One conclusion from this investigation is that meeting the prescriptive NECB minimum requirement including all of the thermal bridging is very challenging. Even with a clear-wall R-value of R-40 (requiring nearly 6" of ccSPF plus an insulated steel stud wall), the overall R-value for a floor-floor height of 9 or 10 ft, would not meet the CZ4 requirements. However, for buildings with small FDWR the trade-off method may allow some designs to pass.

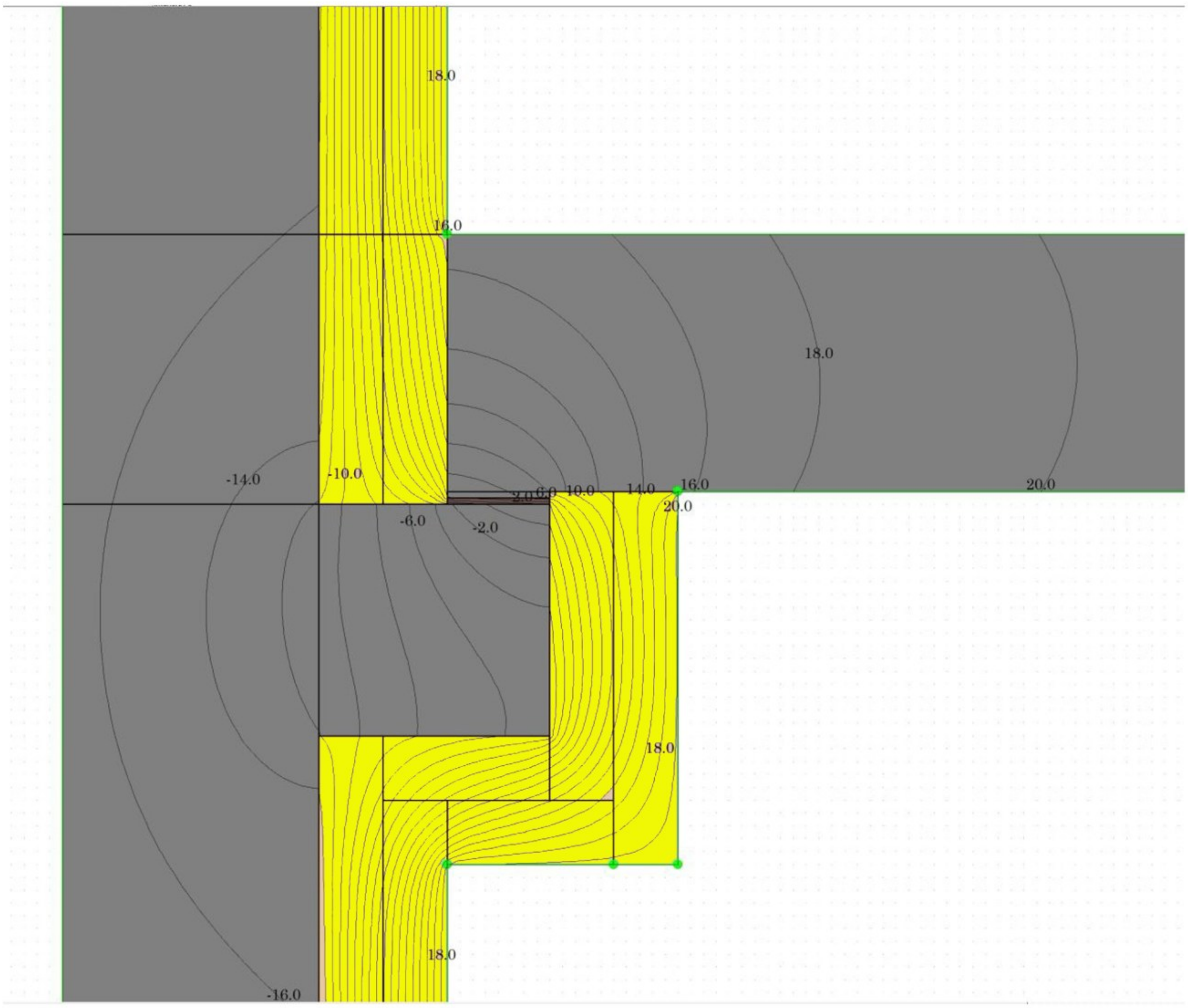


Figure D2: Example of insulated corbel total precast system geometry and isotherms

Table D1: Whole-Wall R-values and RSI-values for Insulated Corbel Approach

	Floor-to-floor (ft)				
Clear-wall R_{cw}	**9**	**10**	**11**	**12**	**16**
5	4.3	4.4	1.8	1.8	4.6
7.5	6.1	6.2	6.3	6.4	6.6
10	7.6	7.8	8.0	8.1	8.5
12.5	9.0	9.3	9.5	9.7	10.3
15	10.3	10.6	10.9	11.1	11.9
17.5	11.4	11.8	12.1	12.5	13.4
20	12.4	12.9	13.3	13.7	14.9
25	14.1	14.8	15.3	15.8	17.4
30	15.6	16.4	17.1	17.7	19.7
35	16.8	17.8	18.6	19.4	21.8
40	17.9	19.0	19.9	20.8	23.6
	Floor-to-floor (m)				
Clear-wall RSI_{cw}	**2.74**	**3.05**	**3.35**	**3.66**	**4.88**
0.88	0.76	0.77	0.78	0.79	0.81
1.32	1.07	1.09	1.11	1.13	1.17
1.76	1.35	1.38	1.41	1.43	1.50
2.20	1.59	1.64	1.67	1.71	1.81
2.64	1.81	1.87	1.92	1.96	2.10
3.08	2.00	2.08	2.14	2.19	2.37
3.52	2.18	2.27	2.34	2.41	2.62
4.40	2.49	2.60	2.70	2.79	3.07
5.28	2.74	2.88	3.01	3.12	3.48
6.16	2.96	3.13	3.27	3.41	3.84
7.04	3.15	3.34	3.50	3.66	4.16

Appendix E: Double Wythe Insulated Wall Panel Inter-wythe Connections

Double wythe wall panels inherently provide continuous insulation, provided the design does not have thickened concrete edges. These designs have become standard in Canada. However, the inter-wythe connectors do conduct some heat through the continuous insulation. It may be necessary to calculate their impact on the whole-wall R-value.

Connectors made of glass- or carbon-fiber reinforced polymers have low thermal conductivity (usually in the range of 0.5 to 1.0 W/mK). Light-gauge (under ¼" / 6 mm diameter) stainless steel wire-based trusses and connectors generally decrease the thermal performance more than polymer-based connectors, but their high strength may allow for fewer and smaller penetrations, thereby minimizing thermal impacts. Plain and galvanized steel connectors have the largest thermal impact (carbon steel has four times the thermal conductivity of stainless steel) but, again, the exact details matter.

The thermal impact of discrete inter-wythe connectors is best calculated using the point thermal bridge methods described in the report. However, finding published chi data for inter-wythe anchors is currently difficult, and project-specific modeling may be needed.

Example: Estimate the thermal impact of 3/8" diameter glass-reinforced polymer inter-wythe connectors used to connect two 3" concrete wythes together through 4" of XPS. The manufacturer provides a chi-factor for each connector of 0.0015 W/K (0.00285 BTU/(h F)). The panel is 8' (2.4 m) wide and 10' 8" (3.25 m) high (an area of 85.3 square feet or 7.92 square meters). The structural capacity of the connector requires a spacing of 12" (300 mm) horizontally and 24" (600 mm) vertically (*Figure 27*).

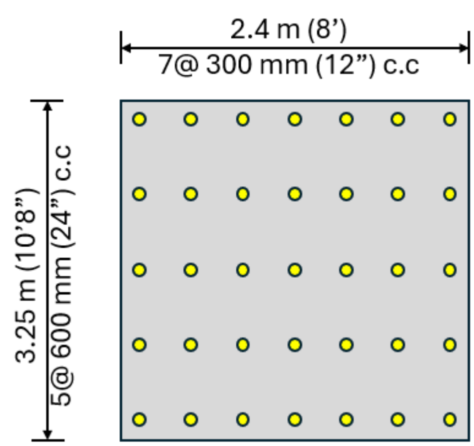


Figure 27: Example Inter-wythe connector layout

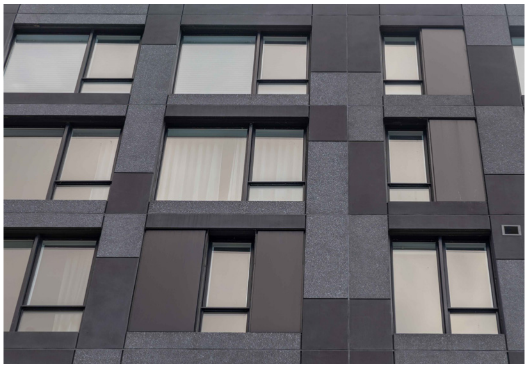
The first step is to estimate the R-value of the panel. With 4" (101.6 mm) of XPS, the panel has a clear-wall R-value of R-21.4 (RSI 3.76). There are no linear thermal bridges in this system but the inter-wythe connectors add point thermal bridges. There are 35 point connections, each with a chi-factor of 0.0015 (0.00285 BTU/(h F)). Entering I-P units into the equation:

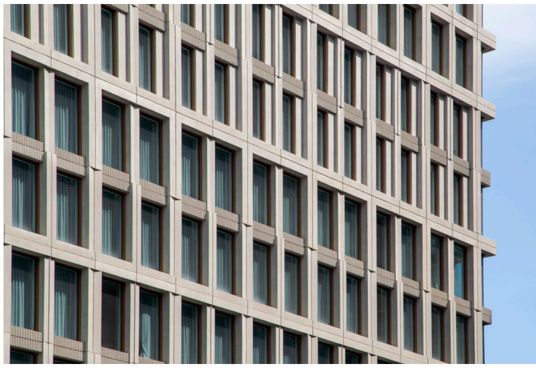
$$R_{WW} = 1 / \{ [A_{wall} / R_{CW} + \Sigma (\Psi_i \bullet L_i) + \Sigma(\chi_j \bullet n_j)] / A_{wall} \}$$

$$= 1 / \{ [85.3/ 21.4 + \Sigma (\Psi_i \bullet 0) + \Sigma(0.00285 \bullet 35)] / 85.3\}$$

$$= 20.88$$

Thus, in this example, the whole-wall R-value would be only about 2.5% lower than the clear-wall value even with a connector located as frequently as every 2 square feet.





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