CANADIAN PRECAST/PRESTRESSED CONCRETE INSTITUTE

Meeting and Exceeding Building Code Thermal Performance Requirements

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RDH BUILDING SCIENCE

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1.0 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, at an early design stage, the thermal performance of precast concrete enclosure wall systems.

1.1 Background

Current Canadian and US building codes are heavily influenced by energy considerations. 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, the National Energy Code for Buildings (NECB) of Canada (NECB 2015), was first introduced in Canada in 1997[1] while the International Energy Conservation Code (IECC) was not introduced in the United States until 2000.

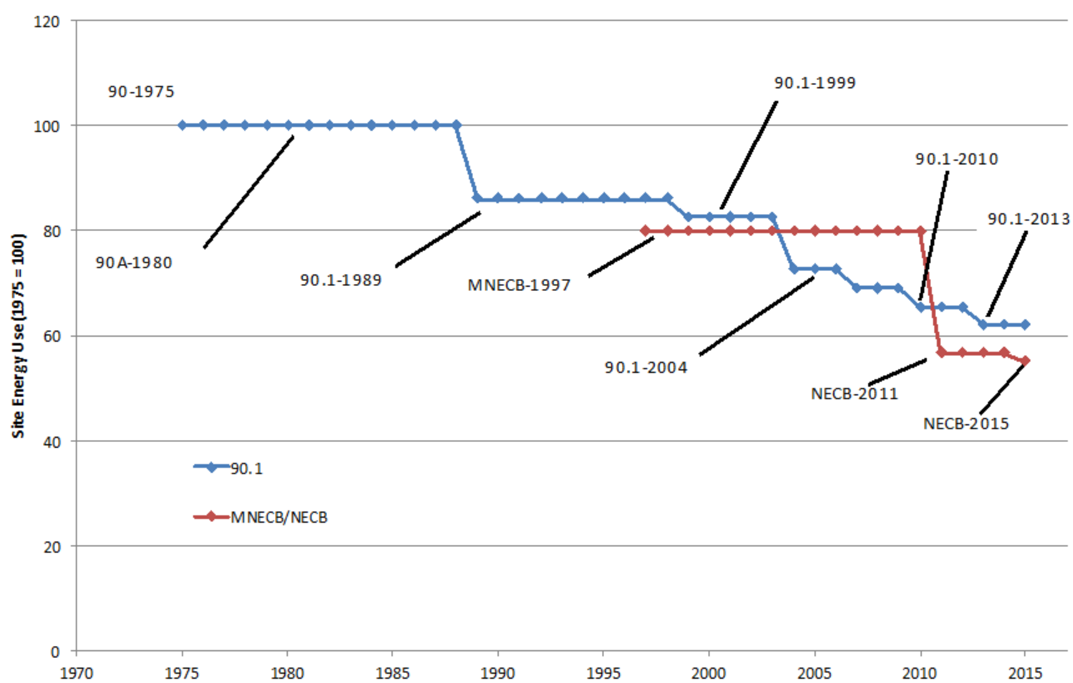

Figure 1: History of energy code performance (information is approximate and differs with building type and climate).

[1] The 1997 version of NECB was dubbed the Model National Energy Code for Buildings, or MNECB.

In the early days neither ASHRAE Standard 90.1 nor either of the two model energy codes were widely adopted. 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). In 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.

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 these changing code requirements and increasing performance expectations. Many different types of building systems are now being used throughout North America, and this has prompted the development of more accurate methods for the comparison and assessment of 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 insulation can be used in walls for different projects. To accommodate this reality and simplify the document, the thermal performance is provided for a range of insulation options.

The thermal performance of select details that are repeated throughout a building are 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 because they are dealt with later in the design.* The influence of dynamic thermal mass, which can only properly be assessed using computer programs for a specific building location, design, and occupancy schedule, has also been excluded.

The approach taken is to:

1. begin with an overview of the current thermal performance requirements in the Canadian codes (Chapter 2),

2. provide an explanation of approximate methods to predict the thermal performance of common precast concrete systems for use during early design stages along with examples (Chapter 3), and
3. present example precast enclosure system solutions, and the calculation of their R-value, to meet the thermal performance requirements (Chapter 4).

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

2.0 Energy Codes and Standards

This chapter provides a brief overview of available code compliance paths and examples of specific code requirements.

Building codes across North America define the lowest performance that designers are legally allowed to provide. Owners or various green building standards routinely set higher performance targets.

The most common energy standards referenced by Canadian building codes are the *National Energy Code for Buildings* (2011 or 2015 versions) and versions of ASHRAE 90.1. The Ontario Building Code provides several different options in *Supplementary Standard SB-10* and Quebec is governed by the *Regulation Respecting Energy Conservation in New Buildings Act*. Appendix D contains a summary of the current state of energy codes in each of the provinces and territories.

Adoption of building codes, acts, and standards, often with modifications, additions and deletions, 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 and professionals with knowledge of local interpretations should perform actual project compliance calculations as the project nears permit application.

2.1 Code Compliance Paths

There are several paths that a designer can use to demonstrate compliance: 1. prescriptive, 2. trade-off and 3. whole building energy modeling. As a result, buildings can be constructed with a wide range of window, roof, floor slab, and wall R-values. Thus,

> **it is not possible to answer the question “what R-value do I have to meet” because three primary compliance paths exist in all relevant building codes.**

Within each of the paths, there are further possible compliance options. For example, in ASHRAE 90.1, under the prescriptive path, there are two options for compliance: installed insulation (R-value) or overall thermal transmittance (U-value). The trade-off method typically involves simple trade-offs between enclosure components (window, wall, roof and below-grade) and ASHRAE 90.1 allows for a more sophisticated trade-off method.

In all codes the climate zone of the project influences the required performance, and in some codes the occupancy and type of enclosure assembly also influences requirements. These three factors are briefly discussed in the sections below.

Table 1provides a summary of these compliance paths, which are broadly similar for each energy standard.

Table 1: Typical Code Compliance Paths for Non-Part 9 Buildings

Project Specifics

Governing Code / Standard	ASHRAE 90.1-2010, NECB 2011/2015, SB-10 (Ontario), etc.
Identify Climate Zone	4 through 8
Occupancy	Residential, Non-residential, Semi-heated
Assembly Construction	Mass (most concrete), Metal Building, Steel- or Wood- Framed

Code Compliance Path

<table>
<tr><td colspan="2">Prescriptive
Use when all building enclosure and HVAC components meet minimum requirements and window area does not exceed minimums.
Each enclosure component has a minimum requirement.
Comparison of tabulated minimums to design demonstrates compliance.</td><td rowspan="2">Trade-Off
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.</td><td rowspan="2">Whole Building
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.</td></tr>
<tr><td>Insulation Compliance
Install insulation with R-value minimum and arrangement prescribed.
Least flexible method.</td><td>R- / U-Value Compliance
Calculate component U-value including thermal bridging.</td></tr>
<tr><td colspan="4">Assembly Design Approach</td></tr>
<tr><td>Select assemblies with insulation R-values at or beyond minimum required.
Confirm window area is less than maximum allowed.</td><td>Adjust insulation thickness / thermal bridging to meet component target.
Confirm window area is less than maximum.</td><td>Adjust calculated performance of each component, along with window area, to meet overall target.
Use compliance software such as COMcheck to include the benefits of thermal mass, solar gain, etc.</td><td>Calculate overall U-value including thermal bridging for components.
Adjust along with component R-/U-values, HVAC, and lighting.</td></tr>
</table>

2.1.1 Climate

Regardless of the code, the climate in which the building is to be located plays an important role in understanding what energy-saving measures are required. The most commonly used climate categories today use a similar zone numbering system as US codes. A map of Canada showing the approximate range of zones is provided in Figure 2, based on Heating Degree Days (HDD) tabulated in Table 2.

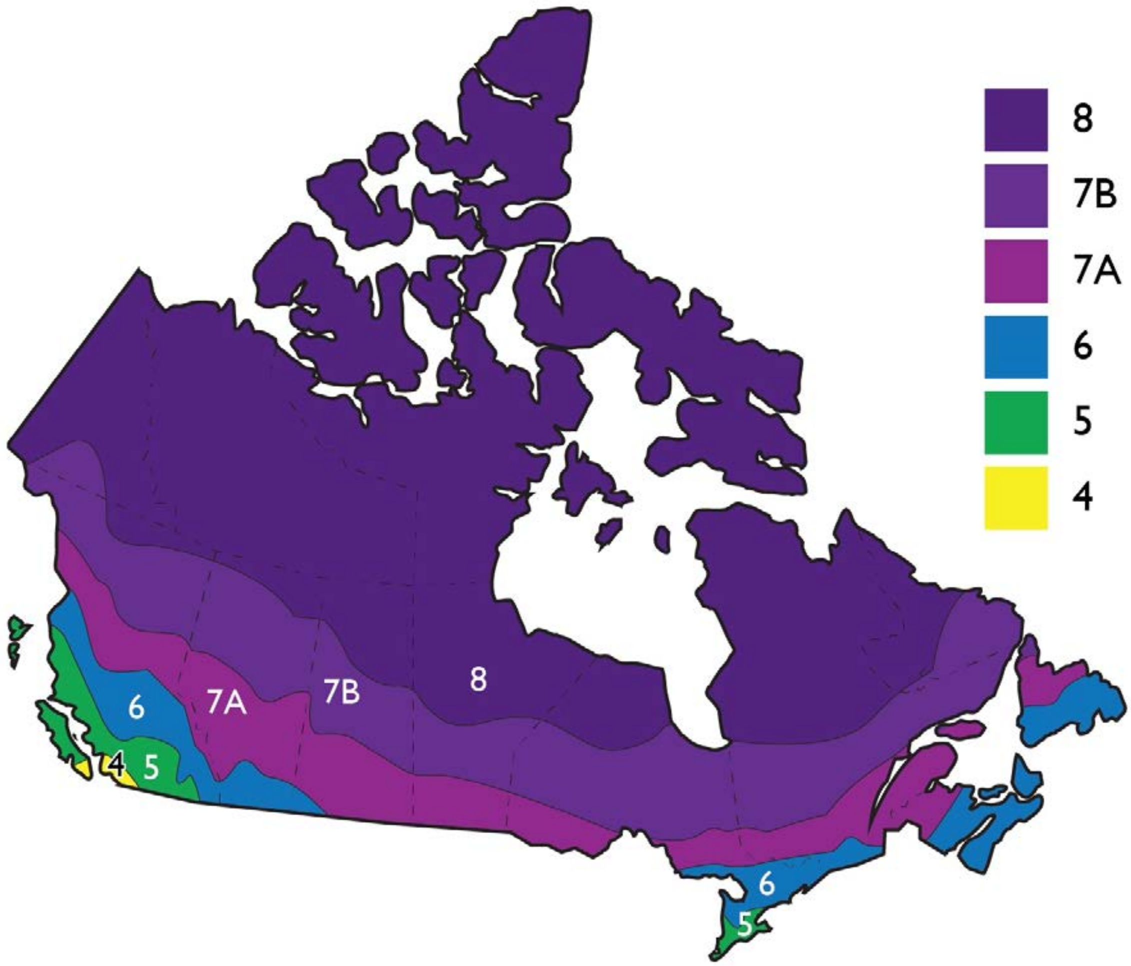

Figure 2: Climate zones for energy compliance.

2.1.2 Occupancy

Many codes require higher thermal performance for enclosures of residential occupancy than non-residential. This is based on the assumption that non-residential occupancy will have higher internal heat gains from lights, equipment, and high occupant density. Another category, semi-heated, is provided in some codes to account for attached storage areas, garages, and the like that are not required to be kept at normal room temperature.

2.1.3 Assembly Construction

Different assembly construction types deliver thermal performance that is quite different than their standard rated R-value because of implicit thermal bridging or thermal mass. To account for this, codes often have different requirements for mass walls (made of concrete or masonry), light-gauge steel framing, pre-engineered metal building systems, and wood framing.

Most of these descriptions are self-evident at an early design stage. However, to meet the mass wall category, specific requirements must be met. A mass wall is defined[2] as a wall with a heat capacity exceeding either

[2] From ASHRAE 90.1-2010

143 kJ/m^2 °C (7 Btu/ft^2 °F), or

102 kJ/m^2 °C (5 Btu/ft^2 °F) provided that the wall has a material unit weight not greater than 1920 kg/m^3 (120 lb/ft^3).

This means that concrete walls (normal weight or lightweight) at least 75 mm (3") thick can be considered mass walls for code compliance purposes.

As codes have moved closer to describing whole-wall R-values, the need to define categories for different assembly types has diminished and the NECB no longer has a category for mass walls. Ontario's SB-10 in force from January 1, 2017 has set the maximum U-value for all types of enclosures to the same values in one compliance option, but allows ASHRAE 90.1 mass benefits in a separate option.

2.2 Prescriptive Approach

The simplest and oldest method of prescribing building energy performance is to specify the minimum required performance for each of the enclosure components (in either U-value or R-value), that is, opaque walls, fenestration, roofs, below-grade components, etc. The "installed insulation" approach is the simplest and least flexible: designers choose the prescribed insulation R-value from a code table and create assemblies based on this value. Today's codes further prescribe how much must be installed within metal framing and how much insulation must be installed as continuous insulation outboard of the metal framing. This simple approach is very restrictive for design, but has the advantage of relatively simple-to-read tables.

The more flexible prescriptive approach is to design assemblies that 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 wide range of designs, can be used to meet the code or standard, usually with less insulation than the installed insulation compliance path. The major disadvantage is that some calculations are required: the focus of this guide is to make such calculations easier to perform.

Table 2 summarizes the maximum allowed assembly U-value (that is, 1 divided by R-value) as a function of climate zone for three common example energy codes: ASHRAE 90.1-2010, the National Energy Code for Buildings (NECB 2011/2015), and Ontario's SB-10.

Both prescriptive paths require all of the prescriptive requirements (including HVAC, lighting, etc.) be met, not just some, and also limit the maximum window area (often to 40% or less).

The specific methods used to calculate the U-value and R-value for all of the compliance methods can vary between different codes and the Authority Having Jurisdiction (AHJ).

Table 2: Prescriptive Enclosure Wall U-value/R-value for ASHRAE 90.1-2010 and NECB-2011

Système international U-values (W/m²K)						
Climate Zone	**HDD (18C)**	**ASHRAE 90.1-2010**		**NECB-2011**	**Ontario SB-10**	
		Non-Residential	**Residential**	**All**	**Non-Residential**	**Residential**
		mass	*mass*	*any*	*mass*	*mass*
4	<3000	0.104	0.09	0.315	--	--
5	3000-4000	0.09	0.08	0.278	0.450	0.400
6	4000-5000	0.08	0.071	0.247	0.400	0.340
7/7A	5000-6000	0.071	0.071	0.21	0.340	0.340
7/7B	6000-7000	0.071	0.071	0.21	0.340	0.340
8	>7000	0.071	0.052	0.18	0.340	0.340
Inch-Pound R-values						
Climate Zone	**HDD (18C)**	**ASHRAE 90.1-2010**		**NECB-2011**	**Ontario SB-10**	
		Non-Residential	**Residential**	**All**	**Non-Residential**	**Residential**
		mass	*mass*	*any*	*mass*	*mass*
4	<3000	9.6	11.1	18.0	--	--
5	3000-4000	11.1	12.5	20.4	12.6	14.2
6	4000-5000	12.5	14.1	23.0	14.2	16.7
7/7A	5000-6000	14.1	14.1	27.0	16.7	16.7
7/7B	6000-7000	14.1	14.1	27.0	16.7	16.7
8	>7000	14.1	19.2	31.5	16.7	16.7

ASHRAE 90.1 (and by reference, SB-10) limits the window-to-wall ratio (WWR) to 40% in the prescriptive compliance method. The NECB specifies a maximum fenestration-and-door-to-wall ratio (FDWR) equation that relates to Heating Degree Days (18˚C base), starting at 40% and dropping to 20% for Climate Zone 8 (Figure 3). These limits on window 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).

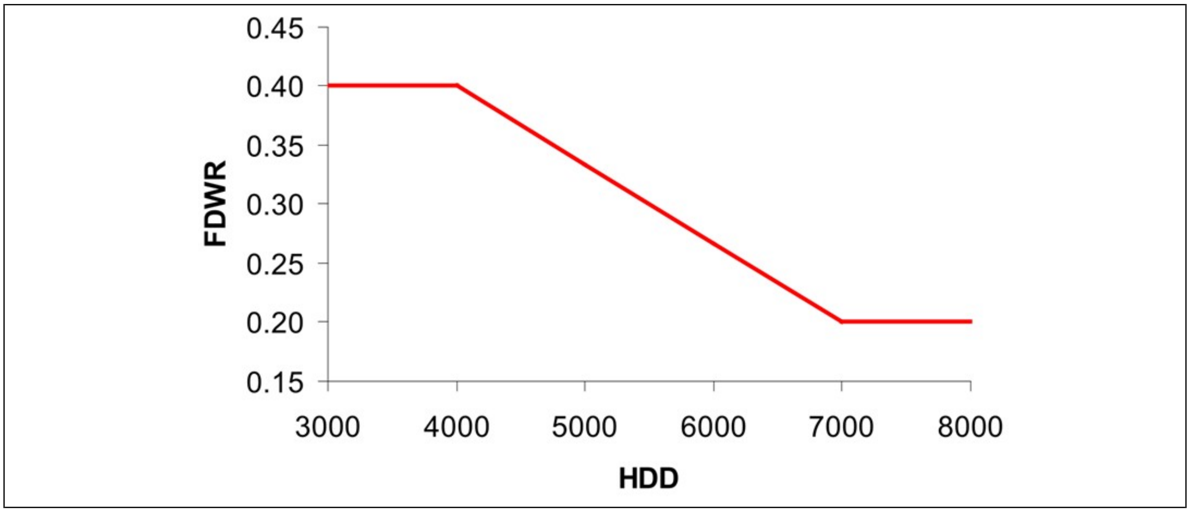

Figure 3: Maximum fenestration-and-door-to-wall ratio (FDWR) under the NECB prescriptive approach.

Despite the fact that window-to-wall ratios of over 40% 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.

To provide designers more flexibility, most modern codes, including the OBC, NECB and ASHRAE 90.1, allow for the trade-off between components: the tabulated prescriptive enclosure R-values can be reduced, and/or WWR increased, if the mechanical and/or electrical lighting system is made more efficient or thermal mass accounted for.

In these cases, either the trade-off path or whole-building modeling must be used to demonstrate compliance with the code. For buildings with very high WWR's, trade-off analysis rarely provides sufficient flexibility, and whole-building energy modeling is used to take advantage of highly efficient mechanical equipment and high-performance HVAC systems (including lighting and domestic hot water) to offset the low thermal performance of the glazing.

If this trade-off approach is taken, there are currently no prescribed minimum R-values: designers can choose very low R-value enclosures if they invest in higher performance heating, cooling, ventilation, and lighting equipment.

2.3 Trade-off Analysis

Both simple and detailed trade-off methods are available. In the simple trade-off method, only enclosure components are traded-off, whereas the detailed method allows a more sophisticated analysis of solar gains for both reducing heating loads as well as increasing cooling loads. Like the prescriptive path, the trade-off path requires that all mandatory parts of the code be met.

The simple enclosure trade-off method is very simple: provided the total heat loss/gain of the proposed building enclosure is equal to or less than a building built to the prescriptive minimum values, the building is code compliant. The total heat loss is simply calculated as the sum of the individual component areas times that component's U-value.

To provide a basis of comparison, the maximum window-to-wall ratio and the maximum U-value accepted by the code provides an overall estimate of the code-accepted minimum performance for the overall above-grade wall enclosure, that is, both windows and walls. This combined overall minimum is presented in Table 3 for the examples of ASHRAE 90.1-2010, NECB, and Ontario's SB-10. It can be seen that overall average vertical enclosure R-value demanded is only between about R-3.8 and R-7.0 up to climate zone 7.

Table 3: Average Overall Vertical Enclosure R-values for Prescriptive Path ASHRAE 90.1-2010, NECB, Ontario SB-10

Système international U-values							
Climate Zone	**HDD (18°C)**	**ASHRAE 90.1-2010**		**NECB-2011**		**OBC SB-10**	
		Non-Residential	**Residential**	**Any occupancy**		**Non-Residential**	**Residential**
		mass	*mass*	WWR (%)	*all walls*	*mass*	*mass*
4	<3000	1.49	1.44	40	1.15	--	--
5	3000-4000	1.33	1.29	40	1.05	1.07	1.03
6	4000-5000	1.29	1.26	37.5	0.98	1.03	1.00
7/7A	5000-6000	1.15	1.15	30	0.81	0.89	0.89
7/7B	6000-7000	1.15	1.15	22.5	0.66	0.89	0.89
8	>7000	1.15	1.09	20	0.46	--	--
Inch-Pound R-values							
Climate Zone	**HDD (18°C)**	**ASHRAE 90.1-2010**		**NECB-2011**		**OBC SB-10**	
		Non-Residential	**Residential**			**Non-Residential**	**Residential**
		mass	*mass*	WWR (%)	*all walls*	*mass*	*mass*
4	<3000	3.81	3.94	40	4.94	--	--
5	3000-4000	4.27	4.39	40	5.42	5.33	5.49
6	4000-5000	4.39	4.49	37.5	5.80	5.49	5.68
7/7A	5000-6000	4.94	4.94	30	7.04	6.41	6.41
7/7B	6000-7000	4.94	4.94	22.5	8.63	6.41	6.41
8	>7000	4.94	5.23	20	12.24	--	--

The significant impact on code-required enclosure wall R-values by varying the window area and performance is explored in greater depth in Chapter 3.

The simple trade-off method is limited to window performance, window area, and wall performance. In the NECB and ASHRAE 90.1 detailed trade-off method, changes across enclosure categories (walls, roofs, windows, doors) are allowed, and both heat loss and solar gains are taken into account and thermal mass can be counted as a benefit. As these calculations are more complex, they are usually undertaken using software. In Ontario and British Columbia, the COMcheck software[3] is accepted for this method. Using the free web-based software allows a designer to generate a compliance report for the Authority Having Jurisdiction (AHJ). This is often an ideal path for buildings of modest size and complexity built with thermal mass.

[3] Google "COMCheck" or go to https://www.energycodes.gov/software/comcheck-desktop-393

2.4 Whole Building Energy

Although specific characteristics (R-value, airtightness, SHGC[4]) 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 have a major impact on large commercial and institutional buildings. Thus, codes for larger buildings (such as ASHRAE 90.1, NECB) often prescribe minimum performance levels for a wide range of mechanical equipment, lighting, and control systems.

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 all enclosure component performance. The cost and effort of whole building modeling usually means this approach is taken for only 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 is possible to build enclosures with effective overall wall R-values as little as half those required by prescriptive limits.

2.5 Codes and Thermal Bridging

Based on research conducted by numerous organizations nationally and internationally, the effect of thermal bridging is now understood to play an important role, especially in well-insulated enclosures. The R-value often does not include the impact of specific thermal bridges such as floor slabs, structural anchors, balconies, etc. Thermal bridges, or at least major thermal bridges, generally are intended to be included in tabulated U-values and code language is currently being strengthened to make this clear.

“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 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.”*

Floor slabs, intersecting walls, parapets, balconies, etc. can result in significant heat loss (Figure 4) and should be covered with insulation to meet the definition of ci as defined by the standards.

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[4] SHGC= Solar Heat Gain Coefficient, the metric used to describe how well a transparent glazing unit prevents solar heat from entering a building; lower is better.
[5] This definition is taken from ASHRAE 90.1-2010, Section 3.

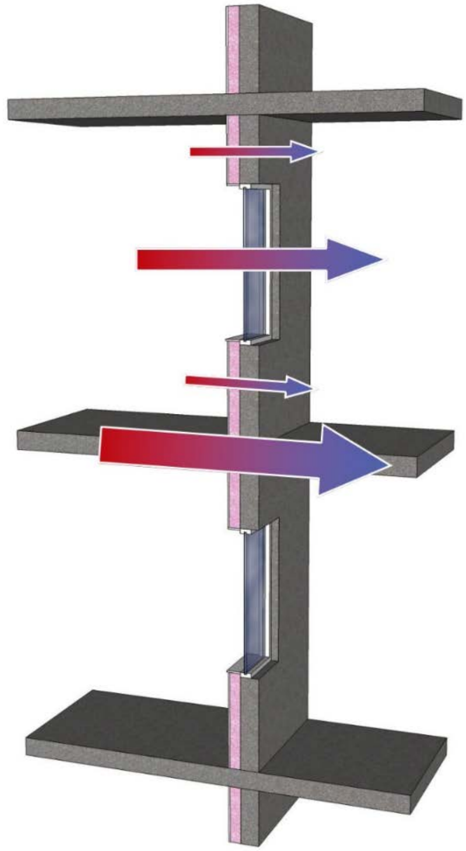


Figure 4: Heat flow paths through centre of wall, floor slab, and windows (arrow size is relative to magnitude of heat flow).

An example of how some codes address thermal bridging more generally is the Ontario Building Code *Supplementary Standard SB-10*. SB-10 references ASHRAE 90.1 as one compliance path, but explicitly does not require full accounting for thermal bridging. Rather it provides exceptions for what are deemed to be modest or difficult-to-solve thermal bridges. Figure 5 provides an excerpt.

For this particular code, the impact of slab edges needs to be accounted for in practice, since, for example, in the case of 8" (204 mm) thick slabs and floor-to-floor heights of 9 feet (2743 mm), the area is 7.4%: this is much more than the 2% limit for thermal bridges waived under sentence 5.5.3.8. However, the small knife-edge steel connections used to attach a precast panel to the structure, and the composite ties used to connect double-wythe insulated sandwich panels, would not need to be accounted for provided they are less than 2% of the enclosure area (they are commonly much less than this).

5.5.3.7 For the purposes of Section 5, the effects of thermal bridging are waived for:

(a) intermediate structural connections of continuous steel shelf angles (or similar structural element) used to support the building façade provided there is a thermal break between the remaining contact surface of the supporting element and the building structure. This provision is intended to substantially reduce thermal bridging effects caused by the continuous bearing between structural elements supporting building façade and the building frame (i.e. steel shelf angle attached to perimeter floor slab to support brick veneer), or

(b) structural connections of load bearing elements where a thermal break cannot be achieved.

5.5.3.8 In addition to the exceptions permitted above, the effects of thermal bridging are also waived for:

(a) exposed structural projections of buildings where the total cross-sectional area of the exposed element does not exceed 2% of the exterior building envelope area and the cross- sectional area of the exposed structural element is measured where it penetrates the insulation component of the building envelope. (For example, if the total cross-sectional area of cantilevered concrete balconies and other projections penetrating the insulation component of the building envelope does not exceed 2% of the exterior building envelope area, their thermal bridging effects need not be taken into account)

(b) ties in masonry construction,

(c) flashing, and

(d) the top exposed portion of foundation walls provided the exposure does not exceed 200 mm measured from the top of the foundation wall to the top of exterior wall insulation which meets the minimum insulation RSI-Value for walls below grade stipulated in the appropriate Tables.

Figure 5: Excerpt from Ontario Building Code Supplementary Standard SB-10 thermal bridging provisions.

The National Energy Code for Buildings requires that the thermal bridging effect of closely spaced repetitive structural members (e.g. studs) and of ancillary members (e.g. sills and plates) be taken into account. The NECB also states that the thermal bridging of major structural elements that must penetrate the building envelope need not be taken into account, provided that the sum of the areas is less than 2% of the above-grade building enclosure.

The 2% wall allowance is of particular interest for penetrating balcony slabs as this threshold is exceeded in many multi-unit residential buildings with continuous balconies. To avoid having to account for exposed balcony penetration, projects would limit the extent of the exposed balconies to below the 2% wall area allowance.

The limit has been plotted in Figure 6. It can be seen that low-rise buildings can have a high portion of balconies around the perimeter while meeting the allowance. This is because the ground floor does not have a balcony. For taller buildings, projects would need to limit balconies to between 30% and 50% of the perimeter length to meet the limit of the allowance.

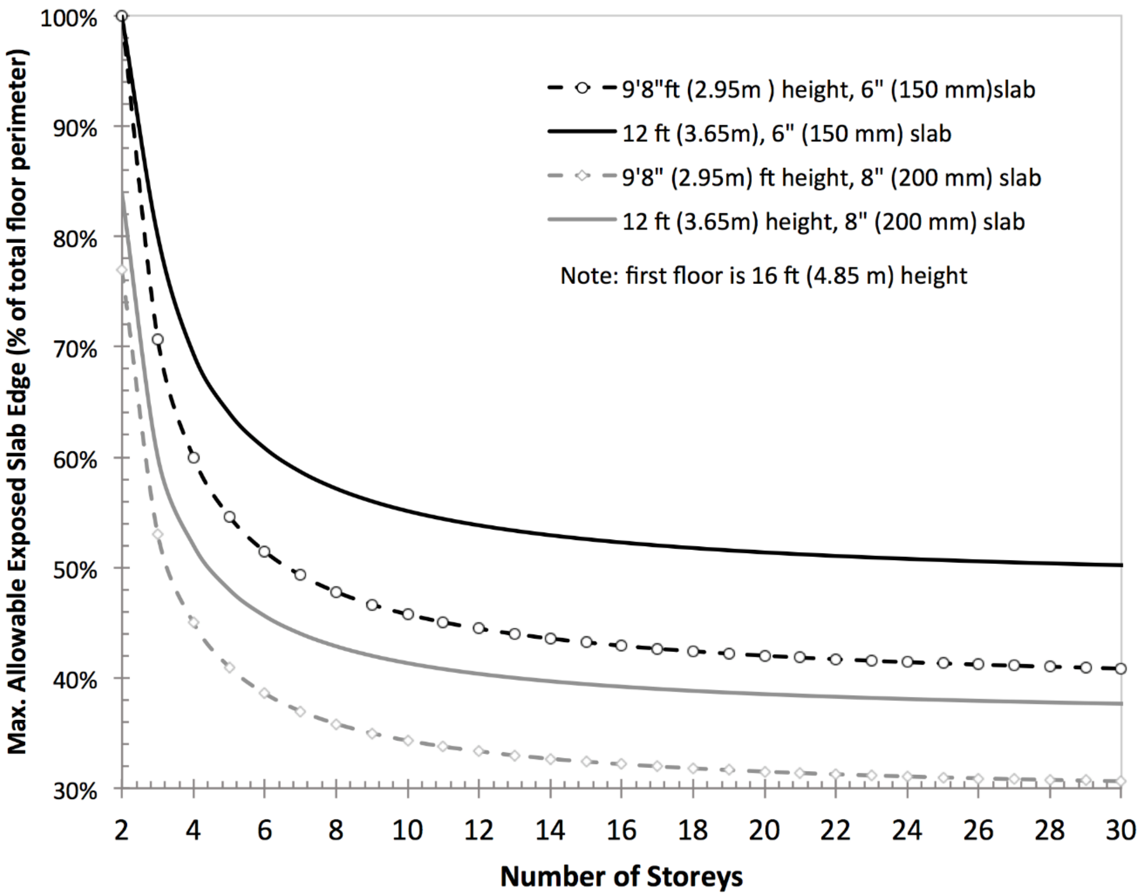


Figure 6: Maximum balcony perimeter per floor assuming 2% thermal bridging waiver.

Future codes are likely to reduce these exceptions over time. The Canadian Green Building Council's (www.cagbc.org) LEED® rating system for example, also provides somewhat more detailed guidance to those seeking certification. Appendix B of their Energy Modeling Guidelines states in part:

> "All of the energy modeling submittal pathways referenced by the LEED Canada rating systems require that thermal bridging in envelope assemblies (e.g. fenestration, opaque walls, roofs, etc.) be reasonably accounted for when determining the overall thermal transmittance of envelope components of the Proposed building .... In general, if an envelope assembly includes significant thermal bridging that cannot be readily assessed, then conservative estimates for the proposed building assembly may be acceptable. Nominal thermal transmittance values (e.g., the value of the installed insulation or the centre-of-glass performance) are not acceptable."

2.6 Closure

More insulation, better airtightness, and less thermal bridging will be required by future codes and green building programs regardless of the type of enclosure wall system considered. Some jurisdictions have indicated a desire for energy codes to provide a path to net zero or net zero ready performance. Because building codes offer several compliance paths there is no one R-value that is required for a specific building in a specific location. Increasingly, trade-off compliance paths are chosen which allow for lower, sometimes significantly lower, enclosure wall R-values than listed in prescriptive tables.

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 changing design details. The thermal performance of precast concrete enclosure systems is considered in more detail in the remainder of this guide.

3.0 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, an understanding of what thermal performance can be achieved is critical.

3.1 Background

Heat can flow across an enclosure by three *modes*: convection (air leakage), conduction, and radiation. Air leakage (bulk convection) is managed by the airtightness of the assembly. For opaque assemblies, the conduction and radiation modes are grouped together. There are two common measures of a building assembly's control of heat flow: R-value and U-value. These measures assume that the assembly is airtight[6].

Although R-value 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. To differentiate the metric (SI) from the traditional (IP) units, metric thermal resistance is reported as RSI and the two can be easily converted.

R-value = RSI * 5.67

RSI = R-value / 5.67

The R-value (or RSI) 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)

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

Table 1, Chapter 26, of the 2013 ASHRAE Handbook of Fundamentals (ASHRAE 2013) and Table A-9.36.2.4 in Appendix A of the 2010 National Building Code of Canada (NBCC 2010) provide authoritative thermal conductivity and R-values for a range of building materials.

The *thermal resistance* of a multi-layer assembly of flat materials (many types of building enclosures), can be calculated from

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

where

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

[6] Precast concrete is an excellent material for use as part of an air barrier system.

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-layer assembly formed of different materials, and 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 7).

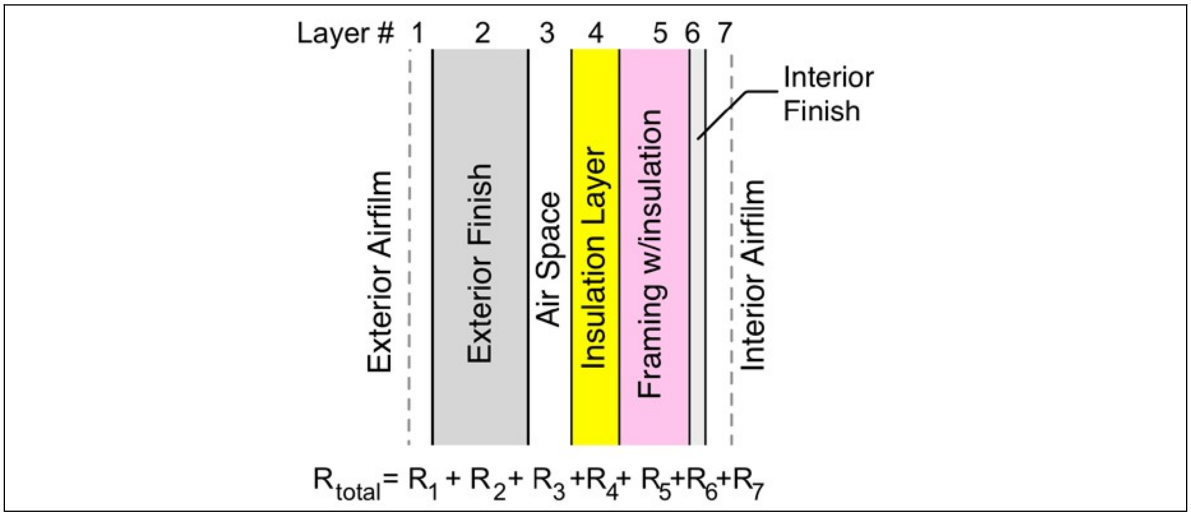


Figure 7: Example calculation of multi-layer assembly thermal resistance.

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

$U = 1 / R_T$

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, standards such as ASHRAE 90.1 and NECB have also listed required maximum U-values (minimum R-values) for entire assemblies, including finish materials, air films, and air gaps. Using this approach requires users to calculate the overall 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, code official, and the different needs of energy modelers and designers. However, the most important distinctions between different definitions involve how thermal bridging is considered.

When heat moves through an enclosure element it flows through more than just the centre of the panel: 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 twenty years ago (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 not). The contribution of other materials is ignored.

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

→ the ***Clear-wall R-value*** (R_{cw}) 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 conductive penetrations (e.g. floors).

→ the ***Whole-wall R-value***, (R_{ww}) which includes the clear-wall R-value (Rcw) *plus* the thermal impact of any additional framing or fasteners at openings (e.g. windows and doors), and the effects of thermal bridges at changes in plane and other interfaces (e.g. foundation-to-above-grade-wall, wall-to-roof, balconies, etc.) but *excludes* window area. For simplicity, sometimes the clear-wall R-value is used when whole-wall R-value should be (i.e., thermal bridging is ignored), but this approach can significantly over-estimate 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 implicit to the simple trade-off methods used to demonstrate compliance (see Chapter 3).

→ **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). 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 to specify thermal resistance, R_{CW}, as an RSI (˚C m^2/W) or R-value (˚F ft^2/BTUh) and U-value (W/m^2 ˚C or BTUh/ft^2 ˚F) is used for 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*.

The thermal contribution of interior finishes, continuous layers of insulation, and interior light-gauge framing are common options for many commercial systems and hence will 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, to provide 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 stud, 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 4) to which the R-value of the gypsum board interior finish can be added (Table 5). The effective R-values recommended by ASHRAE for a typical light-gauge steel framing system are compared to continuous insulation layers in Table 4.

For the common R-13 and R-19 batt 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 4: Effective Clear-wall R-value for Light-gauge Steel Framing Without Sheathing or ci Acting as a Single Layer[7]

Cavity Depth		Rated Cavity R-value	Layer R_{cw}-value @ 16 inch centres	Layer RSI_{cw} @ 405 mm centres
In	mm			
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 (4" ccSPF)	7.6	1.34

Note: "ccSPF" is closed-cell Sprayed Polyurethane Foam insulation

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

Cavity Depth		Rated Cavity R-value	Layer R_{cw}-value @ 16 inch centres	Layer RSI_{cw} @ 405 mm centres
In	mm			
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 (4" ccSPF)	9	1.59

Note: "ccSPF" is closed-cell Sprayed Polyurethane Foam insulation

[7] Data primarily assembled from ASHRAE 90.1-2010 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 of common product categories are provided in Table 7. If a specific product and brand of insulation has been decided upon, the R-value from the producer's data sheet can be used. It can be seen that concrete does not provide a meaningful contribution to R-value (although dynamic thermal mass effects do help reduce energy use).

Table 7: 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		same as semi-rigid mineral wool				
Extruded polystyrene	5.0	10.0	12.5	15.0	17.5	20.0
Polyisocyanurate	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		same as semi-rigid mineral wool				
Extruded polystyrene	0.029	1.8	2.2	2.6	3.1	3.5
Polyisocyanurate	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

[8] Z-girts should never penetrate the insulation or a significant (i.e., more than 50%) reduction in performance will result.

[9] These values are based on NBCC 2010 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.

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 8.

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.

Table 8: R-value of interior and exterior surface films (ASHRAE 2013)

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

3.4 Calculating Thermal Bridging Impacts

Thermal bridging effects not accounted for in the clear-wall performance (R_{cw}) can be captured by several different calculation methods. Computer-based two-dimensional and three-dimensional finite-element thermal models are generally preferred, but the cost of project-specific analysis cannot usually be justified for early-stage design or on 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 the 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, that is, 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. When there are two flow paths, 1 and 2, the following equation would be used:

$$U_{avg} = U_1 \cdot \frac{A_1}{A_1 + A_2} + U_2 \cdot \frac{A_2}{A_1 + A_2} \qquad \text{(Eq. 3)}$$

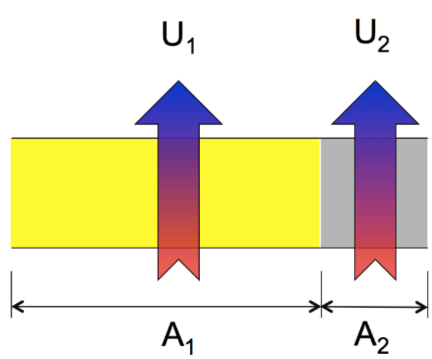


Figure 8: Parallel path heat flow.

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 can be written:

$$R_{avg} = \frac{1}{R_1} \bullet \ \%A_1 + \frac{1}{R_2} \bullet \ \%A_2 \qquad \text{(Eq. 4)}$$

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 ψ and χ, respectively. These have been published for a number of assemblies (RDH 2013, Higgins et. al. 2014, MH 2014) or can be derived from two- and three-dimensional thermal computer models.

Thermal bridging in building practice can usually be divided into two types: linear details that predominately exhibit two-dimensional heat flow, and point details whose heat flow is primarily three-dimensional. 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:

$$Q = [U_{cw} \bullet A + \Sigma(\Psi_i \bullet L_i) + \Sigma(\chi_j \bullet n_j)] \bullet \Delta T \qquad \text{(Eq. 5)}$$

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”, and

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

ΔT is the temperature difference across the wall.

This project has generated a number of Ψ and χ factors (heat transmittances) for use in including the heat loss of thermal bridging in the energy analysis of buildings (Appendix B and E).

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

$$R_{WW} = \frac{1}{\dfrac{\frac{A_{wall}}{R_{CW}} + \Sigma\,(\Psi_i \cdot L_i) + \Sigma\left(\chi_j \cdot n_j\right)}{A_{wall}}} \qquad \text{(Eq. 6)}$$

where

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

R_{CW} is the Clear-wall R-value

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

This calculation can be applied to all enclosure systems, but requires the development of specific thermal bridging factors, most of which have not been published yet

3.5 Windows and Overall R-value

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

Designers of high-performance buildings will generally consider the overall R-value as a measure of the enclosure thermal performance. Codes infer an overall R-value in their prescriptive paths by assuming a maximum window-to-wall area and minimum component R-values.

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:

$$U_{overall} = (1\text{-}WWR) / R_{ww} + WWR \cdot U_V \qquad \text{(Eq. 7)}$$

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 simply

$$R_{overall} = 1 / U_{overall}$$

[10] See Table 3. Currently the overall R-value is in the range of R-4 to R-6 for ASHRAE 90.1-2010 and NECB.

Figure 9 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.

Figure 10 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 average double-glazed aluminum windows (U=0.20, 0.30, and 0.40 respectively, as opposed to code minimum) and R-10 and R-20 opaque walls. The overall R-value (the value used for the simple trade-off compliance path) for several representative codes and climate zones are shown on the plot.

For larger WWR (i.e. about 40% or higher) 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 a whole-wall R-10 mass wall with U=0.3 windows would exceed the minimum requirement for ASHRAE 90.1-2010 (Table 3), Climate Zone 8 residential occupancy provided the window-to-wall ratio was 40% or lower. This arrangement would also be compliant with the more stringent Ontario SB-10 in Climate Zone 6 if the WWR were reduced to 34%.

In practice, when the WWR is over 40% (or some climate-dependent lower value for the NECB) and poor thermally performing windows/curtainwalls 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.

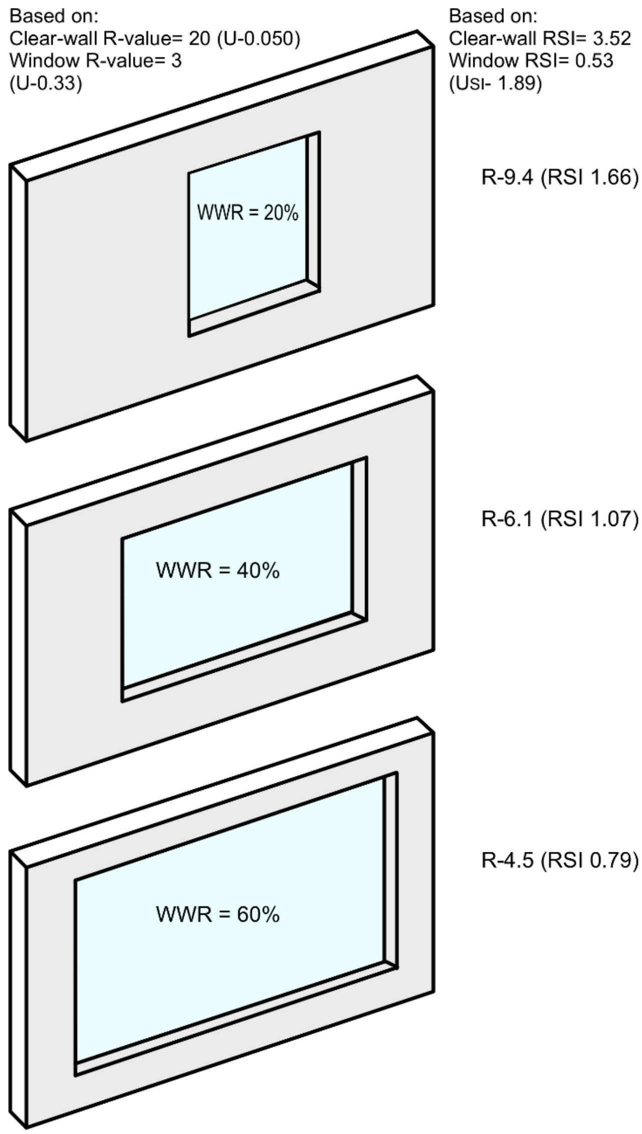


Figure 9: Impact of windows on overall enclosure R-value.

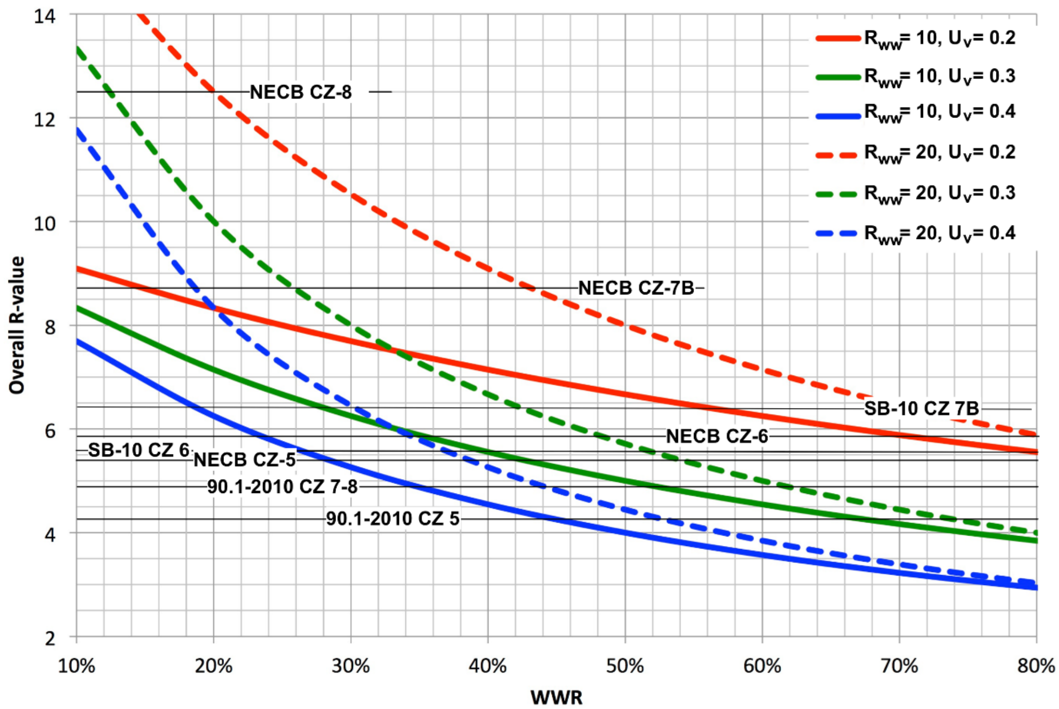


Figure 10: Combined impact of thermal performance of mass walls and windows and WWR (Note: CZ=climate zone, R_{ww} is whole-wall R-value, and U_v is window U-value).

4.0 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/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 being taken. 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

Conventional Panels (aka "Architectural Precast") use precast concrete as large format panels on the exterior as the exterior finish, 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 (aka Sandwich" or "Integrally Insulated Wall Panels") incorporate thermal insulation between an exterior finish wythe and an interior structural 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, vapour, and thermal control.

Precast Concrete Roofs are often used and are most commonly comprised of hollow core planks or double-T slabs. Floors over exterior spaces are another common enclosure made up of this type of precast concrete element. The thermal, air, water, and vapour control are added to the precast component, almost always to the exterior[11]. Interior insulated roofs are possible, but require additional water control layers on the exterior of the concrete element and 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 used is often termed Total Precast as it provides both enclosure and primary structural support.

Total Precast Concrete is a system that employs precast concrete enclosure walls (either conventional or double-wythe panels), partitions, and floors as part of a total structural system,

[11] 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).

carrying all lateral and gravity loads. The enclosure walls of this system also collect enclosure loads such as wind and seismic loads.

4.2 Architectural Precast Concrete

Architectural 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 11.

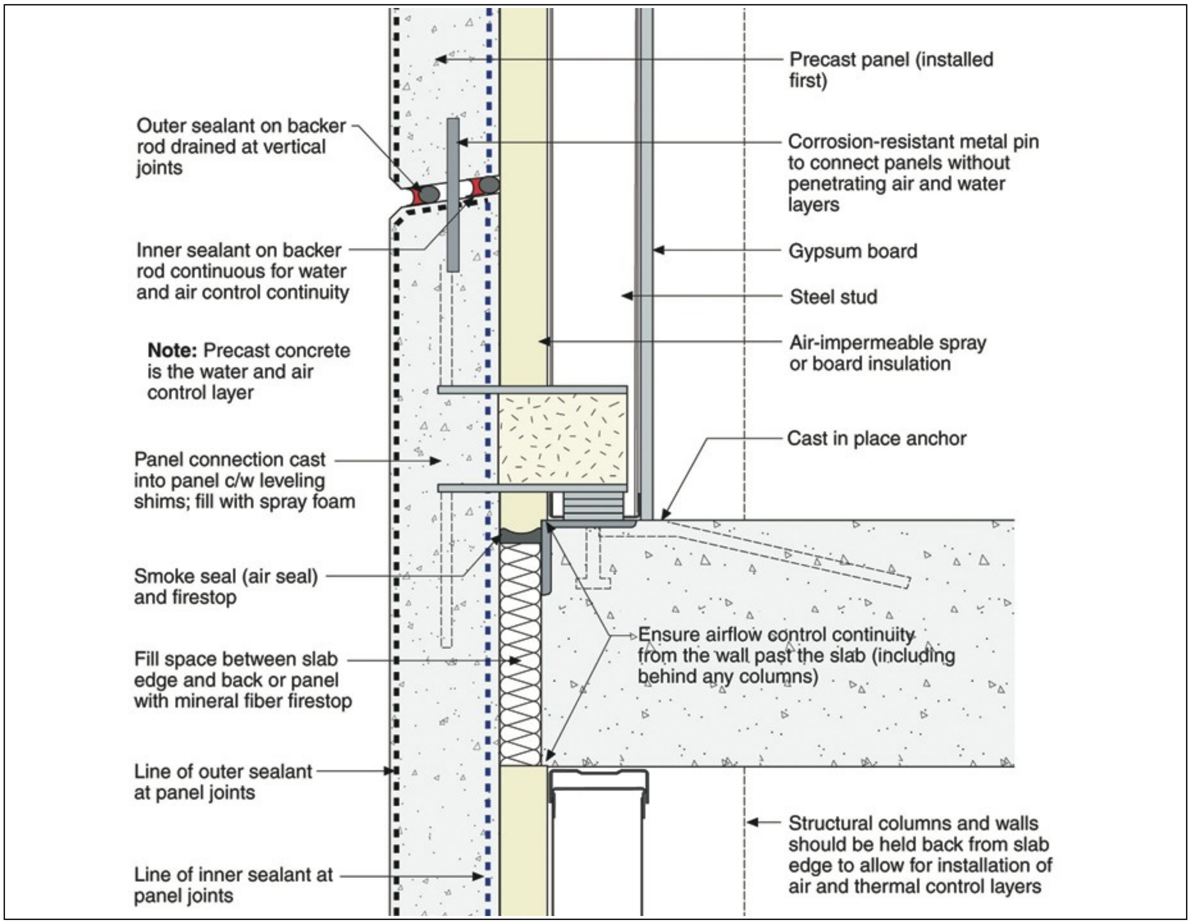
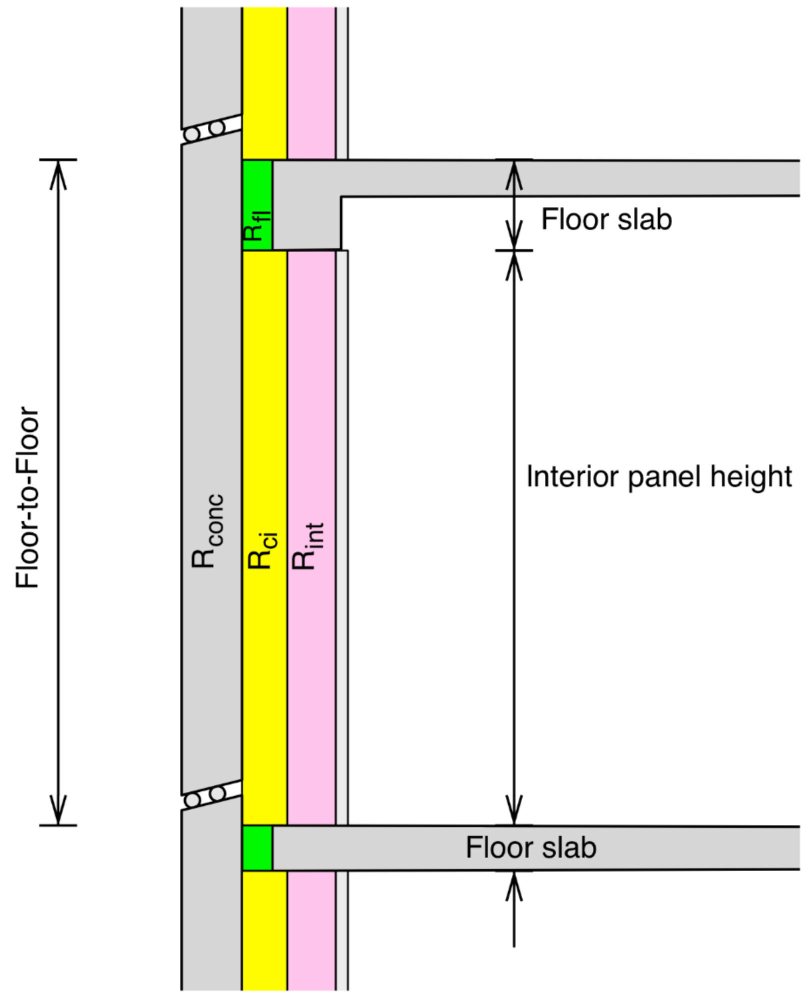


Figure 11: Section at floor of a high-performance architectural precast panel (CPCI 2013).

To achieve good thermal performance, two aspects of their 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 architectural precast concrete panel, often in the field, but can also be quite conveniently added in the factory. To ensure good thermal performance, it is important to provide continuous interior insulation rather than insulation between 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, or polyisocyanurate [PIC]) or spray polyurethane foam. Light-gauge steel stud framing should be installed inboard of this continuous insulation layer and can be left uninsulated or insulated with fibrous or spray insulation[12].

The heat flow through the opaque portions of an architectural precast wall can be calculated with only a few key inputs. The dimensions and layers for which thermal resistance is required are defined in Figure 12.



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 12: Definition of terms for architectural precast thermal calculation.

[12] 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 to 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. Table 7 provides a list of the thermal properties of common insulations.

> **Example**: An architectural precast concrete system is comprised of a 5” (127 mm) reinforced concrete panel, 2” (51 mm) of closed-cell Spray Polyurethane Foam (ccSPF) continuous insulation with an empty 3.5” (89 mm) steel stud framing at 16” (406 mm) on center and 5/8” (16 mm) GWB on the interior (Figure 13).
> From the earlier calculation in Section 3.3.1, the R-value of all interior finish components is R-2.2, and that of 2” of ccSPF is 2 times R-6/inch=R-12 (Section 3.3.2, Table 7). Hence, the clear-wall R-value of this system is the sum of R-2.2 and R-12 = R-14.2. The R-value provided by the concrete (R-0.3) has been ignored
> If one uses R-13 batt within the stud space the calculation would be R-7.4 plus R-12, for a total of R-19.4.

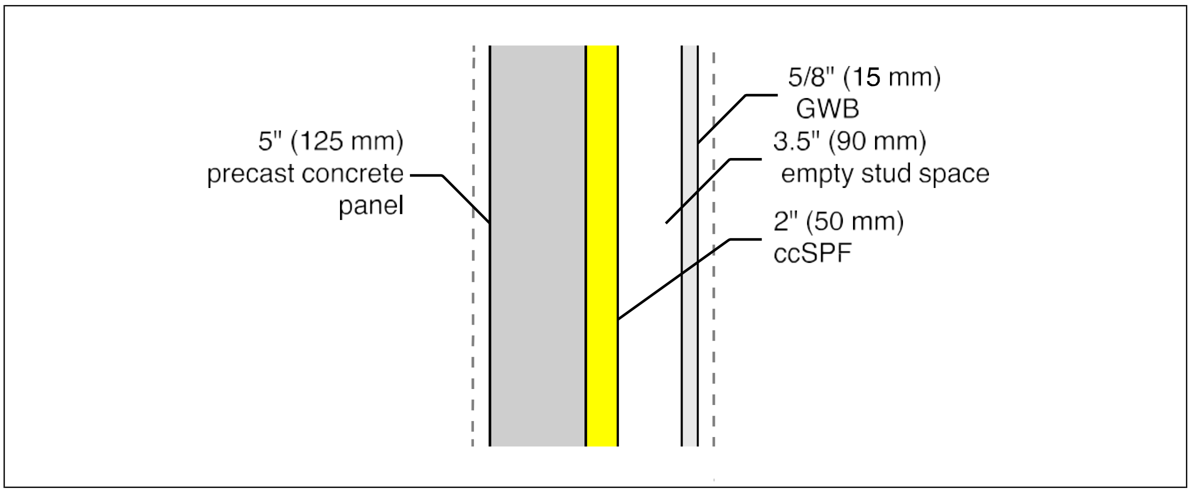


Figure 13: Example architectural precast assembly.

Incidentally, a clear-wall value of R-19.4 (U=0.0515, RSI =3.42) is very respectable performance for a system with a thickness of around 11.5” (292 mm): a steel stud system would need to be 6” (152 mm) deep to resist wind loads in most commercial use, and 2” (38 mm) of ci plus 1/2” (13 mm) of exterior gypsum sheathing would be required to reach the same thermal performance. Thus, the thickness would need to be 9” (225 mm) before any finish is applied to the exterior of such a steel stud system. Even assuming a thin (1/2” or 13 mm) panel cladding system over a 1.5” (38 mm) air gap for cladding attachment and venting the resulting enclosure would be 11” (267 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, 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 depends on the code in force and which thermal bridging effects may be ignored.

The most important potential thermal bridge for this type of enclosure system is the floor slab intersection. The gap between the floor slab and the back of the concrete panel has been provided in the past to allow for dimensional tolerances. However, today the gap also should be sized to provide a reasonable amount of thermal insulation continuity. The gap is almost always filled with stonewool insulation to provide firestopping, 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 an architectural precast enclosure, including the impact of the floor system, the following equation can be used[13]:

$$R_{ww} = 1 / \{ [(FF - T_{fl}) / FF] / R_{cw} + (T_{fl} / FF) / R_{fl} \} \qquad \text{(Eq. 8)}$$

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 metres)

R_{CW} is the Clear-wall R-value

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

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 stonewool, and thus an R-value of R-4 per inch can be assumed. If interior and exterior surface films are added to typical concrete thicknesses, the R-value of the slab intersection can be estimated. Common values for use in early-stage design calculations are provided in Table 9.

Table 9: Total R-value of Floor Slab (R_{fl}) Intersections

Stonewool Firestopping Thickness (in.)	Effective Slab R-value	Effective Slab RSI
1	4.75	0.84
1.5	6.83	1.20
2	8.90	1.57
2.5	11.00	1.94
3	13.10	2.31
3.5	15.15	2.67
4	17.20	3.03
t>4"	4.0*t+1.2	0.704*t+0.21

Example: The architectural precast system from the previous example (R_{cw}=19.4) spans 12'8" (3861 mm) from floor-to-floor. The floors are comprised of a 7" (178 mm) deep reinforced concrete slab with a 10" (254 mm) deep perimeter beam. If a 1" (25.4 mm) gap is specified to be filled with mineral wool firestopping insulation, what is the whole-wall R-value and U-value?

[13] This equation assumes the parallel path method which has been shown to be sufficiently accurate for typical building dimensions.

The whole-wall R-value can be estimated by entering values into Equation 8:

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

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 4.75 (from Table 9).

The whole-wall R-value calculated is R-16.1 (RSI= 2.83, U=0.062, U_{SI}=0.353). This does not include the impact of precast anchors, but their effect currently does not need to be considered by most codes.

Hence, this system would meet the requirement for Zone 5 and 6 in ASHRAE 90.1-2010 for residential and commercial buildings. Increasing the firestop insulation thickness to 2" (R_{fl}=8.9) would change the whole-wall R-value to 18.0 (U_{SI}=0.315), a R-1.9 increase for very little cost.

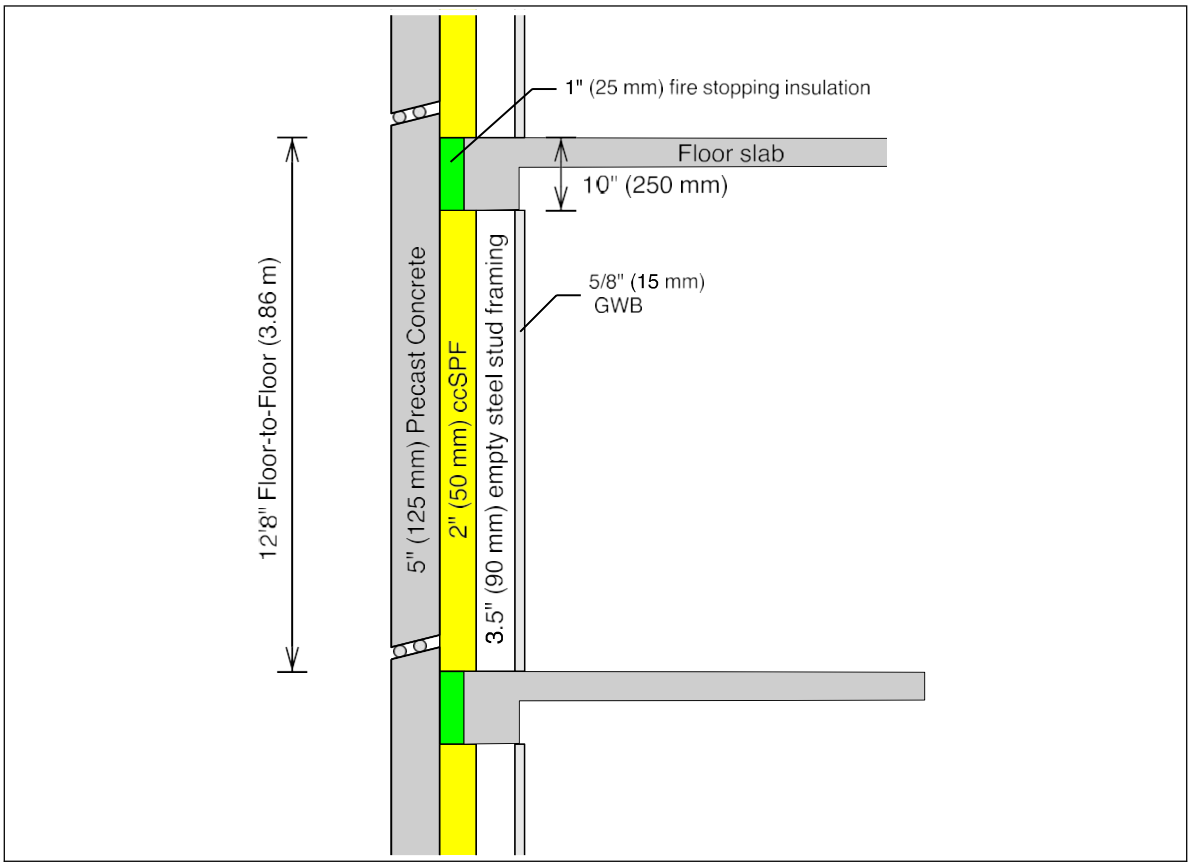


Figure 14: Example architectural precast system.

Higher R-value enclosures are increasingly being demanded for Net Zero Energy buildings, Passive House projects, and Living Building Challenge buildings. Even the 2011 NECB (and Ontario SB-10 2017 requirements) requires R-20.4 (U_{SI} = 0.278) for Climate Zone 5, R-23.0 (U_{SI} = 0.247) for Climate Zone 6, and R-27.0 (U_{SI} = 0.210) for Climate Zone 7. To achieve this level of performance, more than 2" (51 mm) of continuous insulation and at least a 2" (51 mm) firestopping gap will be needed. To exceed a U_{SI}=0.247 target (R_{ww} = 23) in the above example, one solution would be to increase the ccSPF thickness to 3" (76 mm) (or 4" or 102 mm of semi-rigid mineral wool) and the firestopping gap width to 3" (76 mm). To exceed the minimum *prescriptive* requirement in Climate Zone 7 of the NECB, one solution would be a continuous insulation layer of 4" (102 mm) of ccSPF (R-24), a 3.5" (89 mm) stud space filled with R-13 batt finished with 5/8" (16 mm) GWB (R-7.4 including films) and a 3" (76 mm) firestopping gap, to achieve U_{SI}=0.20 (R_{WW}-28.7). **Of course, modest improvements in window performance and/or reductions in window area will also meet the standard through the simple enclosure trade-off method.**

Using the same simple calculations, Table 10 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 of 12" (305 mm) thick floor slabs and metric units.

Table 10: Whole-wall R-value for Architectural Precast Panels (I-P)

8" floor slabs		Floor-to-floor height (ft)						
Rcw	**Slab edge (in)**	**9**	**10**	**12**	**14**	**16**	**20**	**24**
2.1	1	2.2	2.2	2.2	2.2	2.2	2.2	2.1
	2	2.3	2.3	2.2	2.2	2.2	2.2	2.2
7.4	1	7.0	7.0	7.1	7.1	7.2	7.2	7.2
	2	7.5	7.5	7.5	7.5	7.5	7.5	7.5
8.5	1	7.8	7.9	8.0	8.0	8.1	8.2	8.2
	2	8.5	8.5	8.5	8.5	8.5	8.5	8.5
10	1	8.9	9.0	9.2	9.3	9.4	9.5	9.6
	2	9.9	9.9	9.9	9.9	9.9	9.9	9.9
12	1	10.3	10.4	10.6	10.8	11.0	11.1	11.3
	2	11.6	11.6	11.7	11.7	11.7	11.8	11.8
14	1	11.5	11.7	12.0	12.3	12.5	12.8	12.9
	2	13.2	13.2	13.4	13.4	13.5	13.6	13.7
16	1	12.7	12.9	13.4	13.7	13.9	14.3	14.6
	2	14.7	14.8	15.0	15.1	15.2	15.4	15.5
18	1	13.7	14.1	14.6	15.0	15.3	15.8	16.1
	2	16.2	16.3	16.6	16.8	16.9	17.1	17.3
20	1	14.7	15.1	15.8	16.3	16.7	17.2	17.6
	2	17.6	17.8	18.1	18.4	18.6	18.8	19.0
24	1	16.5	17.1	17.9	18.6	19.1	20.0	20.5
	2	20.2	20.5	21.0	21.4	21.7	22.1	22.4
28	1	18.1	18.8	19.9	20.7	21.4	22.5	23.3
	2	22.6	23.1	23.8	24.3	24.7	25.3	25.7
	3	24.9	25.1	25.6	25.9	26.1	26.5	26.7
32	1	19.5	20.3	21.6	22.7	23.6	24.9	25.8
	2	24.8	25.4	26.3	27.0	27.5	28.3	28.9
	3	27.6	28.0	28.6	29.0	29.4	29.8	30.2

4.2.3 Accounting for Anchors

Many codes do not yet require designers to account for the heat flow through the steel anchors that support architectural precast panels. However, some jurisdictions are beginning to request this level of analysis and many designers of high-performance enclosures may wish to estimate their impact. An introduction to assessing the impact of panel anchors is presented next.

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

The most practical and sufficiently accurate method of accounting for the impact of steel connectors passing through precast concrete panels on overall thermal performance is to add the heat loss from each anchor. A chi-factor (Ψ) (see Section 3.4) for a single anchor can be generated using a 3D computer model. The reduction in R-value can then be calculated by dividing the number of anchors by the total area of the precast panel:

$$R_{ww} = A \,/\, [\, A/R_{ww} + \Psi \bullet n \,] \qquad \text{(Eqn 9)}$$

where A is the total panel area,

Ψ is the “chi” heat loss factor of a single anchor, and

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

A 3-D computer model of a generic architectural precast anchor was generated for this guide (see Appendix B) and the results are summarized in Table 11.

Table 11: Chi-factor (χ) for a single generic precast anchor

Stonewool Firestopping Thickness		Anchor Chi	
inches	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 panel system described (Rww= 16.1, RSI= 2.83) in the previous example is hung from two steel knife-edge connectors. The average panel is 12 feet (3658 mm) wide and hence 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 1" (25.4 mm) firestopping gap is 0.31 Btu/F (0.16 W/K). Hence, the whole-wall R-value of panel, including two connectors is

$$R_{ww} = A / [A/R_{ww} + \Psi \bullet n] = 151.9 / [151.9/16.1 + 0.31 \bullet 2] = 15.1$$

Thus, in this scenario, including the anchors in the calculation would lower the R-value from 16.1 to R-15.1 (U=0.066, USI=0.376). Therefore, including anchors would result in the U-value of this design being above the minimum Climate Zone 5 and 6 ASHRAE 90.1-2010 prescriptive requirements. There are numerous techniques that can be used to reduce the thermal impact of anchors such as encasing them in insulation. While thermally effective these methods must be balanced against the potential need to inspect the anchor in the future and the risk of condensation.

A thermally problematic connection can occur in low-rise buildings if the concrete panel is supported directly on a concrete foundation. This detail can be avoided in design by using precast connections similar to the anchors used in high-rise buildings described above, which will allow the insulation to continue below grade in an unbroken manner proud 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 (sandwich) 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 sandwich panel section is shown in Figure 15.

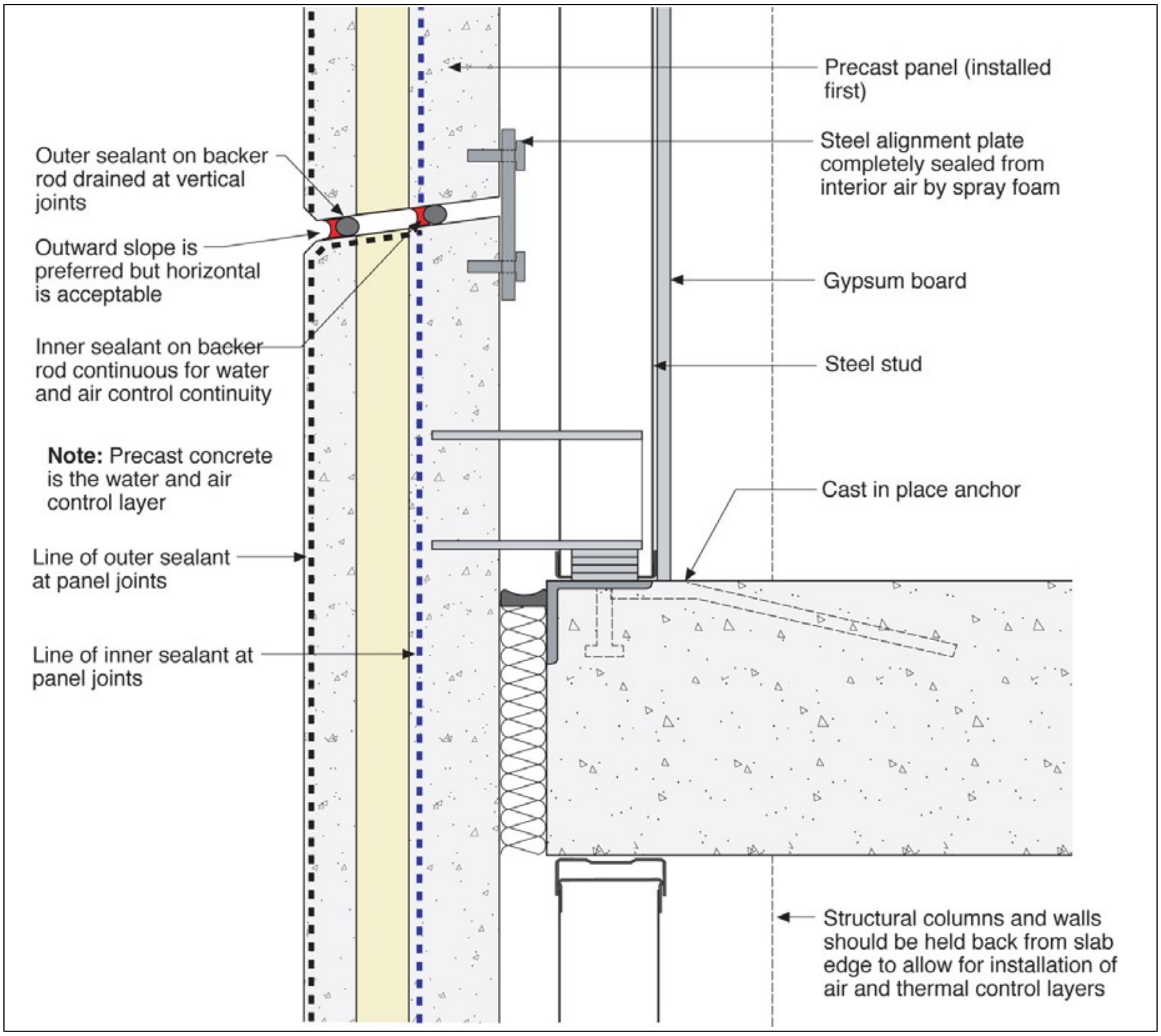


Figure 15: Section at floor of a high-performance double-wythe insulated precast concrete sandwich panel (CPCI 2013).

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. Over the last thirty years connectors have been developed to connect the exterior layer through the insulation with a limited amount of thermal bridging. Stainless-steel wire, glass- and carbon-fiber reinforced plastic provide a wide range of proven structural solutions with little impact on thermal performance.

In most cases codes will accept the full R-value of the continuous insulation layer. However, some code officials may require evidence from the manufacturer that the connection system used does not impair the thermal performance[14].

[14] 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 architectural 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 add only a modest amount, and the wire/composite connectors reduce the performance very 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 sandwich panels using small stainless wire connectors or composite polymer connectors (two technologies with limited thermal impact) is summarized in Table 12 below as a function of insulation type and thickness.

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. Hence, neither condition impacts the thermal performance.

> **Example**: What is the whole-wall R-value and U-value for a double-wythe precast wall system (Figure 16) comprising a 3” concrete outer wythe, 4” of XPS insulation, and 5” concrete inner wythe? The system will span 14’6” (4420 mm) from floor-to-floor. The floors are comprised of an 8” (200 mm) deep reinforced concrete slab with 12” (305 mm) deep drop-panels. A 1” (25.4 mm) 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 floor-to-floor height, firestop thickness, and attachment have no effect on the thermal performance of the enclosure.
>
> A simple estimate, using Table 7, would be R-20 (RSI 3.52), as 4” of XPS is specified. Table 12 provides an estimate of R-21.4 (RSI 3.76) as it includes 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 light-gauge steel studs that support interior drywall.

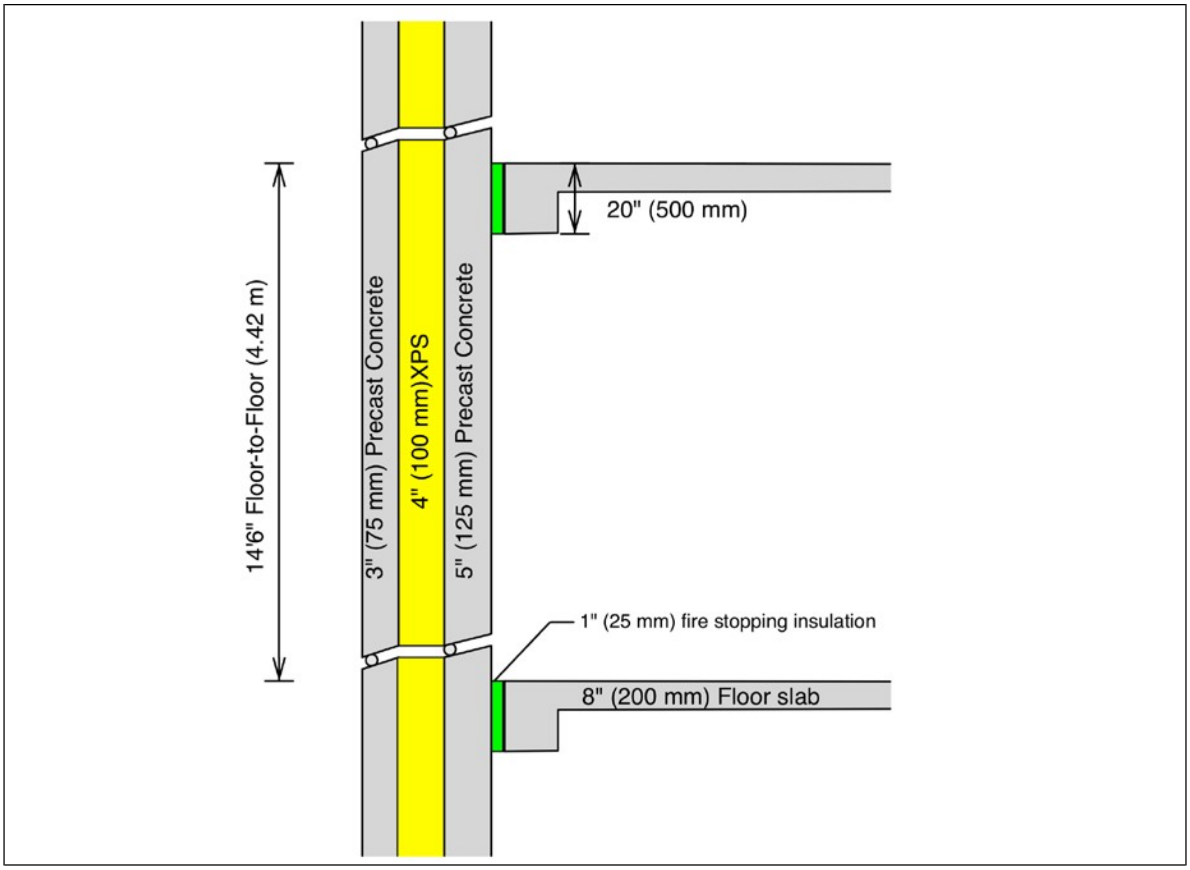


Figure 16: Example double-wythe (sandwich) panel.

Such a system would meet the *prescriptive* requirements of ASHRAE 90.1-2010 up to Climate Zone 8 (or Climate Zone 6 under Ontario's SB-10) and or NECB Climate Zone 5. To achieve higher performance, thicker insulation (6" of XPS would meet all climate zones for the NECB, and 5" of PIC would exceed NECB Zone 7 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, the example system would exceed the requirements of Ontario's SB-10, Climate Zone 6 if windows with a U-value of about 0.35 were specified in a building with a WWR of 40% (see Figure 10). To meet NECB Climate Zone (CZ) 7B buildings, either a 25% WWR ratio and U=0.30 windows, or U=0.20 windows and 42% WWR would be compliant with the simple trade-off compliance path.

Table 12: Approximate Whole-wall Thermal Resistance of Double-wythe Insulated Precast Sandwich Panels

	Insulation Type		
Insulation Thickness (in)	R4/in (MW/EPS)	R5/in (XPS)	R5.5/in (PIC)
2	9.4	11.4	12.4
2.5	11.4	13.9	15.1
3	13.4	16.4	17.9
3.5	15.4	18.9	20.6
4	17.4	21.4	23.4
4.5	19.4	23.9	26.1
5	21.4	26.4	28.9
6	25.4	31.4	34.4
8	33.4	41.4	45.4

Note: Insulation values include air films and 7" (178 mm) of concrete, but assume inter-wythe connections have negligible impact on heat flow

Insulation Thickness (mm)	k=0.036 W/mK (MW/EPS)	k=0.029 W/mK (XPS)	k=0.026 W/mK (PIC)
51	1.65	2.00	2.18
64	2.00	2.44	2.66
76	2.35	2.88	3.14
89	2.70	3.32	3.63
102	3.06	3.76	4.11
114	3.41	4.20	4.60
127	3.76	4.64	5.08
152	4.46	5.52	6.05
203	5.87	7.28	7.99

4.4 Total Precast

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

Total precast double-wythe insulated sandwich panel systems (Figure 17) 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.

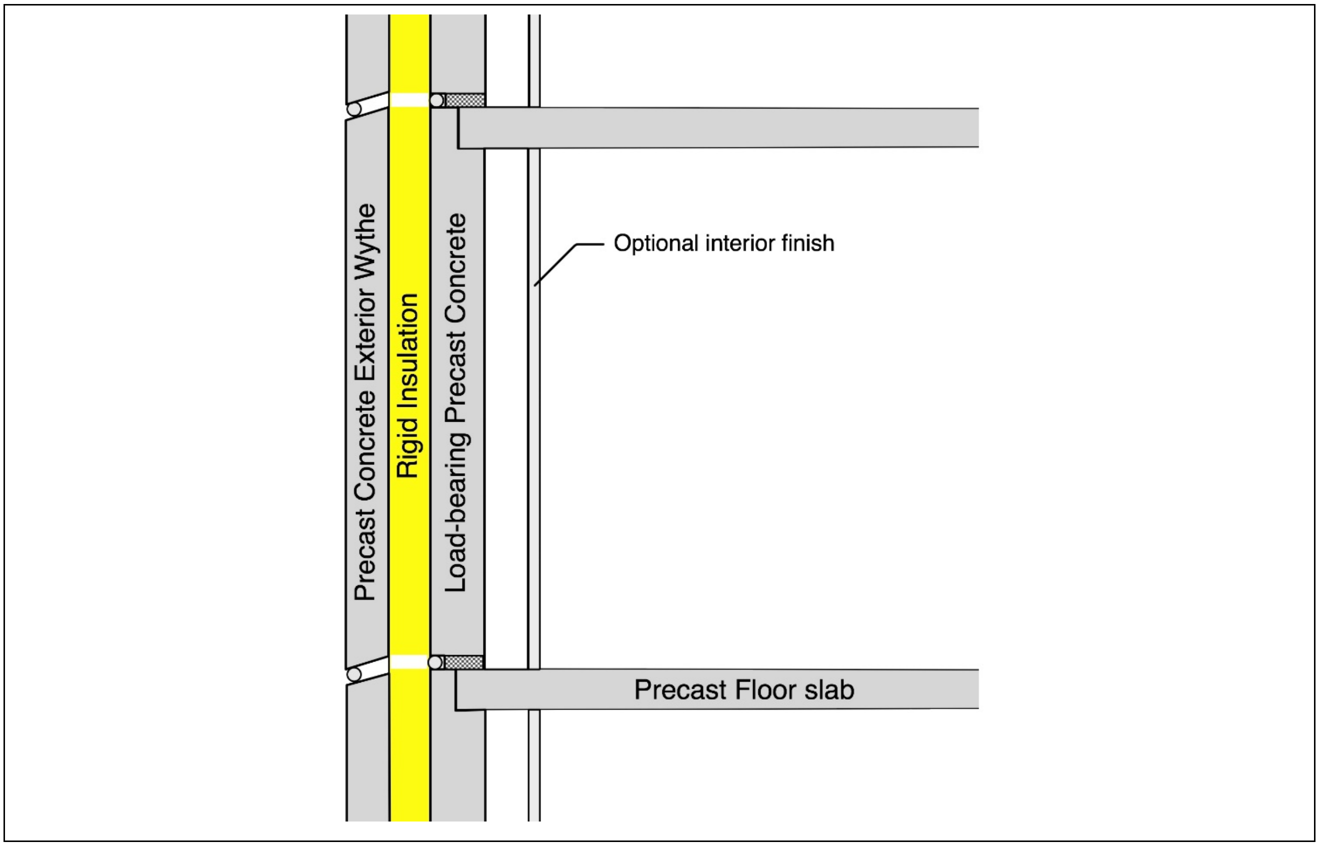


Figure 17: Double-wythe insulated "sandwich" total precast.

4.4.1 Clear-wall R-value

For single-wythe total precast system wall panels used as enclosures, the clear-wall R-value is calculated in exactly the same manner as described in Section 4.2.1 for architectural precast panels.

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

The primary and most important thermal difference between single-wythe total precast and other precast systems is the manner in which heat flows 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[15]. The thermal bridge waivers (e.g., less than 2% of area penetrating the enclosure) do not apply. The following section describes approximate calculation methods for this condition.

The whole-wall R-value for a total precast wall system including the impact of a through-penetrating floor system can be calculated in a similar manner to architectural 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:

$$R_{ww} = 1 / \{ [(FF - T_{fl}) / FF] / R_{cw} + (T_{fl} / FF) / R_{fl} \} \qquad \text{(Eqn 10)}$$

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

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).

Example: A total precast system (Figure 18) with a floor-to-floor height of 9’8” (2.95 m) comprises an 8” (200 mm) concrete wall, 3” (75 mm) of mineral wool, a 3.5” (90 mm) steel stud with R-13 batt, 5/8” (15 mm) gypsum supporting an 8” (200 mm) 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:

[15] 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 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.

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

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

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 may still be code compliant if the window area is reduced, or the window performance is improved, so that the overall R-value is still compliant. For example, using Figure 10 as a guide, this enclosure would be compliant with ASHRAE 90.1-2010 up to Climate Zone 8 if windows of U-value of 0.3 were specified, and Ontario's SB-10 up to Climate Zone 6 if the WWR was also reduced to about 32%. Of course an energy model can be used via the whole building energy compliance path to allow mechanical and electrical system trade-offs to allow more flexibility of window area and performance.

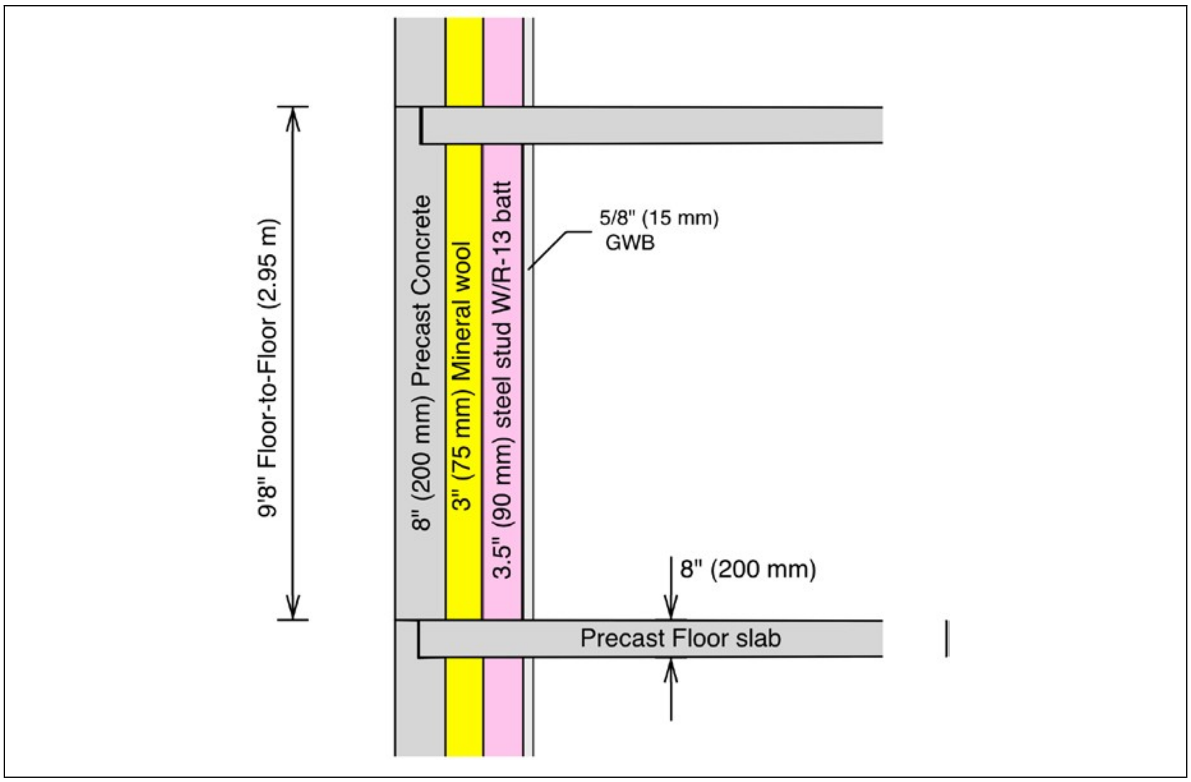


Figure 18: Example generic total precast whole wall.

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 13.

Table 13: Approximate Generic Total Precast Whole-wall R- and RSI-values

	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 19. 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 blunted 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 14) show that the thermal performance is somewhat 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 10’ (3.048m), and R-25 (RSI4.40) 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) and hence Table 14 can be used. The results show an estimated whole-wall R-value of 11.8 (RSI 2.08). Referring to Figure 10, and interpolating between the R-10 and R-20 line, this system would meet the requirements of ASHRAE 90.1-2010 Climate Zone 7 with 40% WWR and window U-value of 0.3, or NECB Climate Zone 5 with 40% WWR and window U-value of 0.3, or Ontario’s SB-10 Climate Zone 6 with 34% WWR and window U-value of 0.3.

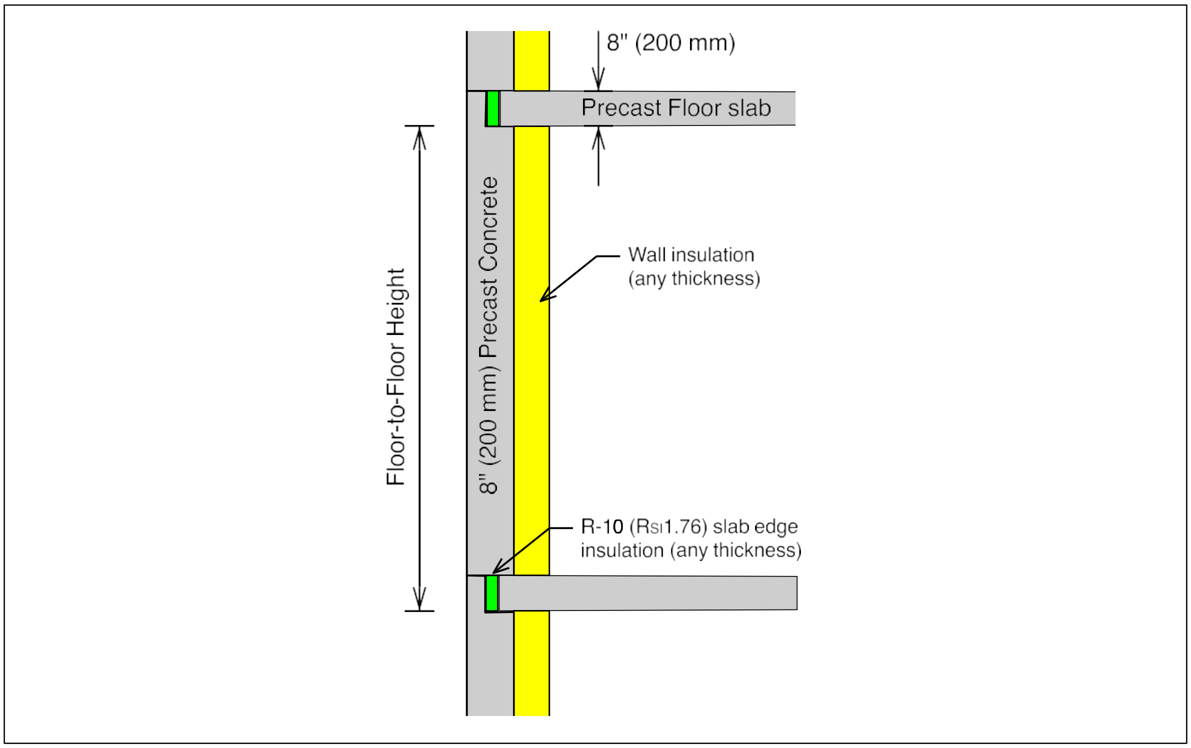


Figure 19: Single-wythe total precast system with slab edge insulation assumed for calculations in Table 14.

An alternate higher performance insulated corbel system was also calculated. This system and the results are described in more detail in Appendix E.

Table 14: Approximate Generic Total Precast Whole-wall R- and RSI-values for Insulated Slab Edge Design of Figure 19

	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

5.0 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 better understanding and 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 clearly 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.

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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, 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 manufacture, 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 (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 stonewool and fiberglass) can vary significantly from one product to another.

The transfer 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 2013). 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: Architectural Precast Concrete 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.

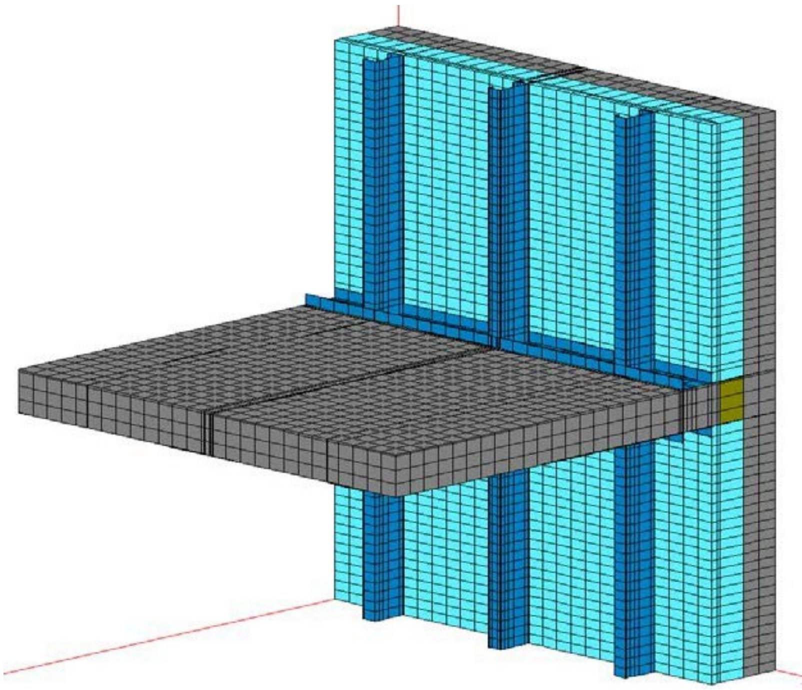
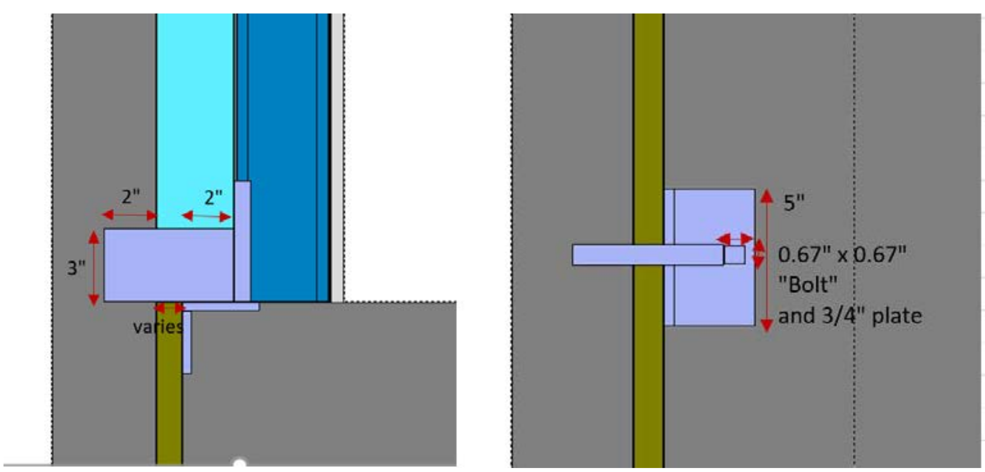


Figure B1: Finite volume model used to assess heat flow at anchors.



Note: 1" =25.4 mm

Figure B2: Vertical and horizontal section of generic precast anchor.

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

	Insulation Thickness	Firestopping Gap Thickness	Clear-wall U (W/m2K)	Psi (W/mK)	Chi (W/K)
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 Stonewool (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 R-value and U-value using the following standard equation:

$$U_{ww} = [U_{cw} \cdot A + \Psi \cdot w + \chi \cdot n]$$

where:

U_{ww} = whole wall thermal transmittance [W/m²C]
U_{cw} = Clear-wall thermal transmittance
A = area of panel [m²]
Ψ = psi value [w/m*k]
w = width of the precast panel [m]
χ = chi value [w/k]
n = number of anchors

Appendix C: Supplementary Tables

Table C1: Whole-wall RSI Values for Architectural 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 Architectural 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: Summary of Current Canadian Energy Codes

Alberta, Manitoba, New Brunswick, Nova Scotia, Northwest Territories, Nunavut, and Yukon

Several provinces and all the territories are currently using the NECB 2011 whose opaque above-grade wall building envelope thermal performance requirements are given in the table below. Some provinces have issued amendments to the code but they do not generally change these requirements. NECB 2011 dictates that calculations can be carried out following a number of given recognized procedures including ASHRAE handbooks, standards, and guidelines. Typically, the calculation procedures in the ASHRAE 90.1 standard are used.

Table D1: NECB 2011 (and NECB 2015) Above-Grade Opaque Wall Thermal Performance Requirements

Climate Zone	Max. U-value SI ($W/m^2\,°C$)	IP ($BTU/\ h\ ft^2\ °F$)
4	0.315	0.055
5	0.278	0.049
6	0.247	0.044
7	0.210	0.037
8	0.183	0.032

Newfoundland and Labrador/Prince Edward Island/Saskatchewan

Newfoundland and Labrador, Prince Edward Island, and Saskatchewan currently follow National Building Code of Canada 2010 only and are expected to soon adopt the NECB 2011.

Quebec

Quebec has an act called the *Regulation Respecting Energy Conservation in New Buildings Act*. This act has separate requirements for buildings with low and high energy requirements for lighting, fans, and pumps. The requirements are given as nominal thermal resistance values and are provided below. Most concrete and masonry wall systems will be considered “Mass Walls.” The Quebec act doesn’t define these wall systems and it is assumed in this guide that definitions in other common energy codes apply which will be discussed later in this section. The act includes a requirement for an additional 20% of thermal resistance for portions of the enclosure where metal posts, metal studs, or metal joists act as thermal bridges and less than 25% of the thermal insulation is continuous exterior insulation. These higher values are listed under “Other Walls – Steel-Framed” in the table below.

Table D2: Quebec New Buildings Act Thermal Resistance Requirements for Walls – SI (IP) units

Zones	Low Lighting, Fan, and Pump Loads		High Lighting, Fan, and Pump Loads	
	Mass Walls	Other Walls – Steel-Framed	Mass Walls	Other Walls – Steel-Framed
A	2.9 RSI (R16)	4.1 RSI (R23)	2.9 RSI (R14)	3.4 RSI (R19)
B	3.1 RSI (R18)	4.3 RSI (R25)	3.1 RSI (R15)	3.6 RSI (R20)
C	3.3 RSI (R19)	4.6 RSI (R26)	3.3 RSI (R16)	3.8 RSI (R22)
D	3.5 RSI (R20)	4.8 RSI (R27)	3.5 RSI (R17)	4.2 RSI (R24)
E	3.7 RSI (R21)	5.0 RSI (R29)	3.7 RSI (R18)	4.6 RSI (R26)
F	3.9 RSI (R22)	5.4 RSI (R31)	3.9 RSI (R20)	4.9 RSI (R28)

British Columbia

The province of British Columbia allows use of NECB 2011 or ASHRAE 90.1-2010. The city of Vancouver has a building by-law which adds additional requirements but uses the same thermal performance requirements for building enclosures. ASHRAE 90.1-2010 Table 5.5 provides maximum assembly U-values and alternative minimum nominal insulation thermal resistances for various wall types. The requirements for concrete wall systems are summarized below for mass walls and steel-framed walls.

Table D3: ASHRAE 90.1-2010 Building Envelope Requirements for Walls, Above Grade - SI (IP)

Climate Zone	Non-residential			Residential		
	Assembly	Insulation		Assembly	Insulation	
	Maximum U-Value	Minimum RSI-Value (R)		Maximum U-Value	Minimum RSI-Value	
		Batt	c.i.		Batt	c.i.
Mass						
4	0.591 (0.104)	NA	1.7 (R9.5)	0.511 (0.090)	NA	2.0 (R11)
5	0.511 (0.090)	NA	2.0 (R11)	0.454 (0.080)	NA	2.3 (R13)
6	0.454 (0.080)	NA	2.3 (R13)	0.403 (0.071)	NA	2.7 (R15)
7	0.403 (0.071)	NA	2.7 (R15)	0.403 (0.071)	NA	2.7 (R15)
8	0.403 (0.071)	NA	2.7 (R15)	0.295 (0.052)	NA	4.4 (R25)
Steel-Framed						
4	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)
5	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)
6	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)
7	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)	0.238 (0.042)	2.3 (R13)	2.7 (R16)
8	0.363 (0.064)	2.3 (R13)	1.3 (R7.5)	0.210 (0.037)	2.3 (R13)	3.3 (R19)

Ontario

The energy performance of buildings in Ontario is governed by *Supplementary Standard SB-10* for which an updated version took effect January 1, 2017. Within the requirements, projects can choose from one of three compliance path energy performance standards:

→ NECB 2015 with amendments;

→ ASHRAE 90.1-2013 with amendments; or

→ ASHRAE 189.1-2014.

NECB 2015 has greater energy performance requirements than NECB 2011 but the prescriptive building enclosure thermal performance requirements are the same and that portion of the standard is not amended by the bulletin. The exception to this is that the SB-10 amendment dictates that a thermal resistance value of U_{SI}-0.183 (R-31) be used across Ontario for electrically heated buildings regardless of climate zone. The amendment also addresses a wider range of thermal bridging issues that are discussed in the guide.

The amendments for ASHRAE 90.1-2013 are significant and more closely align building enclosure requirements with NECB 2015. These are given below. It should be noted that SB-10 includes an allowance to use older requirements for permits applied for between January 1, 2017 and December 31, 2017.

Table D4: Supplemental Bulletin-10 Amended Requirements for Above Grade Walls from ASHRAE 90.1-2013 – SI (IP) units

Climate Zone	Non-residential			Residential		
	Assembly	Insulation		Assembly	Insulation	
	Maximum U-Value	Minimum RSI-Value		Maximum U-Value	Minimum RSI-Value	
		Batt	c.i.		Batt	c.i.
Mass						
5	0.307 (0.0541)	NA	3.0 (R17)	0.273 (0.0481)	NA	3.3 (R19)
6	0.273 (0.0481)	NA	3.3 (R19)	0.261 (0.0460)	NA	3.5 (R20)
7	0.261 (0.0460)	NA	3.5 (R20)	0.261 (0.0460)	NA	3.5 (R20)
Steel-Framed						
5	0.281 (0.0495)	2.3 (R13)	2.1 (R12)	0.281 (0.0495)	2.3 (R13)	2.1 (R12)
6	0.250 (0.0440)	2.3 (R13)	2.6 (R15)	0.250 (0.0440)	2.3 (R13)	2.6 (R15)
7	0.250 (0.0440)	2.3 (R13)	2.6 (R15)	0.215 (0.0379)	2.3 (R13)	3.5 (R20)

ASHRAE 189.1 is more stringent than NECB 2015 or the modified ASHRAE 90.1 2013 requirements. It is not commonly used and is not summarized here.

Appendix E: Alternate Total Precast System Results

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

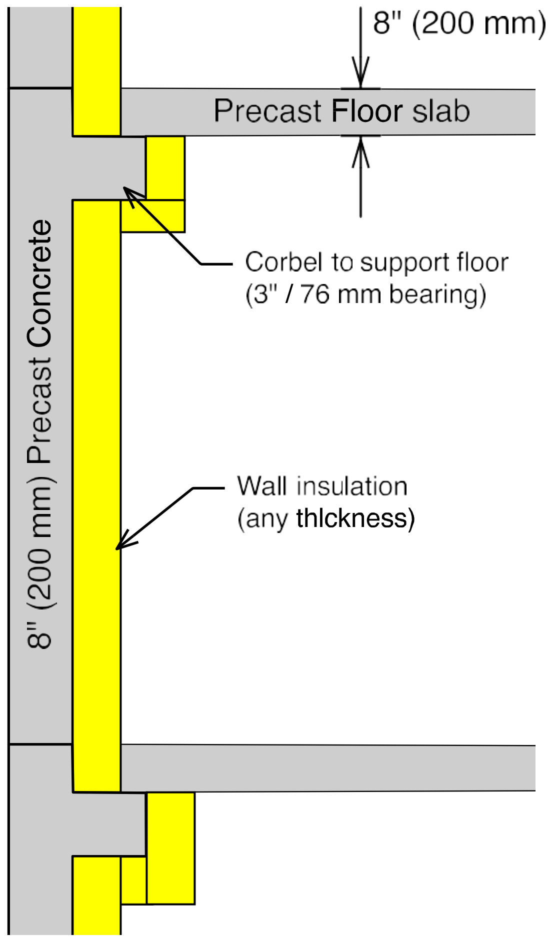


Figure E1: Alternate insulated slab edge solution.

The corbel was assumed to be 8" (200 mm) deep and insulated in the same manner as the wall. The same hollow core precast floor slabs were assumed as for other solutions. An example of the thermal gradients and geometry is shown in the figure below.

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.

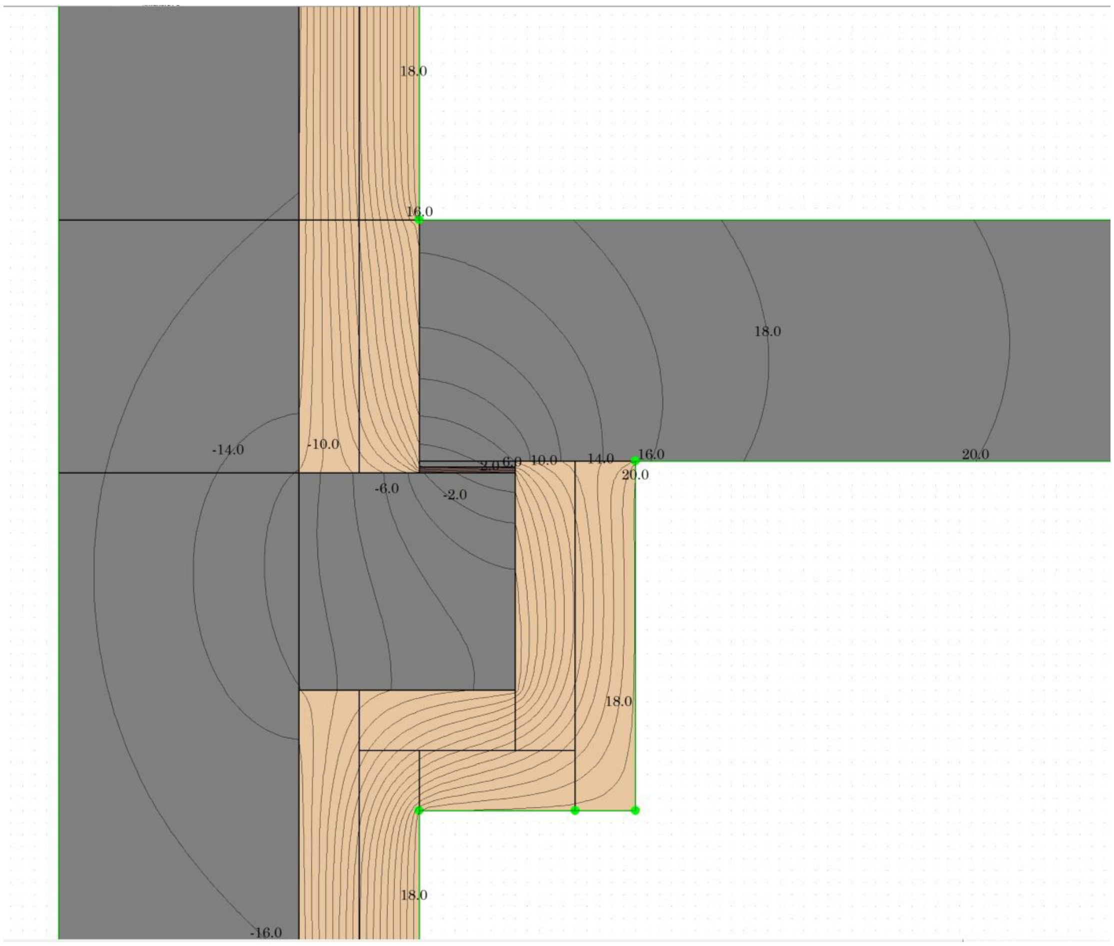
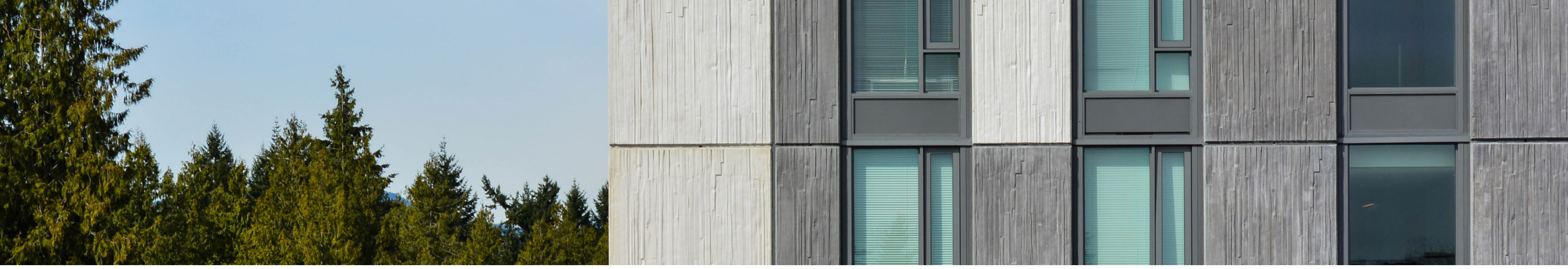


Figure E2: Example of insulated corbel total precast system geometry and isotherms.

Table E1: Total Precast 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



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