CANADIAN PRECAST/PRESTRESSED CONCRETE INSTITUTE

Meeting and Exceeding Building Code Thermal Performance Requirements

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1.1 Introduction

Energy and thermal performance requirements play an increasingly significant role in building codes throughout North America. This document provides designers, builders, and building owners with:

- → an introduction to the need for, and challenges associated in delivering highly-insulated building enclosures (Section 1.2),
- → a summary of the current thermal performance requirements in the Canadian codes (Section 1.4 Energy Codes, Programs, and Standards),
- → an explanation of approximate methods to predict the thermal performance of common precast concrete systems for use during early design stages (Chapter 3), and
- → a catalogue of example precast enclosure system solutions to meet the thermal performance requirements for each Province and climate zones in Canada (Chapter 4).

1.2 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, ASRHRAE Standard 90, in 1975. The earliest national standard for building energy performance, the National Energy Code for Buildings (NECB) of Canada (NECB 2011), was introduced to Canada in 1997 while the International Energy Conservation Code (IECC) was not introduced in the United States until 2000.

In the early days neither ASHRAE Standard 90 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 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 construction materials and systems have 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 to compare and assess their actual in-service thermal performance. The focus on better methods of predicting heat flow has entered, 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.

This guide addresses a range of precast concrete enclosure designs with highly effective thermal resistance and present the reader with approximate methods to predict the thermal performance of common precast concrete systems for use during early design stages.

1.3 Scope and approach

The scope of this guide is limited to early stage design estimates of effective thermal resistance of precast concrete enclosure wall systems with windows. The purpose is to allow design and energy modeling to proceed by demonstrating what thickness of insulation would be required for specific R-value target. The information is also intended to assist designers and owners make better comparisons between systems at the early stage of design (when many irrevocable decisions are made).

Details that increase thermal bridging, such as parapets, balconies, base transitions, window installation, and other 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.

1.4 Energy Codes, Programs, and Standards

The energy used in institutional, commercial, industrial (ICI) and multi-unit residential buildings (MURBs) in cold climates is substantial. The building enclosure and its performance almost always has a greater impact on the energy used in a building than any other building component: more than lighting, more than mechanical systems, more than office equipment. Hence, to reduce the operational energy consumption of buildings high-performance building enclosures are required. In fact, it is almost impossible to conceive of a low-energy consumption building (and all net-zero energy building must first be low-energy consumption buildings) in cold climates that does not have an exceptional building enclosure.

The total energy demand of Canadian office buildings, which are mostly cold climate buildings (even Zone 4 buildings have significant heating loads), surveyed in 2007 is plotted in Figure 1. It can be seen that the largest energy use is clearly space heating and cooling. Heating demand is driven almost entirely by thermal conduction through the enclosure (measured by the U-value or R-value) and air leakage / ventilation. Hence, increasing effective enclosure R-value and airtightness can have a major impact on national building energy use. However, as building enclosures have become better insulated and more airtight, other aspects of energy use in buildings have become important to total building energy use. For example, the efficiency of heating and cooling equipment, lighting, ventilation, pumps, and fans, have the same importance to energy use as the enclosure.

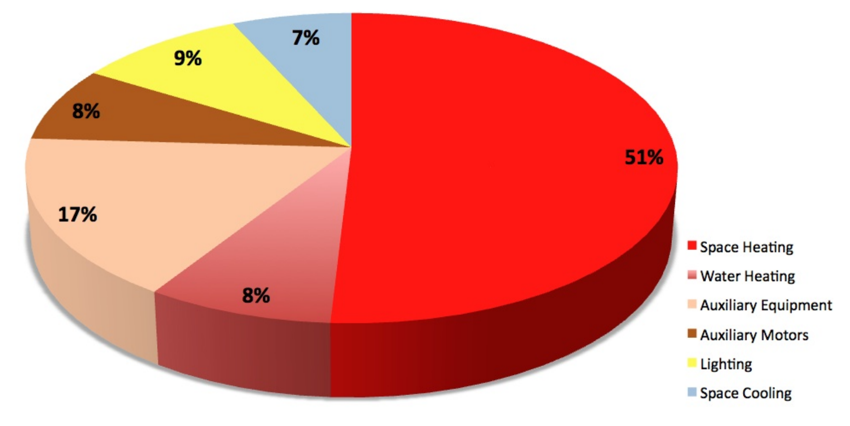


Figure 1: Energy Use in Canadian Office Buildings (Straube 2012)

Building codes across North America typically define the lowest performance that designers are legally allowed to provide. Climate is a major criteria used in most codes to specify what measures are required. The most commonly used climate categories today used a similar zone numbering system as US codes. A map of Canada showing the approximate range of zones is provided in Figure 2.

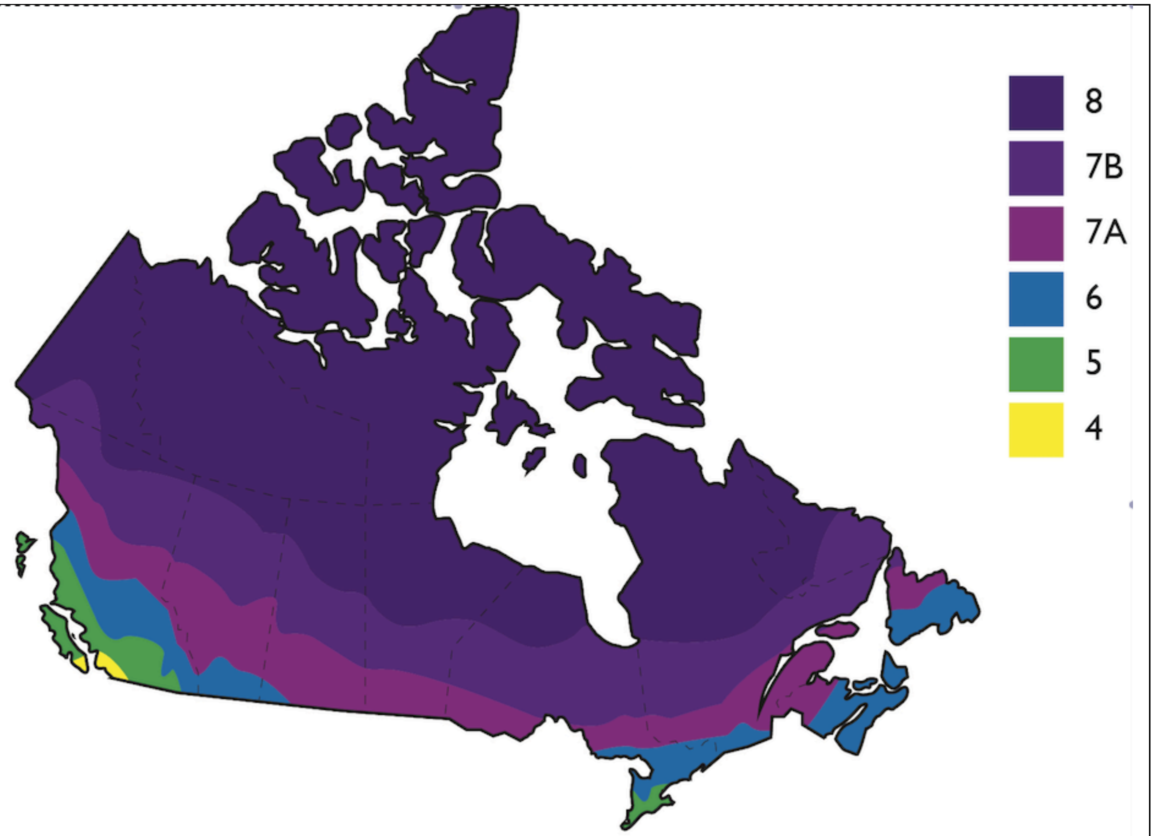
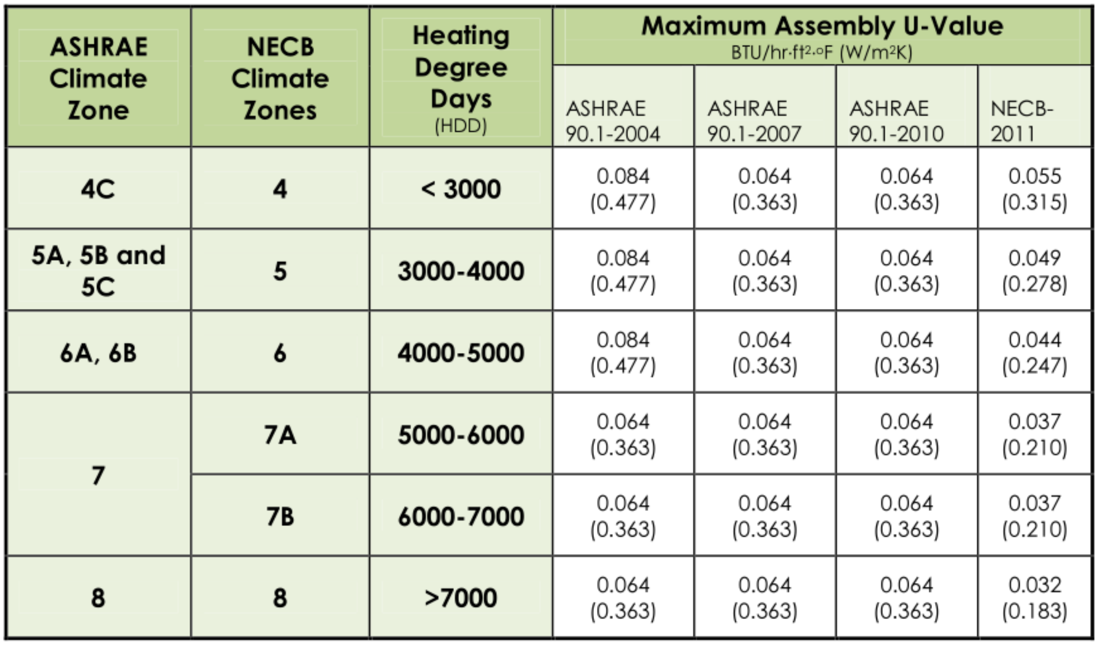


Figure 2: Climate Zones for Energy Code Compliance

The minimum required performance levels demanded by codes have been changing, and becoming more complex, more demanding, and usually more precise since they began to be prescribed shortly after the oil price shocks of the early 1970's. Building rating or labelling programs, such as LEED, Energy Star, BREAM, PassivHaus usually require higher levels of performance than the code minimum. Figure 4 plots the relative whole building energy use for a minimum compliant building and tracks changes from the first ASHRAE 90.1 Energy Standard published in 1975 up to 2013.

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. This approach is still used in many single-family residential energy codes. The advantage of this approach is that relatively simple-to-read tables are provided with minimum or maximum values for each energy consuming component of an enclosure as a function of climate zone. Figure 3 summarizes the maximum allowed assembly U-value (that is, 1 over R-value) for both ASHRAE 90.1 (2004, 2007, and 2010) and the National Energy Code for Buildings (NECB 2011) codes as a function of climate zone.



ASHRAE Climate Zone	**NECB Climate Zones**	**Heating Degree Days** (HDD)	**Maximum Assembly U-Value** BTU/hr·ft^{2}·°F (W/m^{2}K)			
			ASHRAE 90.1-2004	ASHRAE 90.1-2007	ASHRAE 90.1-2010	NECB-2011
4C	**4**	**< 3000**	0.084 (0.477)	0.064 (0.363)	0.064 (0.363)	0.055 (0.315)
5A, 5B and 5C	**5**	**3000-4000**	0.084 (0.477)	0.064 (0.363)	0.064 (0.363)	0.049 (0.278)
6A, 6B	**6**	**4000-5000**	0.084 (0.477)	0.064 (0.363)	0.064 (0.363)	0.044 (0.247)
7	**7A**	**5000-6000**	0.064 (0.363)	0.064 (0.363)	0.064 (0.363)	0.037 (0.210)
	7B	**6000-7000**	0.064 (0.363)	0.064 (0.363)	0.064 (0.363)	0.037 (0.210)
8	**8**	**>7000**	0.064 (0.363)	0.064 (0.363)	0.064 (0.363)	0.032 (0.183)

Figure 3: Changing Prescriptive Wall U-value for ASHRAE 90.1 and NECB

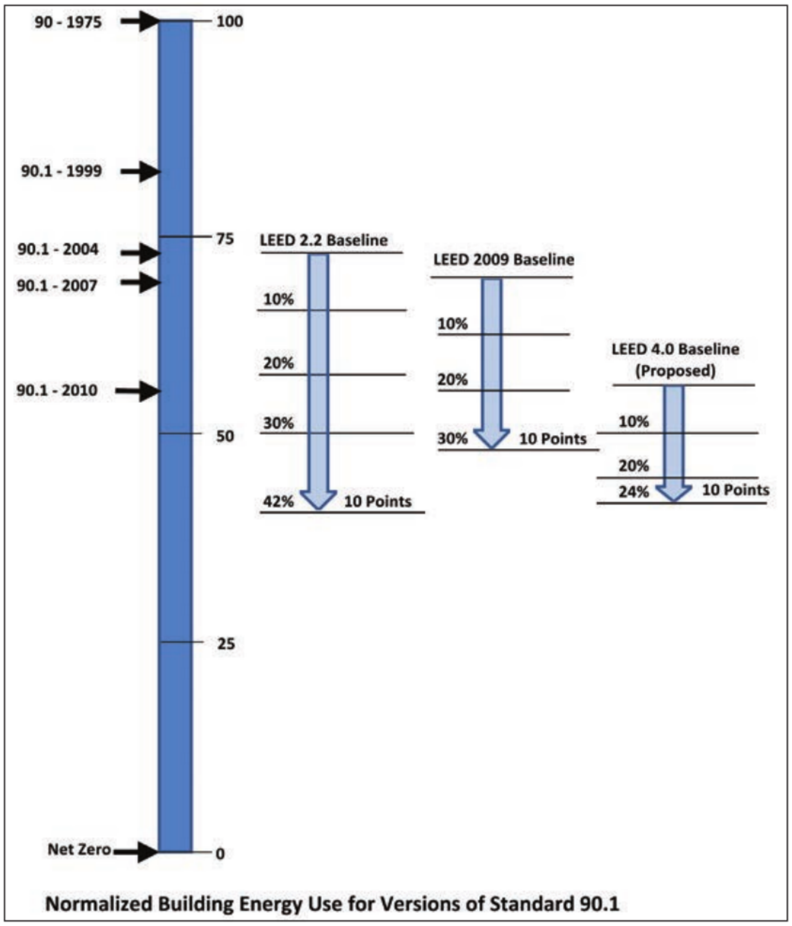


Figure 4: Relative energy use over time along with changes in ASHRAE 90.1 and LEED (ASHRAE 2013). Note that ASHRAE 90.1 – 2010 has been accepted as the baseline for LEED 4.0 (USGBC - http://www.usgbc.org/node/2613358?return=/credits/new-construction/v4/energy-%26amp%3B-atmosphere)

Although specific characteristics (R-value, airtightness, SHGC[1]) of building enclosures can reduce the demand for space heating and cooling, improvements to heating and cooling system efficiencies, lighting design, and mechanical ventilation system 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.

To provide designers the most flexibility, most modern codes, including NECB and ASHRAE 90.1, allow for the trade-off between components: the tabulated prescriptive enclosure R-values can be reduced if the mechanical system is made more efficient. If this trade-off approach is taken (often supported by building energy modeling), there are no prescribed minimum R-values: designers can choose very low R-value skins if they invest in higher performance heating, cooling, ventilation, and lighting equipment.

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[1] 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.

ASHRAE 90.1 limits the window-to-wall ratio (WWR) to 40% in the prescriptive compliance method, and the NECB specifies a maximum fenestration-and door-to-wall ratio FDWR equation that relates to Heating Degree Days (18C base), starting at 40% and dropping to 20% for climate zones 7 and 8 (Figure 5). These limits on window area have been imposed because of many scientific studies demonstrating that window areas greater than these maximums neither reduce lighting energy nor offset winter heating losses with useful solar gains (Carmody et al 2004, Johnson et al 1984, Love et al 2008, Poirazis et al 2008).

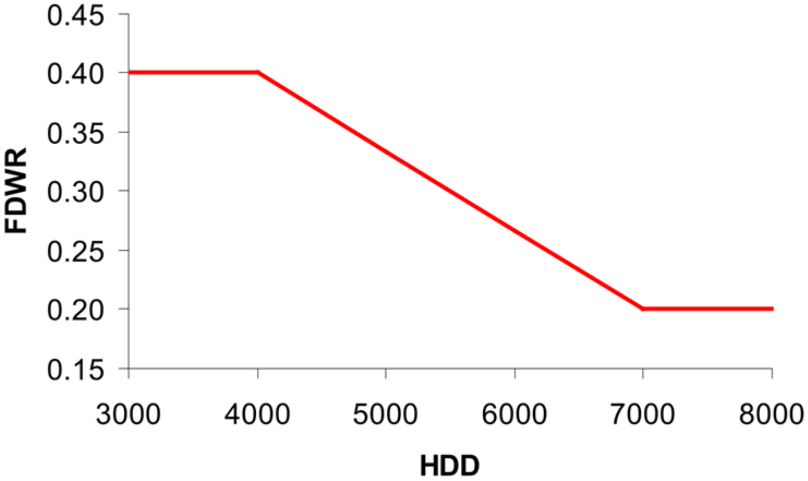

Figure 5: Maximum NECB Fenestration-and-Door-to-Wall-Ratio for using prescriptive approach

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. 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 hotwater) to offset the low thermal performance of the glazing.

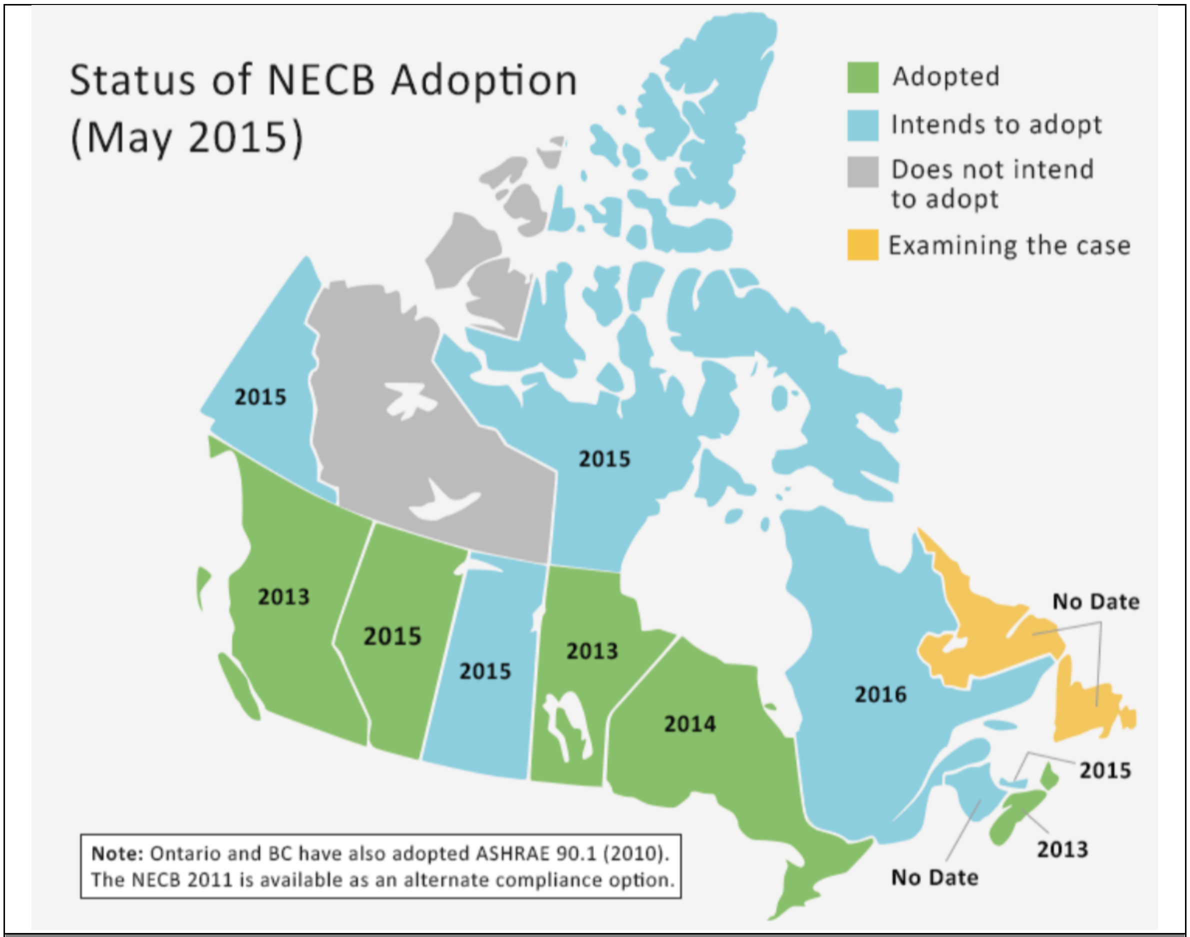

Figure 6: Adoption of Canadian 2011 National Energy Code for Buildings

Codes and standards continue to demand higher R-values (and hence lower U-values) of all opaque wall systems (for example, Figure 7 plots the code change over time in Ontario climate Zone 6). More insulation, better airtightness, and less thermal bridging will be required regardless of the enclosure wall system considered. Precast concrete systems are well-placed to respond to these demands. The thermal performance of precast concrete enclosure systems is considered in more detail in the remainder of this guide.

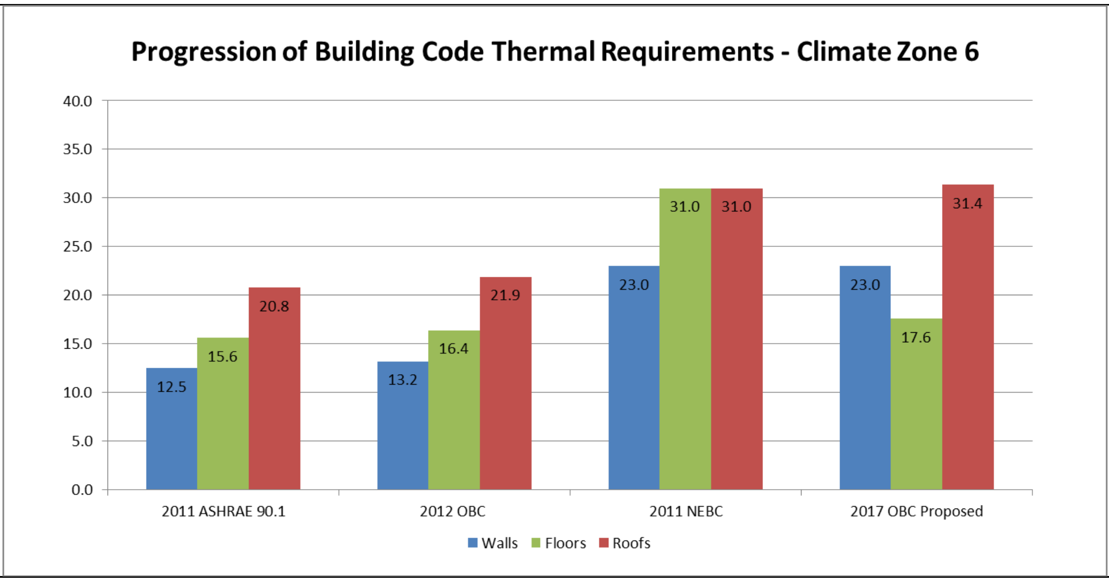

Figure 7: Progression of Building Code Thermal Requirements of the Ontario Building Code-Climate Zone 6

1.5 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).

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 an complete enclosure, with integral fire resistance and air- water- vapor- and thermal control.

Precast Concrete Roofs are often used and are most commonly comprised of hollowcore planks or double-T slabs. Floors over exterior space is another common enclosure made up of this type of precast concrete element. The thermal, air- water- and vapor-control are added to the precast component, almost always to the exterior[2].

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 systems is also used, often termed Total Precast, as it provides both enclosure and primary structural support.

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[2] **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).**

Total Precast Concrete is a system that employs precast concrete enclosure walls, partitions, and floors as part of the total structural system, carrying all lateral and gravity loads. The enclosure walls of this system also collect enclosure loads such as wind and seismic loads.

2 Calculating Heat Flow

There are two common measures of a building assembly's control of heat flow: R-value and U-value.

Although R-value is in traditional units, it remains the most common means of communicating thermal resistance. Canadian codes and standards usually employ metric (SI) units. To differentiate the metric from the traditional, metric thermal resistance is reported as RSI and the two can be easily converted.

R-value = RSI * 5.678

RSI = R-value / 5.678

The R-value (or RSI) is often tabulated 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 = thickness / thermal conductivity = t / k

where

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

t is the thickness of the layer in feet or meters.

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 (most building enclosures), can be calculated from

$R_T = R_1 + R_2 + \ldots + R_n$

where

R_T is total thermal resistance of the assembly, and

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

The U-value is commonly used to describe the *heat transmittance* of an assembly, especially windows and non-standard enclosures, 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. As assemblies have become more varied, and the industry more sophisticated, standards such as ASHRAE 90.1 and NECB have also listed U-values for assemblies. This allows users to calculate the true overall performance of an enclosure assembly to demonstrate compliance.

2.1 Overall Thermal Performance

When heat moves through an enclosure element it flows through more than just the center 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.

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

- → the ***Installed R-value***, or nominal R-value which is arrived at by adding the thermal resistance of all layers (e.g. in a concrete sandwich panel, the outer concrete, insulation, inner concrete),
- → the ***Clear-wall R-value*** (R_{cw})) accounts for the thermal resistance of the layers (Installed R-value) but also includes the two-dimensional effect of standard framing, fasteners and penetrations (e.g. ties in a concrete sandwich panel, or steel studs on the interior of a Total Precast or Architectural panel), and
- → the ***Whole-wall R-value***, (R_{ww}) which includes the Clear-wall R-value *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.
- → The **Overall R-value** ($R_{overall}$) includes the combined effect of Whole-wall R-value plus the heat loss through windows, doors, and curtainwalls. For simplicity, sometimes the Clear-wall R-value is used (i.e., thermal bridging is ignored), but this approach can significantly over-estimate the thermal performance many commercial enclosure systems.

A range of different metrics are used to rate the thermal transmittance of vision and non-vision wall assemblies. For opaque walls it is common to specify thermal resistance, R_{CW}, in an RSI (°C m^2/W) or R-value (°F ft^2/Btuh) while U-value (W/m^2 °C or Btuh/ft^2 °F) is used for thermal transmittance, U_V, of vision glazing. Building codes typically use a nominal R-value/RSI requirement which only accounts for the insulation while window U-values include surface films and should include the thermal bridging effects of framing and edge-of-glass construction.

The thermal performance of an entire vertical assembly can be drastically changed by modifying the Window to Wall Ratio (WWR) (Ross and Straube 2014). 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, is recommended as a single metric. The simple trade-off compliance path in most codes are designed to ensure that this Overall R-value is more than some minimum value (currently the overall R-value is R-4.6 for ASHRAE 90.1-2010 Zones 5 and 6).

Overall equivalent transmittance, $U_{overall}$, (and $R_{overall} = 1/ U_{overall}$) can then be calculated as:

$$U_{overall} = (1\text{-}WWR) / R_{CW} + WWR \cdot A \cdot U_V$$

where

WWR is the Window-to-Wall Ratio,

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

U_V is the U-value of vision areas.

Although not commonly restricted by codes, the whole wall solar heat gain coefficient, $SHGC_{ww}$, captures the effect of glazing ratios and glazing performance. Opaque walls have a very low solar heat gain coefficient and can often be assumed to be zero. Hence, an overall enclosure SHGC can be calculated from the vision SHGC as

$$SHGC_{ww} = WWR * SHGC.$$

2.2 Thermal Bridging

Thermal bridging effects not accounted for in the clear wall performance (R_{cw}) can be captured by adding 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 models.

Clear wall R-value, R_{cw}, 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. The whole-wall R-value for a generic wall system can be calculated using

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

where

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

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

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

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

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

This calculation can be applied to all enclosure systems, but requires the development of specific factors.

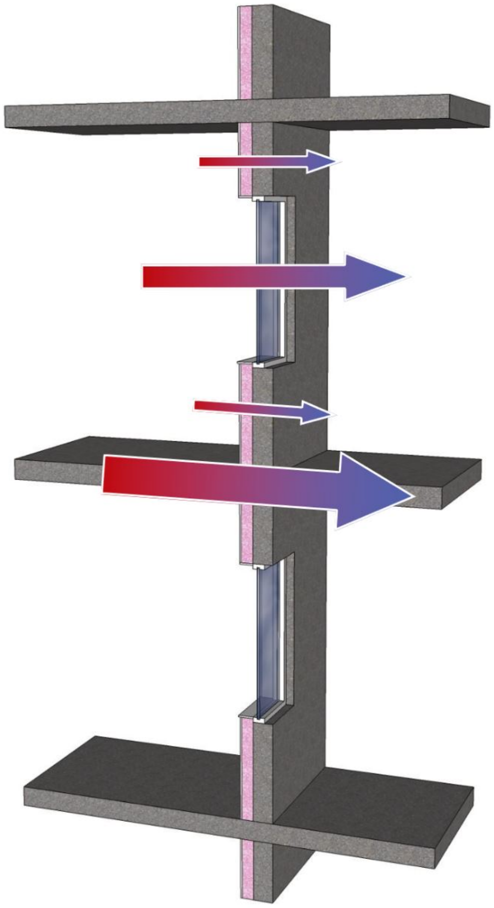


Figure 8: Heat flow through center of wall, floor slab, and window.

Precast concrete systems can often use simpler approaches with standard factors. These will be presented in Chapter 3.

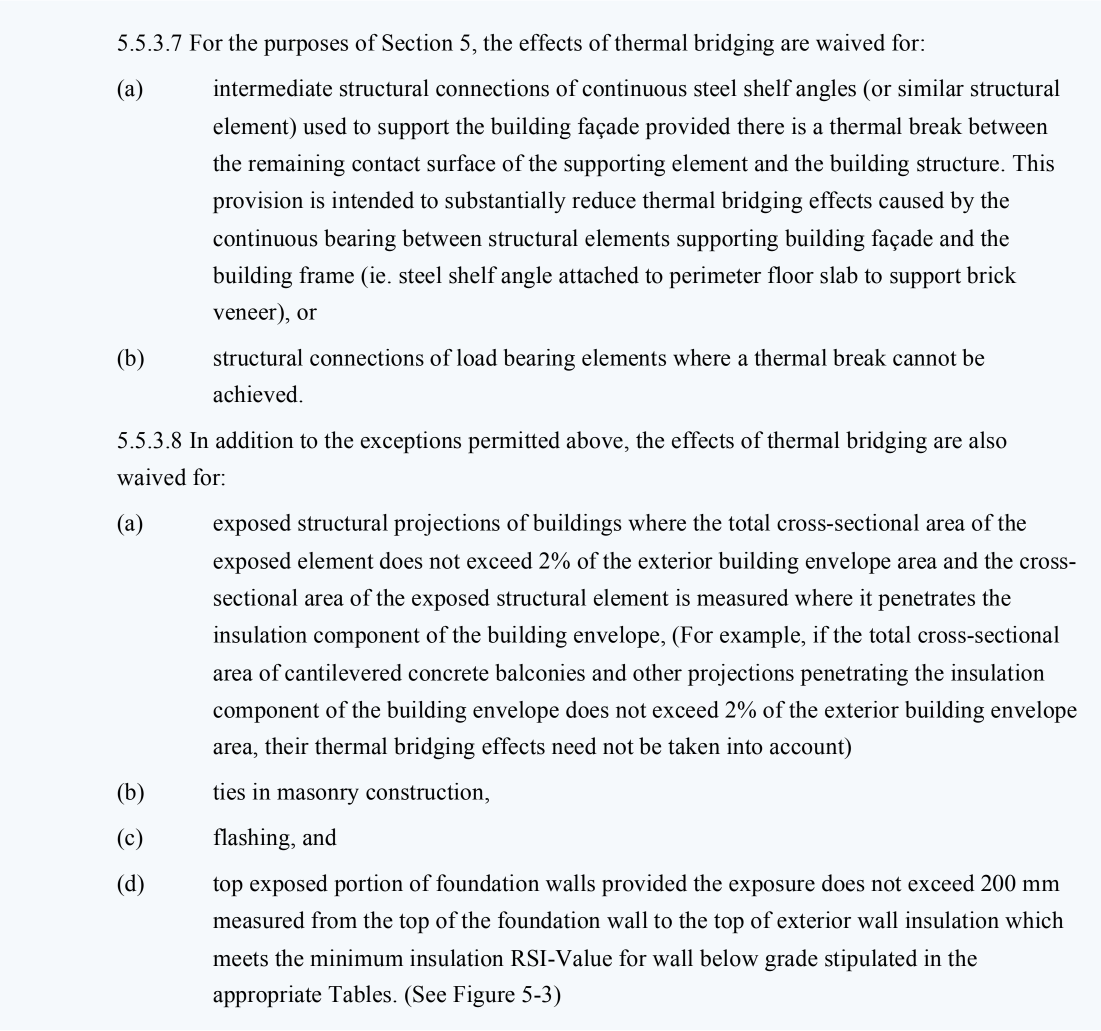
2.3 Codes and Thermal Bridging

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 better insulated enclosures. Hence, building codes and standards are beginning to address the issue.

An example of how codes address thermal bridging is the Ontario Building Code Supplementary Bulletin 10 (SB-10) due to take effect in 2017. Figure 9 provides an excerpt. 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.

For this particular code, the impact of slab edges needs to be accounted for, since, for 8” (204 mm) thick slabs and floor-to-floor heights of 9 feet (2743 mm), the area is 7.4%: 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 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).

Future codes are likely to reduce these exceptions over time.



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 (ie. 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) 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 wall below grade stipulated in the appropriate Tables. (See Figure 5-3)

Figure 9: Excerpt from Proposed 2017 Ontario Building Code Supplementary Bulletin 10 Thermal Bridging Provisions

3 Calculating the Thermal Performance of Precast Concrete Systems

The thermal resistance of simple assemblies can be calculated by adding the resistance of individual layers as described in countless references, including the Appendix to the National Building Code of Canada. To account for thermal bridging, each precast system requires special approximations, described below. The thermal contribution of interior finishes and interior light-gauge framing are common options for all precast systems and hence will be considered first. Each of the common precast enclosure wall systems are then covered in the following sections.

3.1 Interior finishes and Light-gauge Framing

Many precast enclosure employ gypsum wallboard and light-gauge steel framing on the interior to provide a familiar finish and potentially to provide fire resistance or 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 to support interior gypsum may only be 25-gauge. The thicker gauge steel does transmit more heat flow, although 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). The effective R-values recommended by ASHRAE for a typical light-gauge system are shown in Figure 11 and Figure 12. 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.

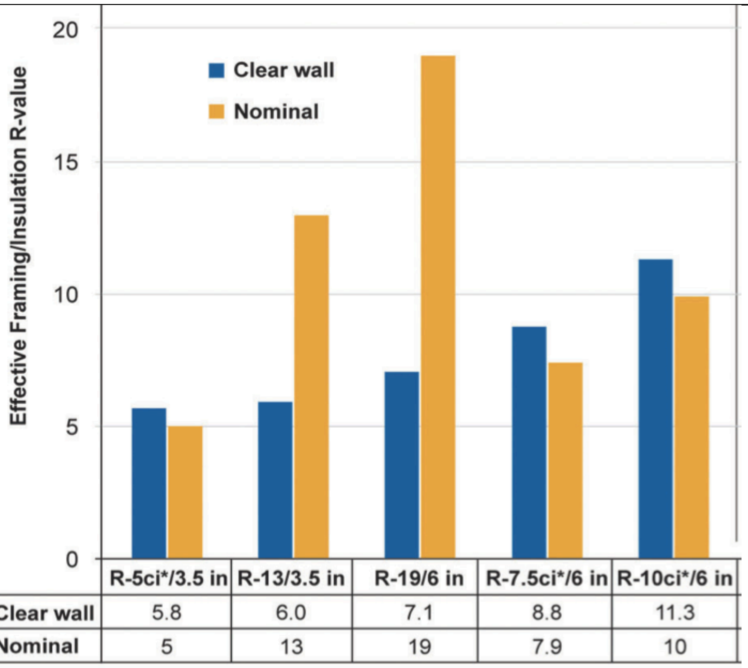
For practical applications, steel stud framing can be simplified as a monolithic layer with an equivalent effective R-value to which the R-value of the gypsum board finish can be added (Figure 10).

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

Figure 10: Thermal Resistance of Gypsum Wallboard Finish

Cavity Depth		Rated Cavity R-value	Effective R-value @ 16 inch centres	Effective RSI @ 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

Figure 11: Effective layer Clear-wall R-value for light gauge steel framing acting as a single layer (note: “ccSPF” is closed cell Sprayed Polyurethane Foam insulation)



	R-5ci*/3.5 in	R-13/3.5 in	R-19/6 in	R-7.5ci*/6 in	R-10ci*/6 in
■ Clear wall	5.8	6.0	7.1	8.8	11.3
■ Nominal	5	13	19	7.9	10

* ci denotes a layer of continuous insulation with no framing penetrations

Figure 12: Effective thermal resistance values of light-gauge steel framing vs nominal (installed) from ASHRAE 90.1-2010

The nominal R-value of continuous layers of insulation added to the inside of precast concrete assemblies can simply be added at the stated value provided that only fasteners and insulation attachments penetrate the layer[3]. The R-value per inch of common products are provided in Figure 13. 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).

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
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	0.072	0.14	0.18	0.22	0.25	0.29

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
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	2.0	0.03	0.03	0.04	0.04	0.05

Figure 13: Recommended R-value of continuous insulation layers and concrete

All assemblies also have an internal and external thermal resistance, sometimes referred to as an "air film". Standard design values are tabulated in Figure 14. Although these provide 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.

	R-Value (SI)	R-Value (IP)
Interior Surfaces	0.120	0.68
Exterior Surfaces	0.029	0.16

Figure 14: R-value of interior and exterior surface films

Example: An enclosure is finished with an empty 3.5" steel stud framing at 16" on center, with 5/8" gypsum wallboard (GWB) on the interior (Figure 15). What would the clear-wall R-value of the inner layers, finishes and air films be?

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[3] Z-girts should never penetrate the insulation or a significant reduction in performance will result.

This can be simply calculated as the sum of the constituent layers. That is: R_{cw}= Interior film + 5/8" (16 mm) GWB + empty 3.5" (89 mm) steel stud + exterior film.

R-0.68 + R-0.56 + R-0.79 + R-0.16 = R-2.2.

Alternatively, if R-13 batt insulation was added within the framing, the R-value of the framing would rise from 0.79 to 6.0 (Figure 11), resulting in a total R-value of 7.4. This is the same value as shown in Figure 16.

Note: 1" = 25.4 mm

Figure 15: Example Wall for Calculation of Clear Wall R-value

The total R-value for common scenarios of interior finishes, framing, and films are provided in Figure 16 for convenience.

Steel Stud Depth		**Rated Cavity Insulation R-value**	**Effective R-value @ 16 inch centres**	**Effective RSI @ 405 mm centres**
In	mm			
2.5	64	Empty	2.1	0.37
3.5	89	Empty	2.2	0.39
		R-13	7.4	1.31
		R-15	7.8	1.38
6.0	152	Empty	2.2	0.40
		R-19	8.5	1.50
		R-21	8.8	1.55
		R-24 (4" ccSPF)	9.0	1.59

Figure 16: Total Effective R-value for 5/8" (16 mm) GWB, Air films, and Steel Stud Framing (note: "ccSPF" is closed cell Sprayed Polyurethane Foam insulation)

3.2 Architectural Precast Concrete

Architectural precast concrete systems are common, especially for taller buildings. They also 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 modern design that can deliver high performance is shown in Figure 17.

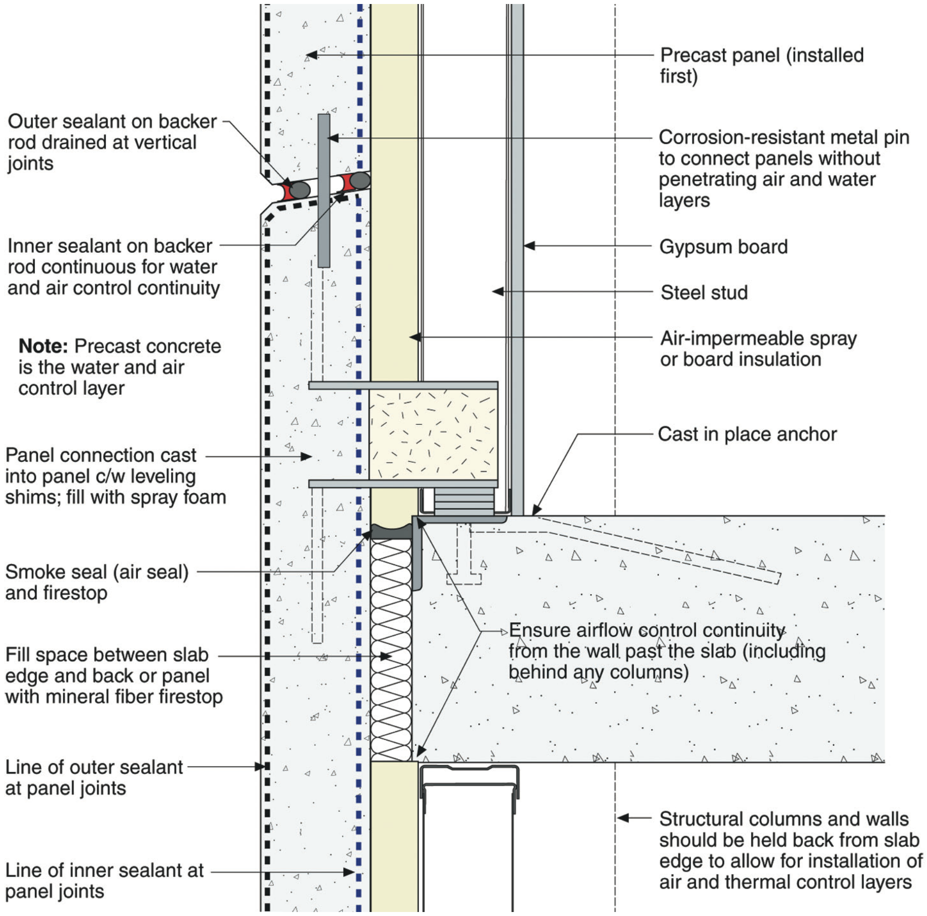

Figure 17: Section at Floor of a High-Performance Architectural Precast Panel (CPCI 2013)

To achieve high 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. 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, board foam (XPS, EPS, or polyiso) 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[4].

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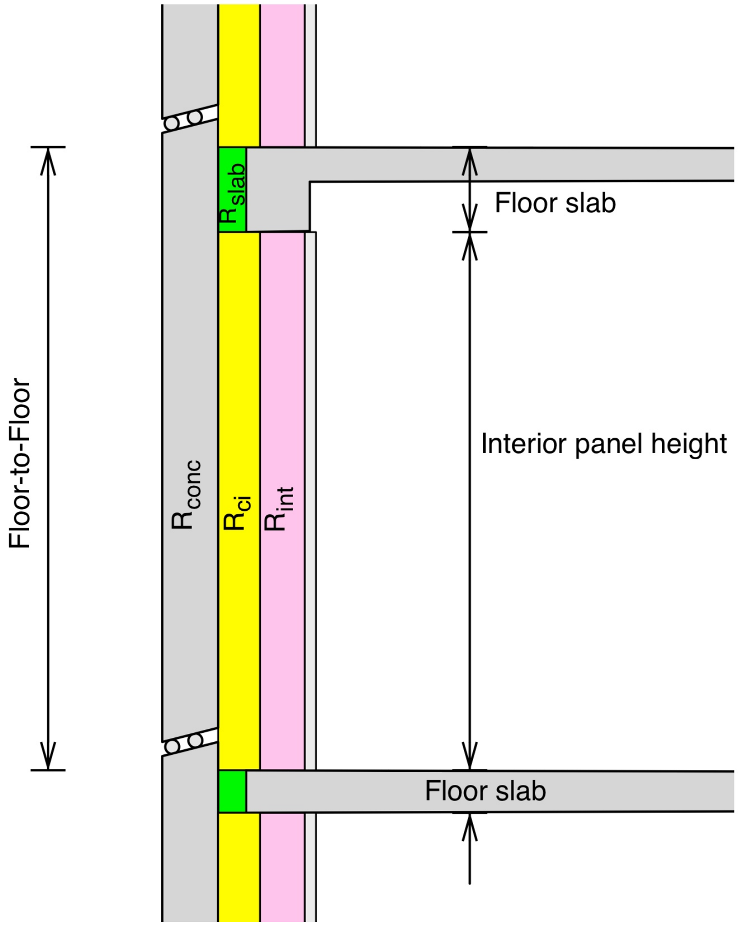
[4] Due to thermal bridging through the steel studs, the addition of insulation to the studspace increases the effective R-value by only about R-5 to R-7, even if filled with closed cell Spray Polyurethane Foam insulation (ccSPF). Adding studspace insulation always increases the risk of cold weather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

The heat flow through the opaque portions of an architectural precast wall can be calculated with only a few key inputs. The layers for which thermal resistance is required are summarized in Figure 18.



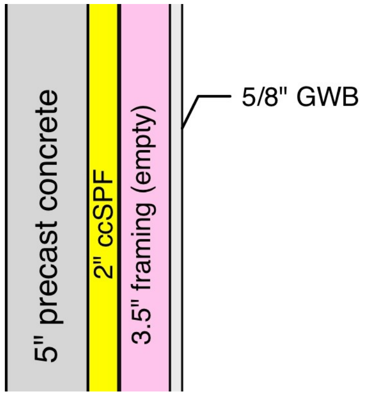
R_{conc} - Concrete panel thermal resistance (Figure 13 or assumed to be zero)
R_{ci} – continuous insulation layer thermal resistance, ignoring small fasteners (Figure 13)
R_{int} – thermal resistance of interior finishes, framing, and any insulation (Figure 16)
Note: **the floor slab height includes** the depth of perimeter beams, if any

Figure 18: Definition of Terms for Architectural Precast Thermal Calculation

3.2.1 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. Figure 13 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 18).



Note: 1” = 25.4 mm

Figure 18: Example Architectural Precast Assembly

From the earlier calculation in Section 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 (Figure 13). 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 (R0.3) has been ignored.

If one uses R-13 batt within the stud space the calculation would R-7.4 plus R-12, for a total of R-19.4.

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 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.

3.2.2 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 are allowed to be ignored.

The most important potential thermal bridge 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[5]:

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

where

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

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

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

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 Figure 19.

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

Figure 19: Total R-value of Floor-slab (R_{fl}) intersections

Example: The architectural precast system from the previous example (R_{cw}=19.4) spans 12’8” (3861 mm) from floor-to-floor (Figure 20). 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?

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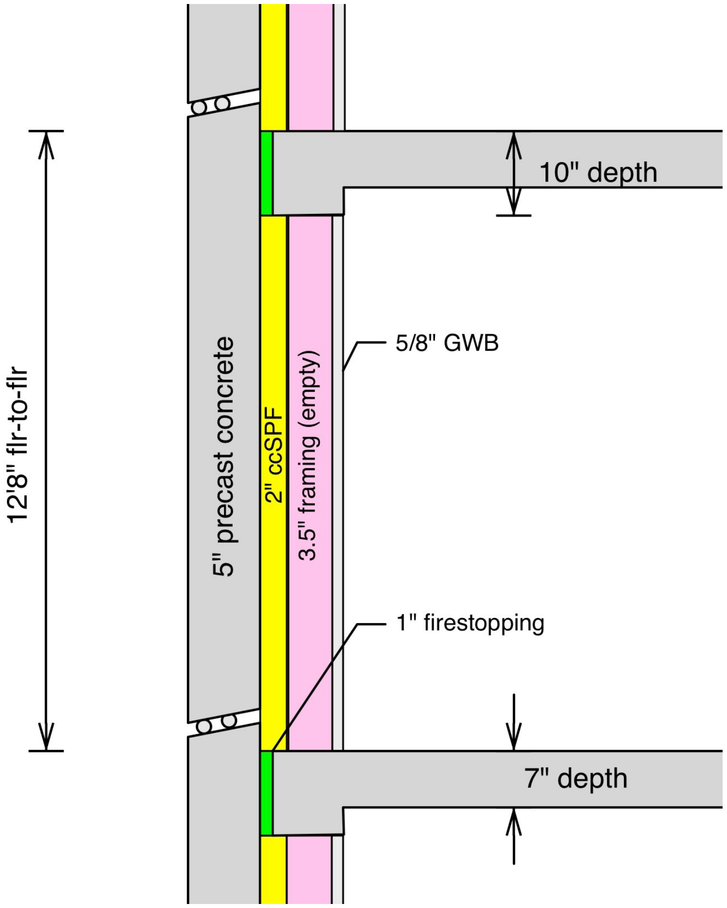
[5] This equation assumes the parallel-path method.



Note: 1” = 25.4 mm

Figure 20: Example Architectural Precast Whole Wall

Entering values into the equation:

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

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 ( ).

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.

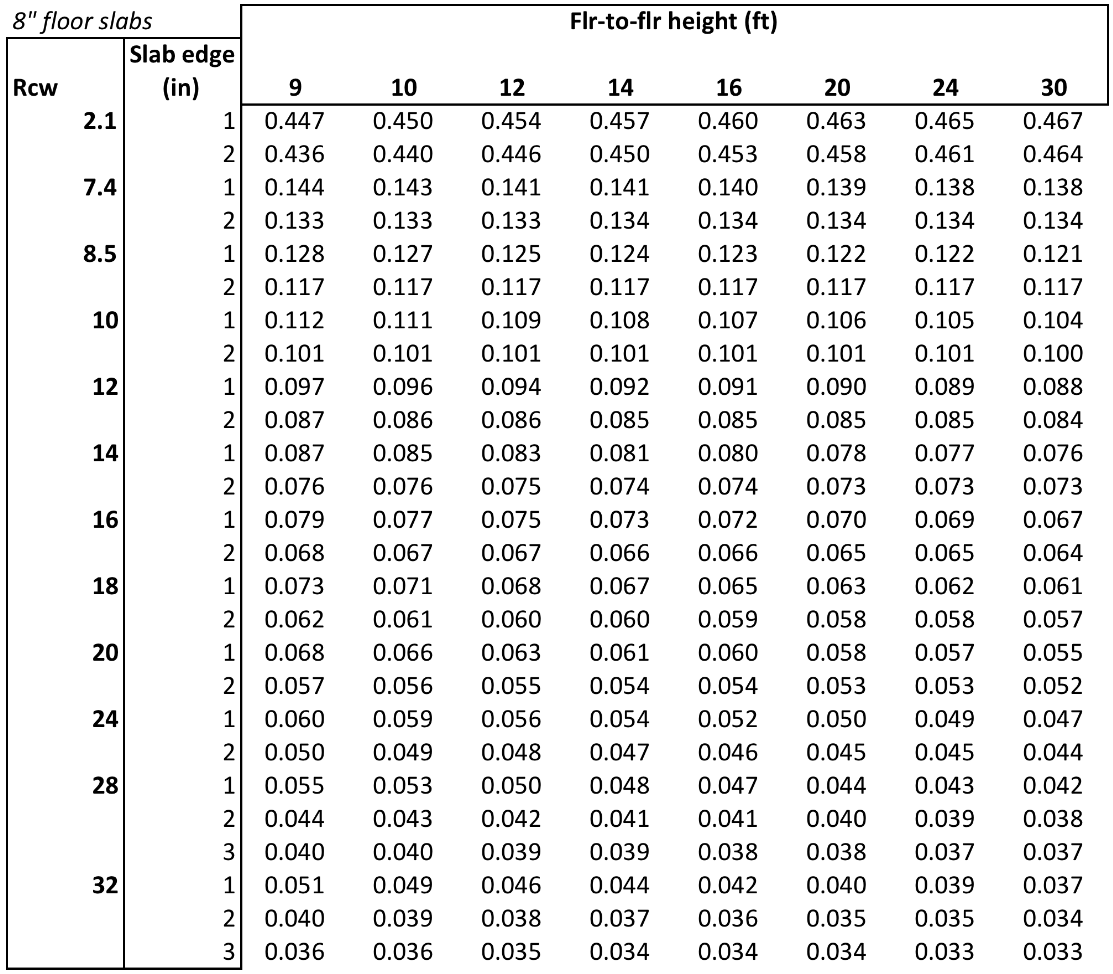
Hence, this system would meet the requirement for Zone 5 and 6 in ASHRAE 90.1-2010 for residential and commercial buildings. Increasing the firestop insulation thickness to 2” (R_{fl}=8.90) would change the whole-wall R-value to 18.0 (U_{SI}=0.315), a R-1.9 increase for very little cost.

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 proposed Ontario SB-10 Standard) 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) thick (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 and 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).

Figure 21 and Figure 22 provide the whole wall R-value for a range of floor to floor heights, clear wall R-values, and slab edge insulation thickness for an 8” thick (200 mm) floor slab. Appendix C contains tables of 12” (305 mm) thick floors slabs and metric units.

8" floor slabs		**Floor-to-floor height (ft)**							
Rcw	**Slab edge (in)**	**9**	**10**	**12**	**14**	**16**	**20**	**24**	**30**
2.1	1	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.1
	2	2.3	2.3	2.2	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	7.3
	2	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.4
8.5	1	7.8	7.9	8.0	8.0	8.1	8.2	8.2	8.3
	2	8.5	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	9.6
	2	9.9	9.9	9.9	9.9	9.9	9.9	9.9	10.0
12	1	10.3	10.4	10.6	10.8	11.0	11.1	11.3	11.4
	2	11.6	11.6	11.7	11.7	11.7	11.8	11.8	11.9
14	1	11.5	11.7	12.0	12.3	12.5	12.8	12.9	13.1
	2	13.2	13.2	13.4	13.4	13.5	13.6	13.7	13.7
16	1	12.7	12.9	13.4	13.7	13.9	14.3	14.6	14.8
	2	14.7	14.8	15.0	15.1	15.2	15.4	15.5	15.6
18	1	13.7	14.1	14.6	15.0	15.3	15.8	16.1	16.5
	2	16.2	16.3	16.6	16.8	16.9	17.1	17.3	17.4
20	1	14.7	15.1	15.8	16.3	16.7	17.2	17.6	18.1
	2	17.6	17.8	18.1	18.4	18.6	18.8	19.0	19.2
24	1	16.5	17.1	17.9	18.6	19.1	20.0	20.5	21.1
	2	20.2	20.5	21.0	21.4	21.7	22.1	22.4	22.7
28	1	18.1	18.8	19.9	20.7	21.4	22.5	23.3	24.1
	2	22.6	23.1	23.8	24.3	24.7	25.3	25.7	26.1
	3	24.9	25.1	25.6	25.9	26.1	26.5	26.7	27.0
32	1	19.5	20.3	21.6	22.7	23.6	24.9	25.8	26.9
	2	24.8	25.4	26.3	27.0	27.5	28.3	28.9	29.5
	3	27.6	28.0	28.6	29.0	29.4	29.8	30.2	30.5

Figure 21: Whole Wall R-value for Architectural Precast Panels



8" floor slabs

		Flr-to-flr height (ft)							
Rcw	**Slab edge (in)**	**9**	**10**	**12**	**14**	**16**	**20**	**24**	**30**
2.1	1	0.447	0.450	0.454	0.457	0.460	0.463	0.465	0.467
	2	0.436	0.440	0.446	0.450	0.453	0.458	0.461	0.464
7.4	1	0.144	0.143	0.141	0.141	0.140	0.139	0.138	0.138
	2	0.133	0.133	0.133	0.134	0.134	0.134	0.134	0.134
8.5	1	0.128	0.127	0.125	0.124	0.123	0.122	0.122	0.121
	2	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117
10	1	0.112	0.111	0.109	0.108	0.107	0.106	0.105	0.104
	2	0.101	0.101	0.101	0.101	0.101	0.101	0.101	0.100
12	1	0.097	0.096	0.094	0.092	0.091	0.090	0.089	0.088
	2	0.087	0.086	0.086	0.085	0.085	0.085	0.085	0.084
14	1	0.087	0.085	0.083	0.081	0.080	0.078	0.077	0.076
	2	0.076	0.076	0.075	0.074	0.074	0.073	0.073	0.073
16	1	0.079	0.077	0.075	0.073	0.072	0.070	0.069	0.067
	2	0.068	0.067	0.067	0.066	0.066	0.065	0.065	0.064
18	1	0.073	0.071	0.068	0.067	0.065	0.063	0.062	0.061
	2	0.062	0.061	0.060	0.060	0.059	0.058	0.058	0.057
20	1	0.068	0.066	0.063	0.061	0.060	0.058	0.057	0.055
	2	0.057	0.056	0.055	0.054	0.054	0.053	0.053	0.052
24	1	0.060	0.059	0.056	0.054	0.052	0.050	0.049	0.047
	2	0.050	0.049	0.048	0.047	0.046	0.045	0.045	0.044
28	1	0.055	0.053	0.050	0.048	0.047	0.044	0.043	0.042
	2	0.044	0.043	0.042	0.041	0.041	0.040	0.039	0.038
	3	0.040	0.040	0.039	0.039	0.038	0.038	0.037	0.037
32	1	0.051	0.049	0.046	0.044	0.042	0.040	0.039	0.037
	2	0.040	0.039	0.038	0.037	0.036	0.035	0.035	0.034
	3	0.036	0.036	0.035	0.034	0.034	0.034	0.033	0.033

Figure 22: Whole Wall U-value for Architectural Precast Panels

3.2.3 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. An introduction to assessing the impact of panel anchors is presented next.

The overwhelming majority of panels are connected to the primary building structure by two load-bearing connectors (i.e., the two anchors transfer all of the wind, gravity, and seismic loads to the primary structure), with additional connectors used to attach the panel to the neighbouring panels. This approach results in the best thermal performance. 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 adding the impact of steel connectors passing through precast concrete panels is to add the heat loss from each anchor. It is becoming more common to calculate the heat loss of specific thermal bridges using a three-dimensional computer model. Such models generate a so-called chi-factor (Ψ) for a single anchor. The reduction in R-value can then be calculated by dividing the number of anchors by the total area of the precast panel:

$R_{ww} = A / [\, A/R_{ww} + \Psi \bullet n \,]$

where A is the total panel area,

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

n is the number of anchors (typically 2).

A 3-D computer model of a generic precast anchor was generated for this guide (see Appendix B) and the results are summarized in Figure 23.

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

Figure 23: Chi-factor (χ) for a single generic precast anchor.

Example: The panel system described (R_{ww}= 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 (or 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. Hence, the whole-wall R-value of panel, including 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, U_{SI}=0.376). Therefore, including anchors would result in the U-value of this design rising above the minimum Climate Zone 5 and 6 ASHRAE 90.1-2010 requirements.

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. If the concrete panel must bear on the foundation wall, a 2D heat flow analysis should be conducted to quantify the impact.

3.3 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 24.

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 or cast-ins. In the last twenty 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-fibre reinforced plastic provide a wide range of structural solutions with little impact on the 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[6].

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[6] A three-dimensional computer model of one tie and its associated tributary area is typically sufficient evidence.

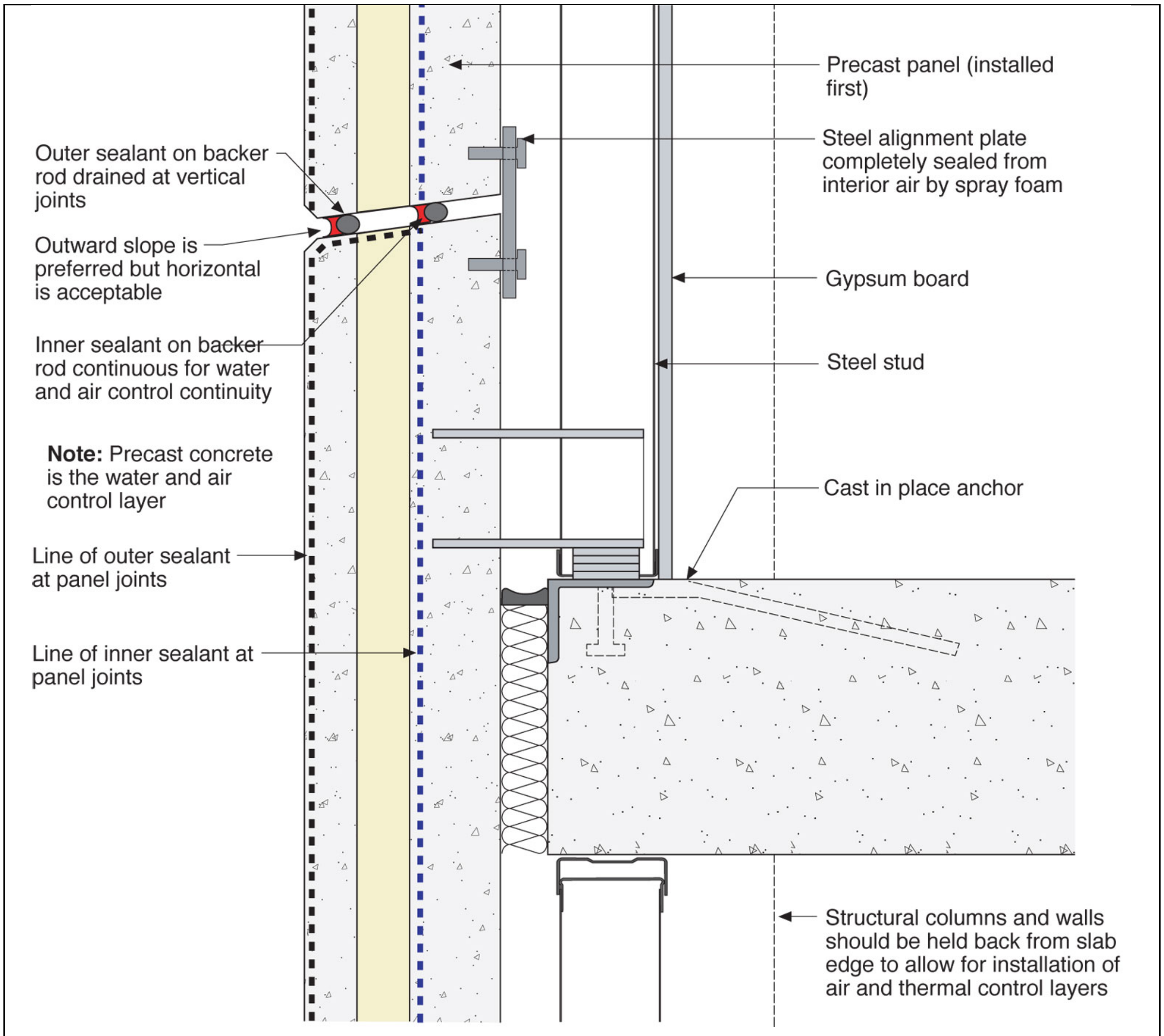


Figure 24: Section at Floor of a High-Performance Double-wythe Insulated Precast Concrete Sandwich Panel (CPCI 2013)

The performance of a double-wythe panel is approximately that of the insulation installed. The concrete itself and air films add a little, and the wire/composite connectors reduce some. 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 is summarized in Figure 25 below as a function of insulation type and thickness.

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

Insulation Thickness (mm)	k=0.036 W/mK (MW/EPS)	k=0.029 W/mK (XPS)	k=0.024 W/mK (PIC)
50.8	1.65	2.00	2.35
63.5	2.00	2.44	2.88
76.2	2.35	2.88	3.41
88.9	2.70	3.32	3.94
101.6	3.06	3.76	4.46
114.3	3.41	4.20	4.99
127	3.76	4.64	5.52
152.4	4.46	5.52	6.58
203.2	5.87	7.28	8.69

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

Figure 25: Approximate Whole Wall Thermal Resistance of a Double-wythe Insulated Precast Sandwich Panels

3.4 Total Precast

Total precast systems either use the architectural single wythe precast of an architectural precast arrangement (Figure 26) or the inner wythe of a double-wythe (insulated) panel as a vertical load bearing element in a total system of precast floors, walls, and core elements.

Total precast double wythe insulated panel sandwich panel systems perform thermally in the same manner as non-gravity-load bearing panels (Section 3.3 Double Wythe Insulated (Sandwich) Panels). No additional calculations are needed.

For single-wythe exterior panels, the Clear-Wall R-value is calculated in exactly the same manner as described in Section 3.2. 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 desirable, to provide a thermally broken joint in this location filled with fire-resistant mineral fiber insulation. At this detail, the thermal performance can be evaluated using the methods outlined in Section 3.2.2. Heat loss through the floor slab-wall panel load-bearing structural connection is a major thermal bridge and must be accounted for. The thermal bridge waivers (e.g., less than 2% of area in SB-10) do not apply. The following section describes approximate calculation methods for this condition.

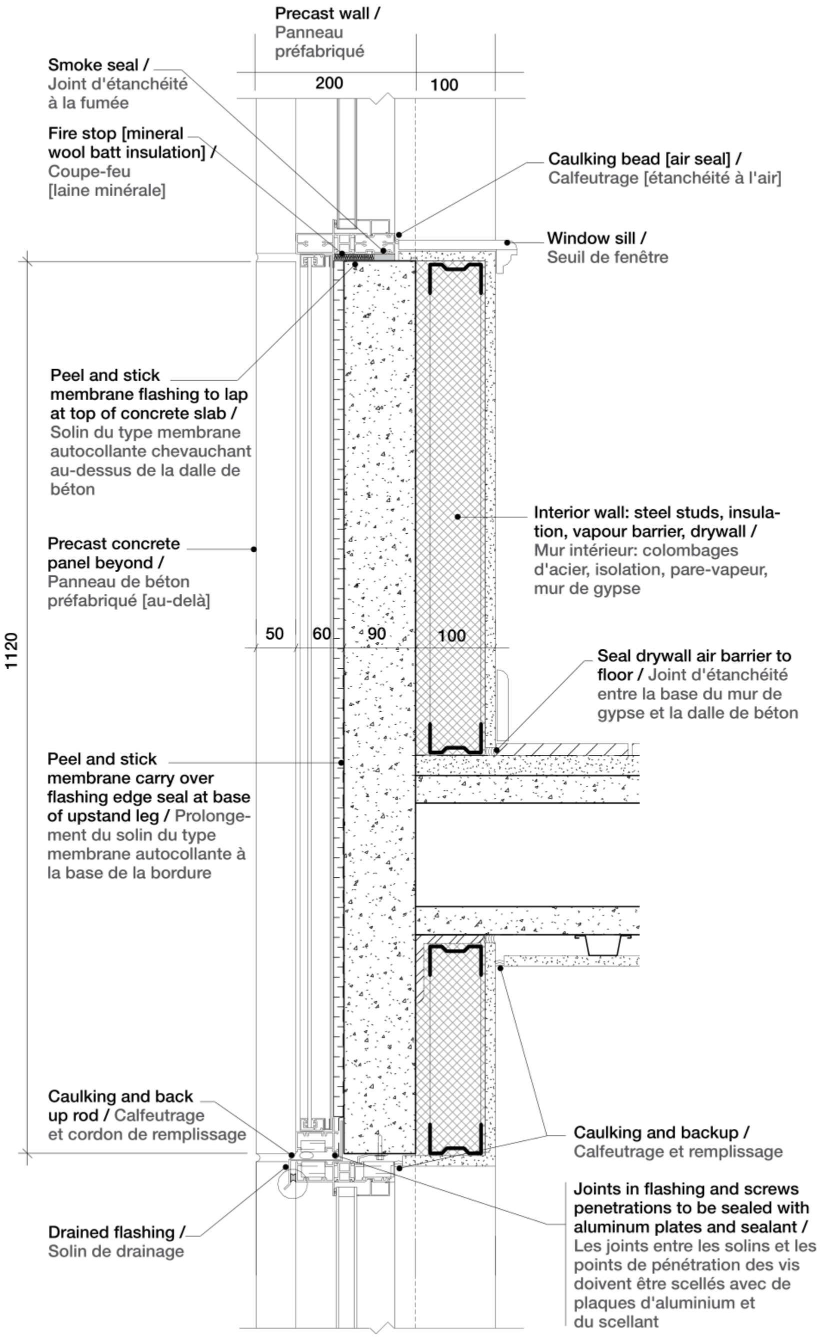


Figure 26: Vertical Section through a Typical Total Precast Enclosure (Imagineering Magazine Spring 2016)

3.4.1 Accounting for Loadbearing Floor Slab Connections

To calculate 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.

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

where

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

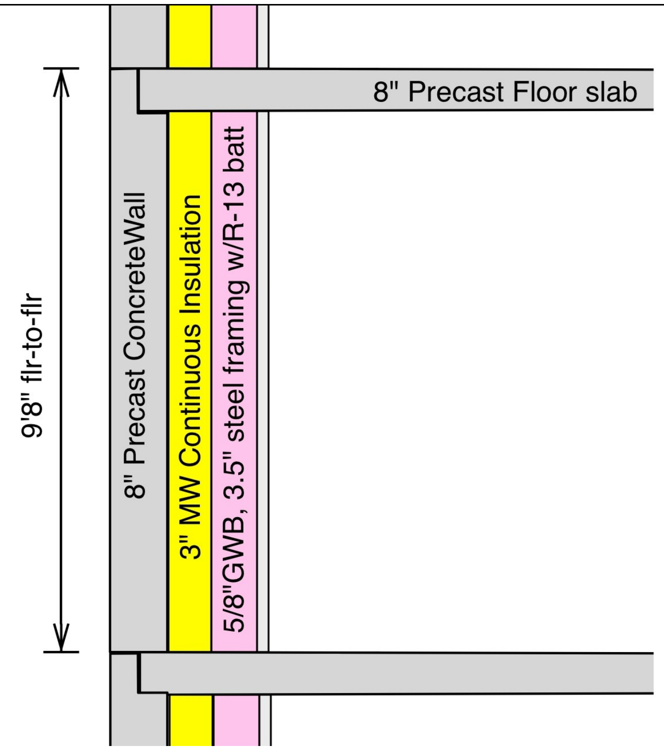
FF is the floor-to-floor height (feet or meters)

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

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

The R-value of a typical concrete slab is approximately R-1.5 (RSI0.264).

Example: A Total Precast System with a floor-to-floor height of 9'8" (2946 mm) comprises an 8" (203 mm) concrete wall, 3" (76 mm) of mineral wool, a 3.5" (89 mm) steel stud with R-13 batt, 5/8" (16 mm) gypsum supporting an 8" (203 mm) thick precast concrete hollow core slab. Calculate the clear-wall R-value and the whole-wall R-value.



Note: 1" = 25.4 mm

Figure 27: Example Total Precast Whole Wall

Using Figure 16, the interior finishes 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 Figure 12) = 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 whole-wall R-value is significantly reduced by the floor slab. The impact can be estimated, using R-1.5 for the slab and the parallel path method

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

$$= 1/ \{ [(9.66-0.66) / 9.66] /20. + (0.66/ 9.66) / 1.5\} = R\text{-}10.8$$

Thus, the whole-wall R-value drops from R-20 to R-10.8 because of the floor slab penetration. 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. If an energy model is used to calculate total annual energy, mechanical system trade-offs may also allow for this type of system.

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, shown in Figure 28, demonstrate that the significant impact of the penetrating floor slabs if the clear wall is improved beyond steel studs with batt (the second and third Clear Wall values are representative of a 4” (102 mm) and 6” (152 mm) steel stud system with R-12 and R-20 batt respectively). For a 4” (102 mm) batt-filled stud frame (R_{cw}-4.7) with 2” (51 mm) of ccSPF (R-12) and 8” (203 mm) of concrete (R-0.56), the assembly R_{cw} would be about R-17. By interpolation, for a total precast system with a floor-floor-height of 10 ft (3048 mm) would have a Whole Wall R-value of about R-10.6 (or RSI1.8).

	floor-to-floor (ft)				
Clear Wall R_{cw}	**9**	**10**	**11**	**12**	**16**
1.2	1.8	1.8	1.8	1.8	1.8
4.7	4.7	4.7	4.8	4.8	4.9
7.1	6.2	6.3	6.4	6.5	6.7
10	7.6	7.9	8.0	8.2	8.7
12	8.5	8.8	9.0	9.2	9.9
14	9.3	9.6	9.9	10.2	11.0
16	9.9	10.3	10.7	11.0	12.0
18	10.5	11.0	11.4	11.8	12.9
20	11.0	11.6	12.0	12.5	13.8
22	11.5	12.1	12.6	13.1	14.6
24	12.0	12.6	13.2	13.7	15.4
28	12.7	13.5	14.1	14.7	16.7
30	13.1	13.8	14.5	15.2	17.3
34	13.6	14.5	15.3	16.0	18.5
40	14.4	15.3	16.2	17.1	19.9

	floor-to-floor (m)				
Clear Wall RSI_{cw}	**2.74**	**3.05**	**3.35**	**3.66**	**4.88**
0.21	0.32	0.32	0.32	0.32	0.32
0.83	0.82	0.83	0.84	0.85	0.87
1.25	1.1	1.1	1.1	1.1	1.2
1.76	1.3	1.4	1.4	1.4	1.5
2.11	1.5	1.5	1.6	1.6	1.7
2.47	1.6	1.7	1.7	1.8	1.9
2.82	1.7	1.8	1.9	1.9	2.1
3.17	1.9	1.9	2.0	2.1	2.3
3.52	1.9	2.0	2.1	2.2	2.4
3.87	2.0	2.1	2.2	2.3	2.6
4.23	2.1	2.2	2.3	2.4	2.7
4.93	2.2	2.4	2.5	2.6	2.9
5.28	2.3	2.4	2.6	2.7	3.1
5.99	2.4	2.6	2.7	2.8	3.3
7.04	2.5	2.7	2.9	3.0	3.5

Note: Floor slabs and wall panels are assumed to be 8” (203 mm) thick

Figure 28: Approximate Generic Total Precast Whole Wall R-values

3.5 Influence of Windows and Curtainwalls

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. Designers of high performance building will generally consider the Overall R-value as a measure of the enclosure thermal performance. This approach emphasizes that window area can be reduced to increase overall performance. Codes infer an Overall R-value in their prescriptive paths by assuming a window-to-wall area and minimum component R-values.

As described in the introduction, window and curtainwall R-values are much lower than that required of opaque walls. Because heat flows preferentially through low-thermal resistance components, much more heat flows through windows in most buildings, even those buildings with limited glazing area.

For example, in a building with ASHRAE 90.1-2010 compliant 40% WWR of U=0.45 (R-2.2) metal windows and 60% U=0.090 for a mass wall (appropriate for precast concrete), over 75% of heat loss occurs through the windows. The total heat loss can be reduced by increasing the insulation value of either the precast concrete or the window. If the precast is insulated with an additional R-5, the heat flow the entire enclosure decreases by 8%. Specifying a window with U=0.35 (R-2.85) instead would reduce heat loss by twice as much (by 17%). This disproportionate effect is due entirely to the higher heat loss of windows.

Figure 29 plots the overall effective R-value for a good thermal performance window (U=0.35, vs code minimum of U=0.45) and R-10, R-20, and R-30 opaque walls. For larger WWR (40% or higher) is can be seen how little performance is gained by increasing wall insulation. A very high performance window is also shown: a U=0.18 window would be triple-glazed, have thermally non-conductive frames (e.g., fiberglass), super-spacers and gas-filled units. When combined with an effective R-20 wall, the performance at 40%WWR is twice that of ASHRAE 90.1. Of course, the combination of good windows with more modest window ratios is almost always the lowest cost approach to energy efficiency.

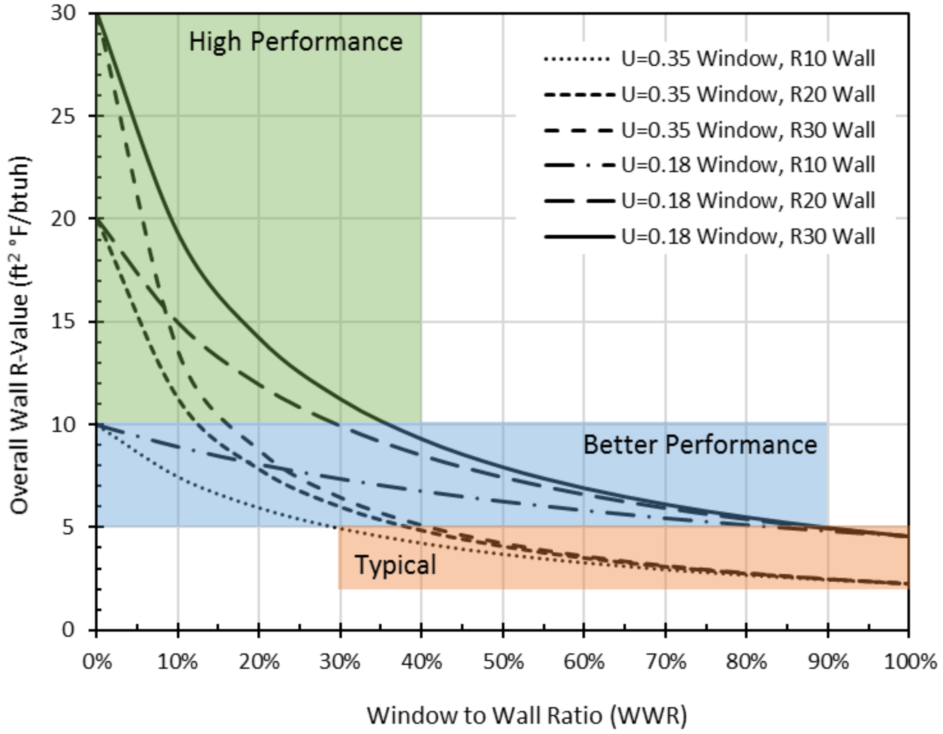


Figure 29: Effective Overall R-value vs WWR and Enclosure Performance

In practise, when the WWR is over 40% (or lower for the NECB), 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 window and opaque wall systems to achieve compliance.

4 Summary

Building codes, standards, and building owners are increasing their demands for better performing buildings. Increasing thermal performance in modern buildings will require 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 mechanisms

The methods presented are not onerous to use, and reasonably accurate. More detailed computer-based modeling will often be justified for more complex systems and more accurate results. The examples presented are clearly many ways for precast concrete enclosure systems to deliver high levels of effective insulation, often more easily and more economically than other types of enclosure systems.

5 References

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BS EN ISO 10077 Thermal performance of windows, doors and shutters -- Calculation of thermal transmittance -- Part 2: Numerical method for frames

Appendix A: Calculating Heat Flow

The effect of thermal bridging can be assessed through the use of differential heat loss coefficients that are added to the heat loss coefficient for an enclosure with no thermal bridge such that:

$$Q = (U_o \bullet A + H_{TB}) \bullet \Delta T \qquad (1)$$

where,

Q is the rate of heat loss at a given time

U_o is the heat loss coefficient for the enclosure component without considering thermal bridges.

A is the area of the enclosure component

H_{TB} is a factor to account for the additional heat loss caused by thermal bridges (a heat transfer coefficient)

ΔT is the temperature difference across the enclosure

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 □ to the transmittance of heat in two-dimensional details and the symbol □ 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:

$$Q = [U_o \bullet A + \Sigma(\Psi_i \bullet L_i) + \Sigma(\chi_j \bullet n_j)] \bullet \Delta T \qquad (2)$$

where

U_o is the clear wall heat transmittance ($1 / R_{cw}$)

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

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

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

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

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

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).

Due to the generally limited magnitude of χ factors and the extra effort required for their calculation, most junctions are best accounted for with linear thermal bridge Ψ factors. However, point thermal bridges or χ factors for elements such as steel point connections, balcony connections or steel columns may have a significant effect on energy use if often repeated in a building. Condensation may be an important issue at these points, depending on the magnitude of the χ factor, and may be a sufficient reason to take action to solve even if the occur rarely in a building.

Material Properties

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 55 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 used in precast assemblies 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 140 pcf concrete exposed to humidity of 9.86 Btu/hr/ft^2/in F (1.4 W/m K). In more common units, this is R_{imp} 0.10 per inch thickness. This value is used by National Concrete Masonry Association (NCMA) Thermal Guide (NCMA 2012).

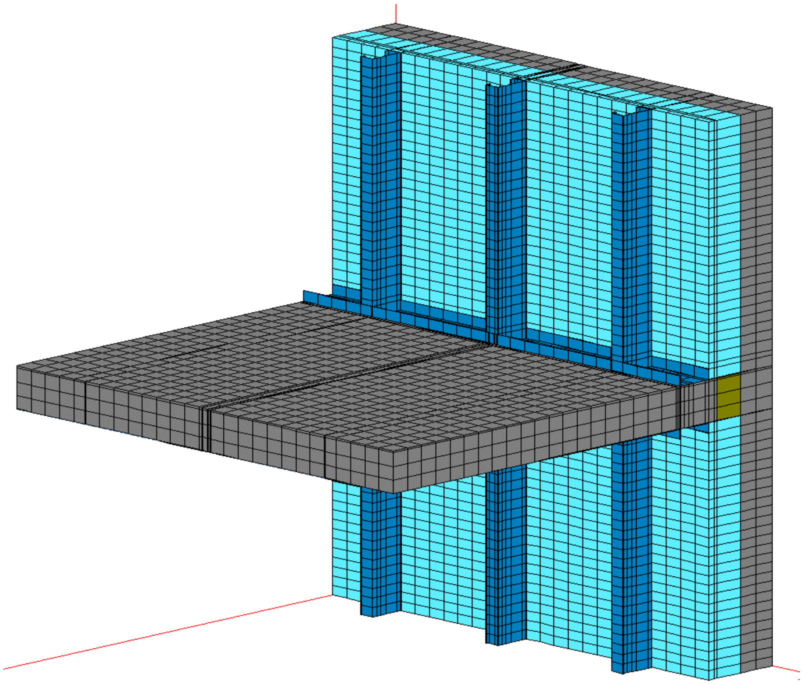
Insulation, of course, has the largest impact on the overall results. It is recommended that material properties are taken at standard North American rating conditions of a mean of 24 °C (75°F) as these are the most commonly available.

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”. ASHRAE provides recommended values (summarized below in Table 2) intended for design conditions. **For most practical cases, and value of R-0.85 or RSI 0.15 should be assumed for the combined effect of both interior and exterior films.**

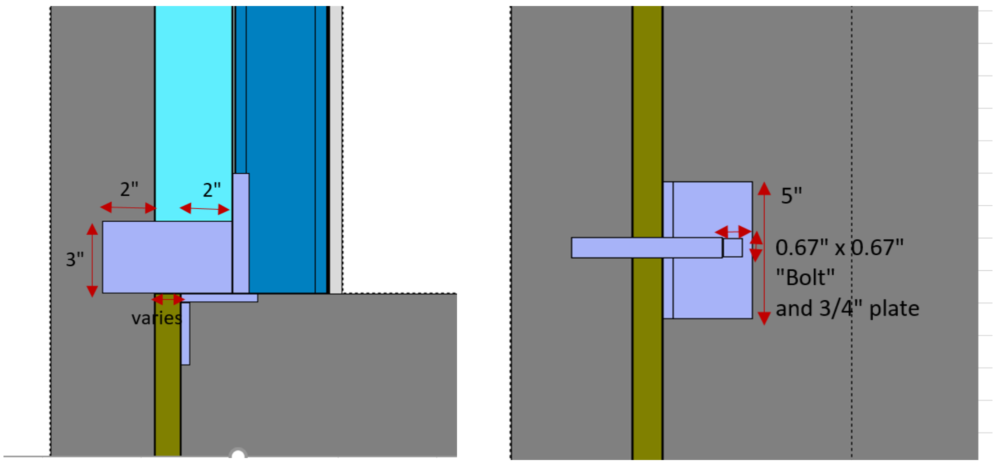
A detailed table of numerous factors affecting heat transfer across airspaces is provided in Table 3 of Chapter 26 of the ASHRAE Handbook (ASHRAE 2013). The value for heat transfer given for a mean temperature of 10 °C with a temperature difference of 16.7°C is recommended for basic analysis. For more detailed work, enclosed air spaces within curtain wall 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 Heat 3 v7.0 was used to develop thermal conductance values for a number of thermal bridges.



Finite Volume Model Used to Assess Heat Flow at Anchors



Note: 1" =25.4 mm

Vertical & Horizontal Section of Generic Precast Anchor

Continuous Insulation ccSPF (k=0.024 W/mK) w/ Slab Edge Insulation (k=0.036 W/mK)	3" (76 mm)	1" (25 mm)	0.278	0.178	0.184
		2" (51 mm)		0.072	0.196
		3" (76 mm)		0.032	0.199
	4" (102 mm)	1" (25 mm)	0.214	0.195	0.168
		2" (51 mm)		0.089	0.198
		3" (76 mm)		0.047	0.199
		4" (102 mm)		0.024	0.200
	6" (152 mm)	1" (25 mm)	0.148	0.211	0.143
		2" (51 mm)		0.109	0.168
		3" (76 mm)		0.066	0.175
		4" (102 mm)		0.041	0.184
Continuous Insulation 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

Summary of Thermal Bridge Results

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

$$U = [USI, eff \quad * A + \Sigma * w + \chi * \mathrm{n}]$$

where:

U= whole wall thermal transmittance [W/m^{2}C]

n = number of anchors (2 in most cases)
w = width of the precast panel [m]
A = area of panel [m²]
ΔT = temperature difference from inside to outside

$U_{SI,eff}$ = clear wall heat transfer coefficient [W/m²K]
Q = heat flow calculated above [W]
A = width * height of the panel [m²]

Appendix C: Supplementary Tables

204 mm floor slabs

		Floor-to-floor height (m)							
RSIcw	**Slab edge (mm)**	**2.7**	**3.0**	**3.7**	**4.3**	**4.9**	**6.1**	**7.3**	**9.1**
0.37	25	0.39	0.39	0.39	0.39	0.38	0.38	0.38	0.38
	51	0.40	0.40	0.39	0.39	0.39	0.38	0.38	0.38
1.30	25	1.23	1.23	1.25	1.25	1.26	1.27	1.27	1.28
	51	1.33	1.33	1.32	1.32	1.32	1.31	1.31	1.31
1.50	25	1.38	1.39	1.40	1.42	1.43	1.44	1.45	1.46
	51	1.50	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	1.70
	51	1.74	1.74	1.74	1.75	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	2.01
	51	2.03	2.04	2.05	2.06	2.07	2.08	2.08	2.09
2.47	25	2.03	2.06	2.12	2.16	2.20	2.25	2.28	2.32
	51	2.32	2.33	2.35	2.37	2.38	2.40	2.41	2.42
2.82	25	2.23	2.28	2.35	2.41	2.45	2.52	2.56	2.61
	51	2.59	2.61	2.64	2.67	2.68	2.71	2.73	2.74
3.17	25	2.42	2.48	2.57	2.64	2.70	2.78	2.84	2.90
	51	2.85	2.88	2.92	2.95	2.98	3.02	3.04	3.07
3.52	25	2.60	2.67	2.78	2.87	2.93	3.04	3.11	3.18
	51	3.09	3.13	3.19	3.23	3.27	3.32	3.35	3.38
4.23	25	2.91	3.01	3.16	3.28	3.37	3.51	3.62	3.72
	51	3.56	3.61	3.70	3.77	3.82	3.90	3.95	4.00
4.93	25	3.19	3.31	3.50	3.65	3.78	3.96	4.10	4.24
	51	3.98	4.06	4.18	4.28	4.35	4.45	4.53	4.60
	76	4.38	4.43	4.50	4.56	4.60	4.67	4.71	4.75
5.64	25	3.44	3.58	3.81	4.00	4.15	4.38	4.55	4.73
	51	4.37	4.47	4.63	4.75	4.85	4.99	5.09	5.19
	76	4.86	4.93	5.03	5.11	5.17	5.26	5.32	5.38

RSI values for Architectural Precast Panels

204 mm floor slabs

RSIcw	**Slab edge (mm)**	**Floor-to-floor height (m)**							
		2.7	**3.0**	**3.7**	**4.3**	**4.9**	**6.1**	**7.3**	**9.1**
0.37	25	2.54	2.55	2.58	2.60	2.61	2.63	2.64	2.65
	51	2.47	2.50	2.53	2.56	2.57	2.60	2.62	2.63
1.30	25	0.81	0.81	0.80	0.80	0.79	0.79	0.79	0.78
	51	0.75	0.75	0.76	0.76	0.76	0.76	0.76	0.76
1.50	25	0.73	0.72	0.71	0.71	0.70	0.69	0.69	0.69
	51	0.66	0.66	0.67	0.67	0.67	0.67	0.67	0.67
1.76	25	0.64	0.63	0.62	0.61	0.61	0.60	0.59	0.59
	51	0.58	0.57	0.57	0.57	0.57	0.57	0.57	0.57
2.11	25	0.55	0.55	0.53	0.52	0.52	0.51	0.50	0.50
	51	0.49	0.49	0.49	0.48	0.48	0.48	0.48	0.48
2.47	25	0.49	0.48	0.47	0.46	0.45	0.45	0.44	0.43
	51	0.43	0.43	0.42	0.42	0.42	0.42	0.42	0.41
2.82	25	0.45	0.44	0.42	0.41	0.41	0.40	0.39	0.38
	51	0.39	0.38	0.38	0.38	0.37	0.37	0.37	0.36
3.17	25	0.41	0.40	0.39	0.38	0.37	0.36	0.35	0.34
	51	0.35	0.35	0.34	0.34	0.34	0.33	0.33	0.33
3.52	25	0.39	0.38	0.36	0.35	0.34	0.33	0.32	0.31
	51	0.32	0.32	0.31	0.31	0.31	0.30	0.30	0.30
4.23	25	0.34	0.33	0.32	0.31	0.30	0.28	0.28	0.27
	51	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
4.93	25	0.31	0.30	0.29	0.27	0.26	0.25	0.24	0.24
	51	0.25	0.25	0.24	0.23	0.23	0.22	0.22	0.22
	76	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.21
5.64	25	0.29	0.28	0.26	0.25	0.24	0.23	0.22	0.21
	51	0.23	0.22	0.22	0.21	0.21	0.20	0.20	0.19
	76	0.21	0.20	0.20	0.20	0.19	0.19	0.19	0.19

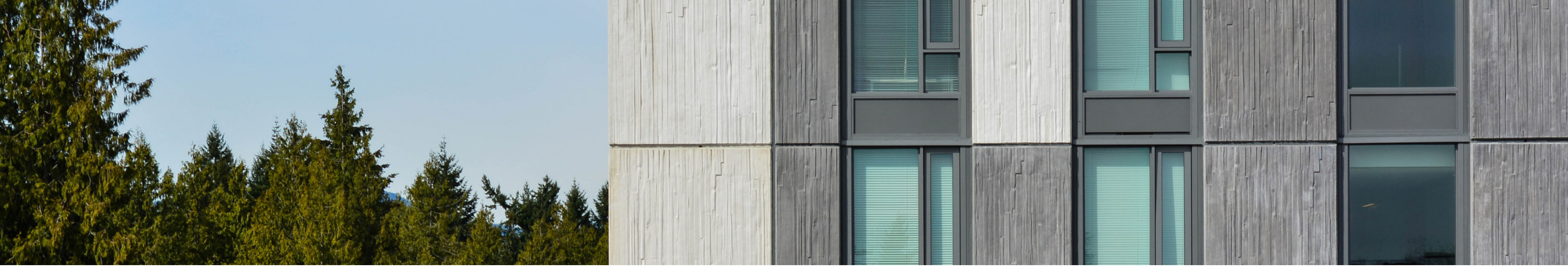
U-values for Architectural Precast Panels

	floor-to-floor (m)				
R_{cw}	**2.74**	**3.05**	**3.35**	**3.66**	**4.88**
2.1	0.38	0.38	0.38	0.38	0.38
7.4	0.16	0.15	0.15	0.15	0.14
8.5	0.14	0.14	0.14	0.14	0.13
10	0.13	0.13	0.12	0.12	0.12
12	0.12	0.11	0.11	0.11	0.10
14	0.11	0.10	0.10	0.10	0.09
16	0.10	0.10	0.09	0.09	0.08
18	0.10	0.09	0.09	0.08	0.08
20	0.09	0.09	0.08	0.08	0.07
22	0.09	0.08	0.08	0.08	0.07
24	0.08	0.08	0.08	0.07	0.07
28	0.08	0.07	0.07	0.07	0.06
30	0.08	0.07	0.07	0.07	0.06
34	0.07	0.07	0.07	0.06	0.05
40	0.07	0.07	0.06	0.06	0.05

U-values for Total Precast System (Imperial units)

	floor-to-floor (m)				
R_{cw}	**2.74**	**3.05**	**3.35**	**3.66**	**4.88**
0.37	2.15	2.15	2.14	2.14	2.13
1.30	0.90	0.88	0.86	0.85	0.82
1.50	0.82	0.80	0.79	0.77	0.74
1.76	0.74	0.72	0.71	0.69	0.65
2.11	0.67	0.65	0.63	0.61	0.57
2.47	0.61	0.59	0.57	0.56	0.52
2.82	0.57	0.55	0.53	0.52	0.47
3.17	0.54	0.52	0.50	0.48	0.44
3.52	0.51	0.49	0.47	0.46	0.41
3.87	0.49	0.47	0.45	0.43	0.39
4.23	0.47	0.45	0.43	0.41	0.37
4.93	0.45	0.42	0.40	0.39	0.34
5.28	0.43	0.41	0.39	0.37	0.33
5.99	0.42	0.39	0.37	0.35	0.31
7.04	0.39	0.37	0.35	0.33	0.28

U-values for Total Precast System (Metric Units)



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