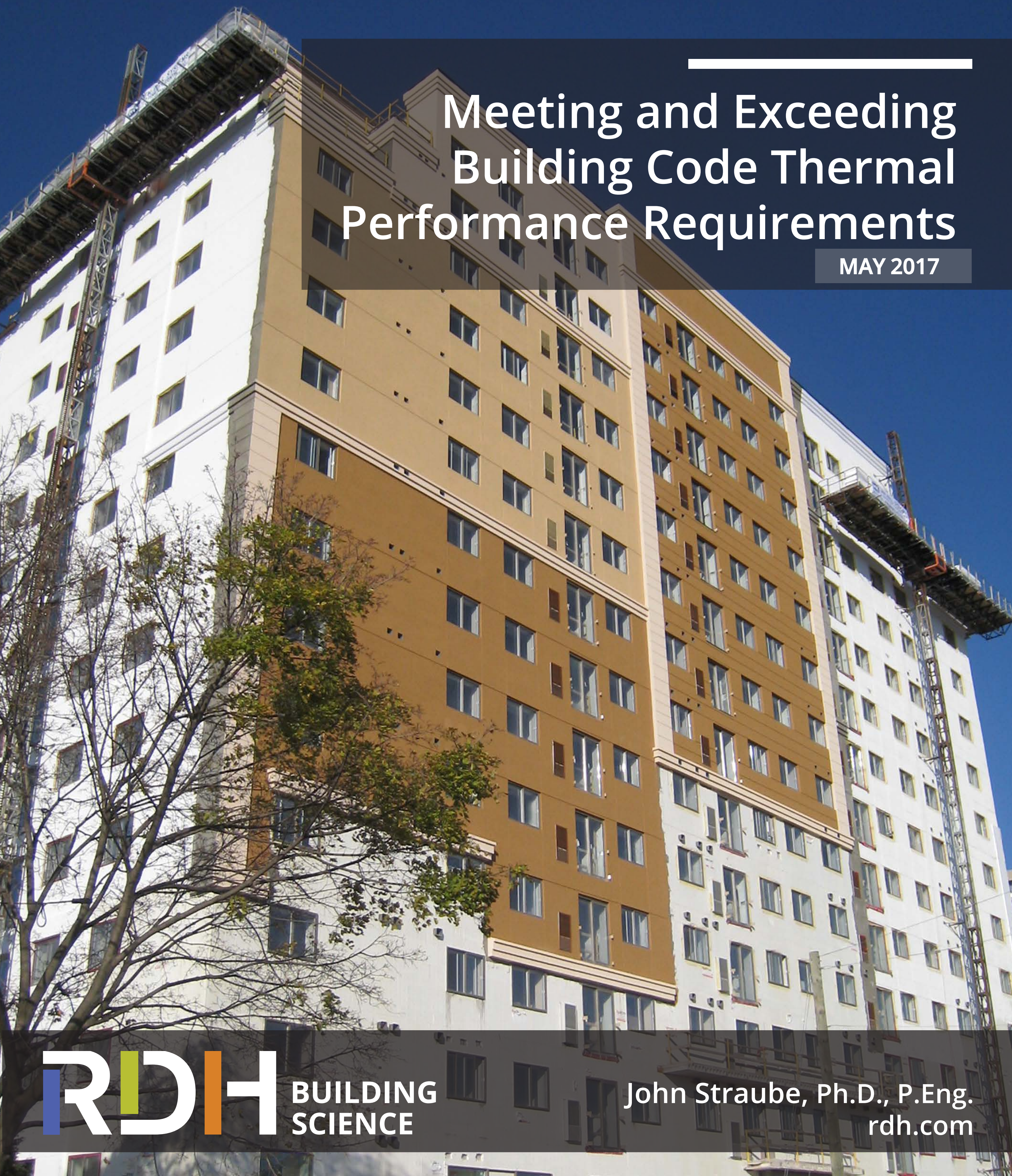
CANADIAN READY-MIXED CONCRETE ASSOCIATION +
INSULATING CONCRETE FORMS MANUFACTURERS ASSOCIATION

Meeting and Exceeding Building Code Thermal Performance Requirements

MAY 2017



RDH BUILDING SCIENCE

John Straube, Ph.D., P.Eng.
rdh.com

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1 Introduction

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

This guide provides designers, builders, and building owners with a brief introduction to compliance options for modern building codes, and details calculation methods suitable for quickly estimating, at an early design stage, the thermal performance of concrete enclosure wall systems. The guide is *not* a comprehensive summary of energy codes in force or of their different interpretations across the country, which remains the responsibility of the designer of record.

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 2011), was introduced to Canada in 1997[1] while the International Energy Conservation Code (IECC) was not introduced in the United States until 2000.

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.

The improvements resulting from changes to codes since the 1970's are plotted in Figure 1.

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

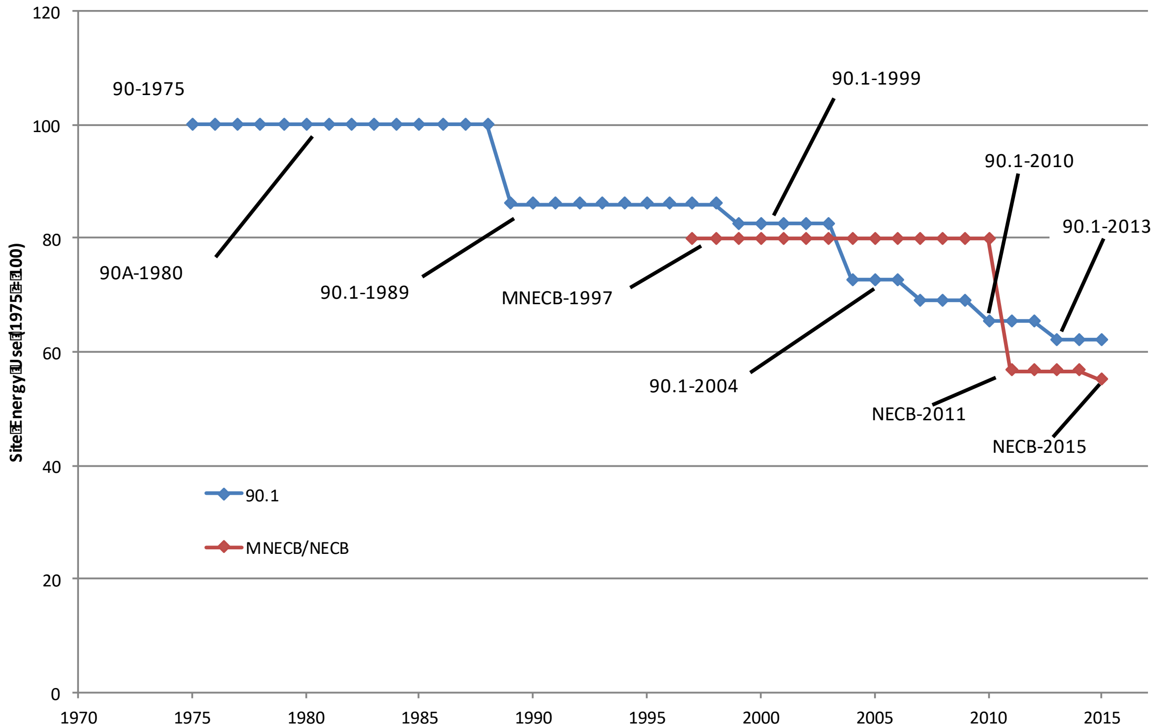


Figure 1: History of energy code performance (information is approximate and differs with building type and climate).

Dependence on traditional materials and enclosure 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 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 concrete enclosures.

1.2 Scope and Approach

The scope of this guide is limited to early-stage design estimates of the thermal resistance of 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 at the early stage 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 some representative current thermal performance requirements in the Canadian codes (Section 2 Energy Codes and Standards),
2. provide an explanation of approximate methods to predict the thermal performance of common enclosure systems for use during early design stages along with examples (Chapter 3), and
3. present example enclosure system solutions, and the calculation of their R-value, to meet thermal performance requirements (Chapter 4).

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

2 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 ASHRAE 90.1 (2010 versions and amended 2013 versions). The Ontario Building Code provides several different options in *Supplementary Standard SB-10* (SB-10) and Quebec is governed by the *Regulation Respecting Energy Conservation in New Buildings Act*. Numerous variations and interpretations exist across the country. Appendix B contains a high-level summary of the current state of energy codes in each of the provinces and territories.

Adoption, often with modifications, additions and deletions of building codes, acts, and standards are 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, as this guide is intended for early-stage design decisions, professionals with knowledge of local energy codes and their interpretations should confirm 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 1 provides 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 (window, 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. The HDD of many cities and locations can often be found in local codes, the ASHRAE Handbook, or the National Building Code of Canada.

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.

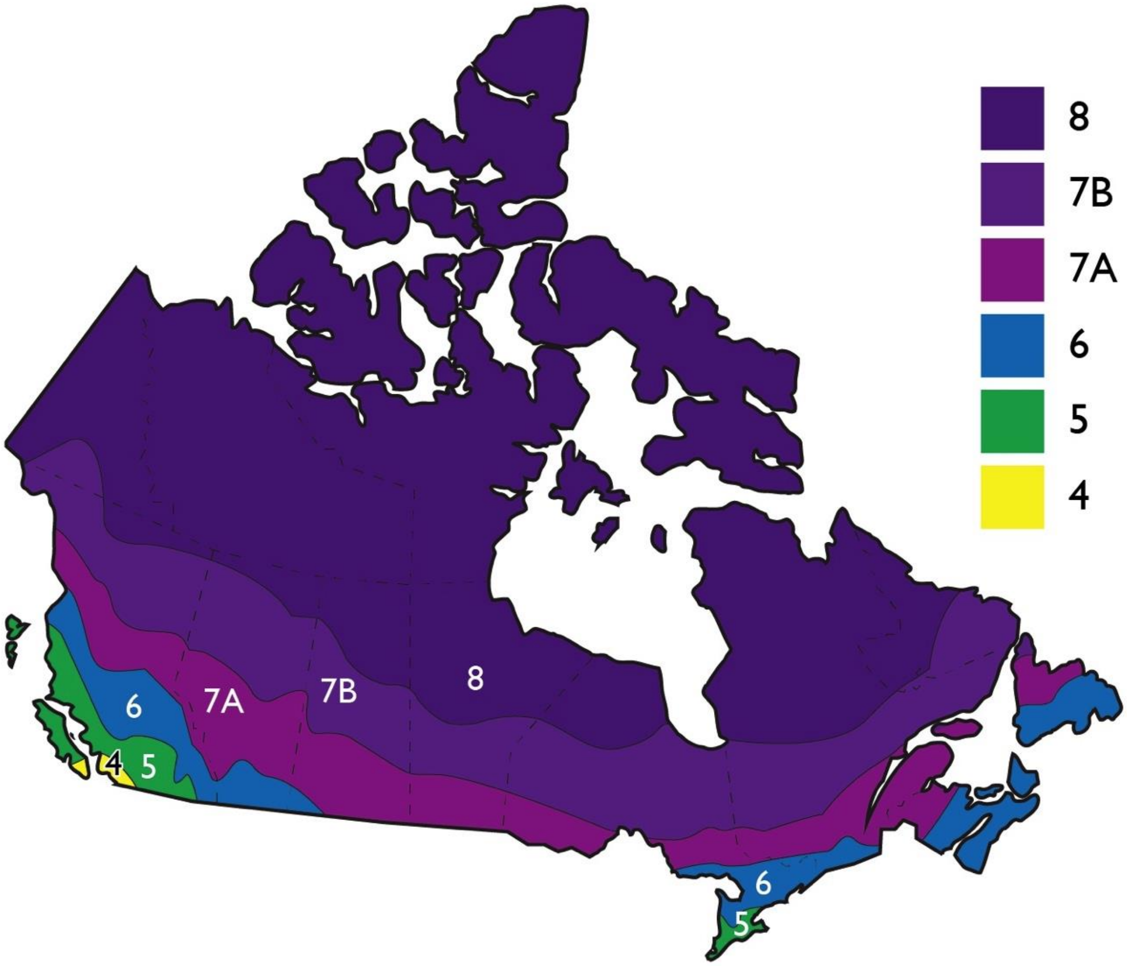


Figure 2: Climate zones for energy compliance.

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

> 143 kJ/m² °C (7 Btu/ft² °F), or
>
> 102 kJ/m² °C (5 Btu/ft² °F) provided that the wall has a material unit weight not greater than 1920 kg/m³ (120 lb/ft³).

This means that concrete walls (normal weight or lightweight) at least 75 mm (3") thick and normal density masonry walls of more than about 4" thick can be considered mass walls for code compliance purposes.

[2] From ASHRAE 90.1-2010

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. ASHRAE 90.1-2010 and 2013 both allow for mass benefits in their prescriptive requirements.

2.2 Prescriptive Approach

The simplest and oldest method of prescribing building enclosure energy performance is to specify the insulation installed or the 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) for three common example energy codes: ASHRAE 90.1-2010, the National Energy Code for Buildings (NECB 2011/2015), and Ontario’s SB-10 as a function of climate zone.

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, NECB-2011, and Ontario's SB-10

Système international U-values (W/m²K)						
Climate Zone	**HDD (18C)**	**ASHRAE 90.1-2010 Non-Residential**	**ASHRAE 90.1-2010 Residential**	**NECB-2011 All**	**Ontario SB-10 Non-Residential**	**Ontario SB-10 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	0.210	0.340	0.340
7/7B	6000-7000	0.071	0.071	0.210	0.340	0.340
8	>7000	0.071	0.052	0.180	0.340	0.340

Inch-Pound R-values						
Climate Zone	**HDD (18C)**	**ASHRAE 90.1-2010 Non-Residential**	**ASHRAE 90.1-2010 Residential**	**NECB-2011 All**	**Ontario SB-10 Non-Residential**	**Ontario SB-10 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).

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.

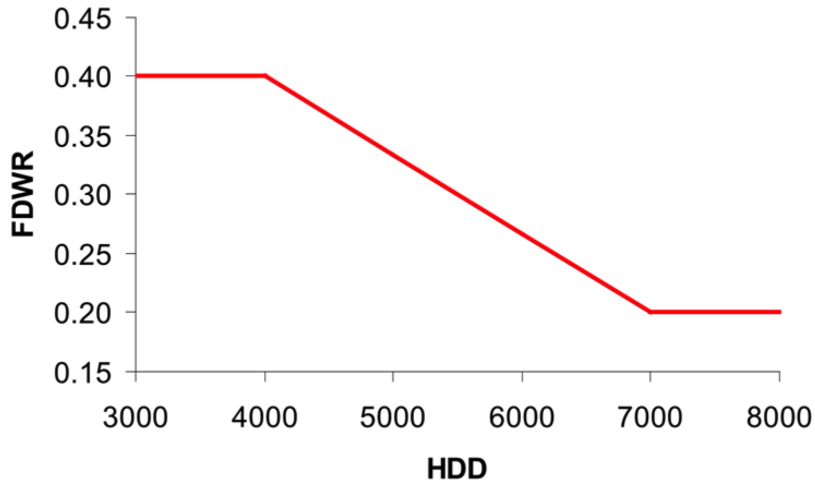


Figure 3: Maximum fenestration-and-door-to-wall ratio (FDWR) varies with the Heating Degree Days (HDD) of the climate under the NECB prescriptive approach.

To provide designers more flexibility, most modern codes, including the OBC, NECB and ASHRAE 90.1, allow the tabulated prescriptive enclosure R-values to 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 skins 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 components' 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 7A.

Table 3: Average Overall Vertical Enclosure R-values for Prescriptive Path ASHRAE 90.1-2010, NECB 2011, Ontario SB-10

		Inch-Pound R-values					
		ASHRAE 90.1-2010		**NECB-11**		**OBC SB-10 2017**	
Climate	**HDD**	**Non-Residential**	**Residential**			**Non-Residential**	**Residential**
Zone	**(18C)**	*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	--	--

		Système International U-values					
		ASHRAE 90.1-2010		**NECB-11**		**OBC SB-10 2017**	
Climate	**HDD**	**Non-Residential**	**Residential**	**Any occupancy**		**Non-Residential**	**Residential**
Zone	**(18C)**	*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	--	--

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.

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 the 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.

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

[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.

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, heat, 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. (Figure 4). 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”, “ci” or “c.i.” is a common terminology encountered in modern prescriptive codes. This was added to code language to minimize thermal bridging, primarily of steel- and wood-framed enclosures. Continuous insulation 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.”*

Floors 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.

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 important 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 that penetrate the insulation around the entire perimeter of all floors needs to be accounted for, 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, if cantilevered concrete balcony slabs penetrate only 25% of each floors perimeter, the area penetrating the enclosure would be only be 1.85%, and hence could be ignored.

Of course, more than slab edges and balconies can penetrate the insulation layer: metal ties used to attach masonry to an externally insulated cast-in place concrete walls, or the composite polymer ties used to connect double-wythe insulated sandwich panels and insulated concrete form (ICF) panels, all normally do not need to be accounted for provided they are less than 2% of the enclosure area (they are commonly much less than this).

[5] This definition is taken from ASHRAE 90.1-2010, Section 3.

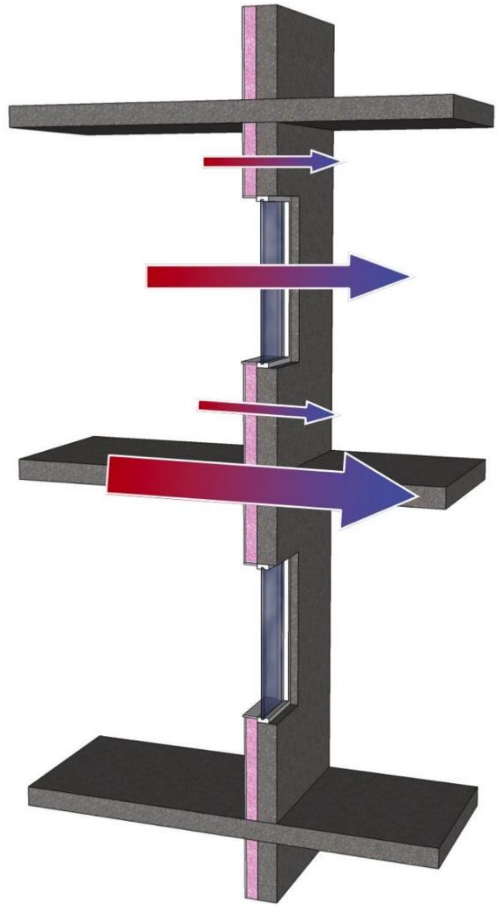


Figure 4: Heat flow paths through center of wall, floor slab, and windows (arrow size is relative to magnitude of heat flow).

The National Energy Code for Buildings (NECB) 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.

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 wall below grade stipulated in the appropriate Tables.

Figure 5: Excerpt from Ontario Building Code Supplementary Standard SB-10 Thermal Bridging Provisions.

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. This 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.

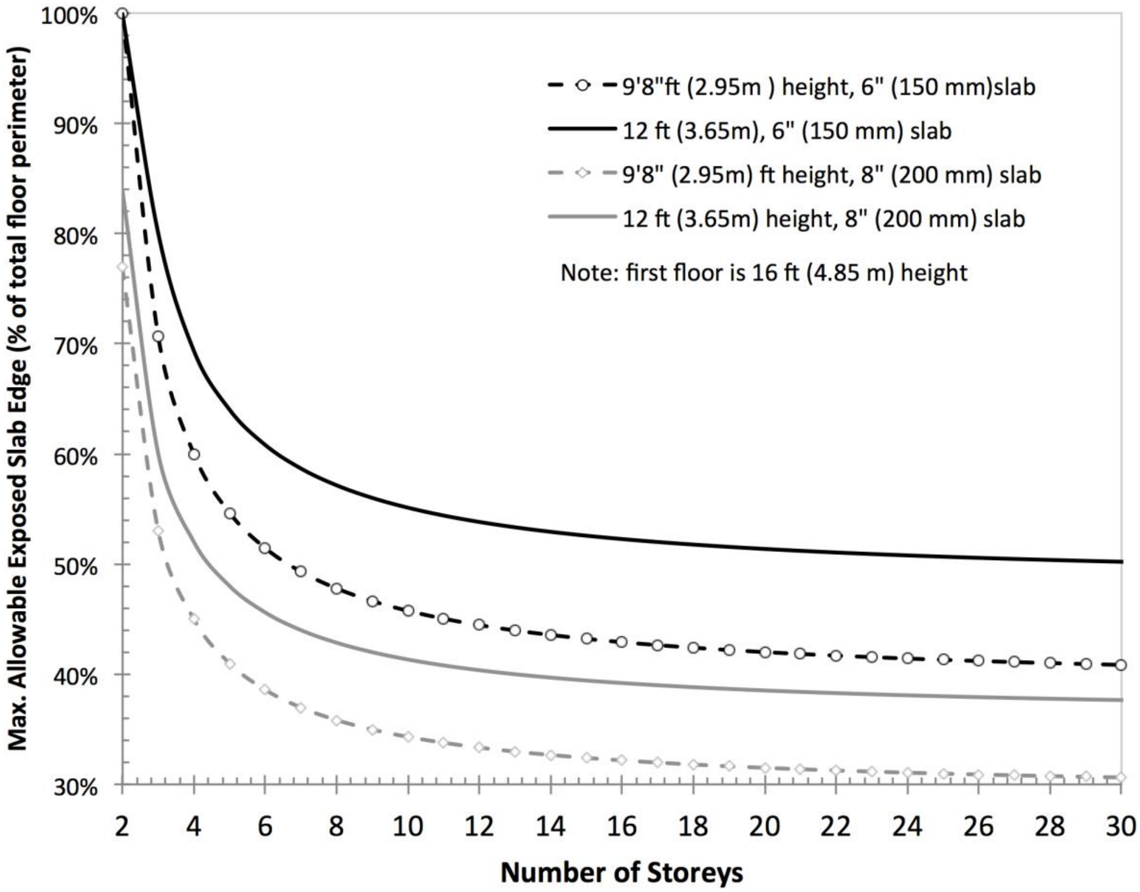


Figure 6: Maximum balcony perimeter per floor assuming 2% thermal bridging waiver.

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.

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

3 Calculating Enclosure Thermal Performance

Many owners do not wish to provide more performance than the minimum code requirement, and hence designers need to design buildings that “just meet” these codes. This requires both an understanding of the code-minimum performance and how to calculate the performance of their building enclosure. Other projects have different goals, or have a longer-term perspective. In this case, designers are driven to make the best choices between many competing alternative enclosure design systems and materials. In either case, 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 * 5.678

RSI = R-value / 5.678

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 = thickness / thermal conductivity = t / k (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 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 (many types of building enclosures), can be calculated from

$R_T = R_1 + R_2 + \ldots + R_n$ (Eq. 2)

where

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

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

[6] Reinforced concrete can be part of an air barrier system.

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).

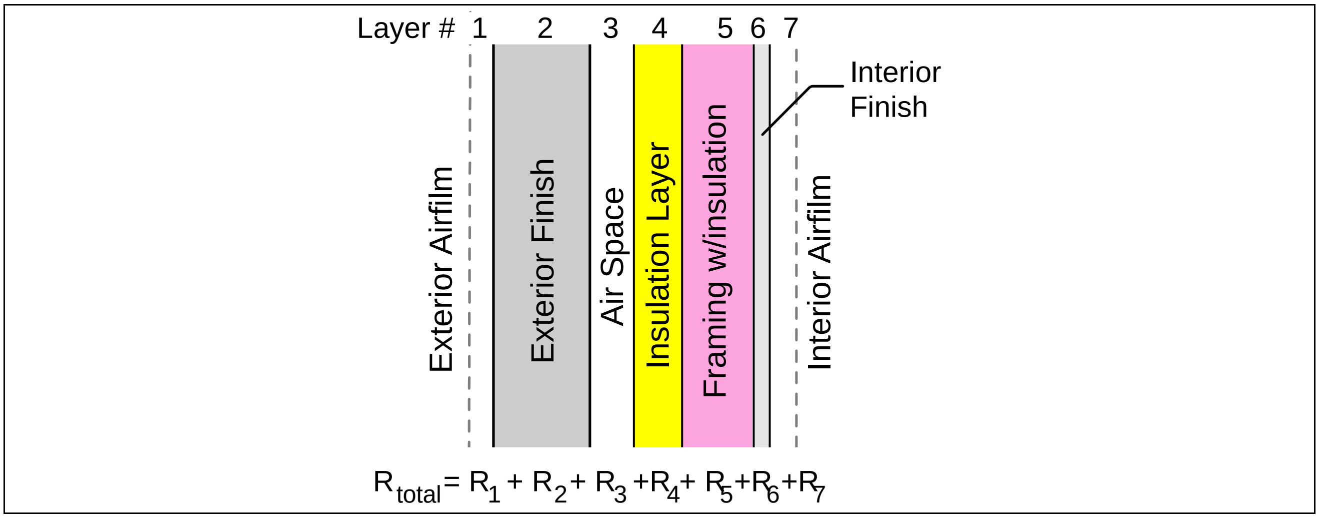


Figure 7: Example calculation of multi-layer assembly thermal resistance.

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 (min 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 modellers 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 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. 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 ***Rated*** or ***Labelled R-value*** is the value printed on the package or technical data sheet along with the thickness intended for use.

→ The ***Installed R-value***, or nominal R-value 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 ***Center-of-Cavity*** is calculated by assuming the assembly is one-dimensional and simply adding the thermal resistance of all layers (e.g. in a 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).
- The ***Whole-wall R-value***, (R_{ww}) includes the clear-wall R-value (R_{cw}) *plus* the thermal impact of conductive penetrations (e.g. floors) and 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 used as a term in all of the major energy standards. 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 3-1/2" (90 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 for a typical light-gauge steel framing system with 5/8" GWB and interior and exterior air films (Sections 3.3.3) are tabulated for easy use in Table 7.

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) for an equivalent layer of 3.5 or 6" depth. If the additional framing details of double-studs at windows, closer-than-nominal spacing and floor slabs are accounted for, the actual R-values provided are actually, and closer to R-4 to R-5.

Table 4: Clear-wall R-value for Light-gauge Steel Framing without Sheathing or ci Acting as a Single Layer (note: "ccSPF" is closed cell Sprayed Polyurethane Foam insulation)[7]

Cavity Depth		**Rated Cavity R-value**	**Layer R_{cw}-value @ 16 inch centers**	**Layer RSI_{cw} @ 405 mm centers**
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

Table 5: Thermal Resistance of Interior Gypsum Wallboard

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

[7] Data primarily assembled from ASHRAE 90.1-2010 Appendices, eg. Table A9.2B, A3.1A, A3.1D, A3.3

Table 6: Clear-wall R-value for Light-gauge Steel Framing including Air Films and One Layer of 5/8" Gypsum Wallboard

Cavity Depth In	mm	**Rated Cavity R-value**	**Layer R_{cw}-value @ 16 inch centers**	**Layer RSI_{cw} @ 405 mm centers**
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

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.

The table includes concrete and masonry veneer layers as well. It can be seen that concrete or masonry do not provide a significant contribution to the R-value of modern insulated assemblies (although dynamic thermal mass effects do help reduce energy use).

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

Table 7: Recommended 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 (ocSPF)	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
Closed-cell Foam (ccSPF)	6.0	12.0	15.0	18.0	21.0	24.0
Reinforced Concrete	0.06	0.12	0.15	0.18	0.21	0.24
Clay Brick Veneer	0.13				0.45	

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 (ocSPF)	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
Closed-cell Foam (ccSPF)	0.024	2.1	2.6	3.2	3.7	4.2
Reinforced Concrete	2.4	0.02	0.03	0.03	0.04	0.04
Clay Brick Veneer	1.2				0.08	

3.3.3 Air Films and Air Spaces

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 (a total of 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.

Air gaps are often used behind some cladding systems, especially those that require a gap for ventilation and dimensional tolerances. The thermal resistance of such air gaps, is about RSI-0.18 (R-1.0) for spaces between about ¾” (20 mm) and 1.5” (40 mm). If one or both sides of the cavity has a reflective (low-emissivity) surface, the thermal resistance will be higher and reference should be made to the ASHRAE *Handbook of Fundamentals* for resistance values.

[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.

Table 8: R-value of Interior and Exterior Surface Films and Air Space (ASHRAE 2013)

Condition	RSI-value	R-value
Interior Surfaces	0.120	0.68
Exterior Surfaces	0.029	0.16
20 mm (3/4") Air Space	0.18	1.0

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 finite-element thermal models of two and three dimensions are generally preferred, but the cost of project-specific analysis can usually not be justified for early-stage design or small projects.

Simpler hand calculation methods, such as the parallel path and zone method can and have been used for years to assess thermal bridging. Many concrete enclosure 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. Heat flow paths with significantly different thermal performance, such as a stud and cavity insulation, an insulated wall and an uninsulated column, or a wall and a penetrating balcony are calculated separately and their U-values weighted in proportion to their relative area. If there were two flow paths, 1 and 2, the following equation would be used:

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

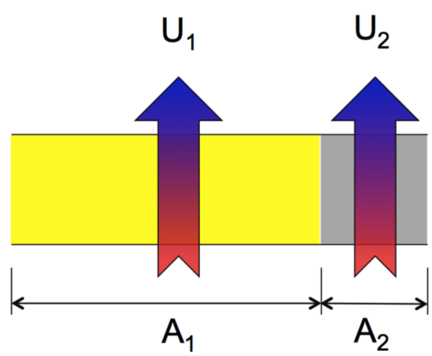


Figure 8: Parallel path heat flow.

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

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

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

ΔT is the temperature difference across the wall.

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

$$R_{WW} = \frac{1}{\frac{\frac{Awall}{Rcw} + \Sigma(\Psi \cdot L_i) + \Sigma(X_j \cdot n_j)}{Awall}} \qquad \text{(Eq. 6)}$$

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 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 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.

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

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

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-values (the value used for the simple trade-off compliance path) for several representative codes and climate zones are shown on the plot.

[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.

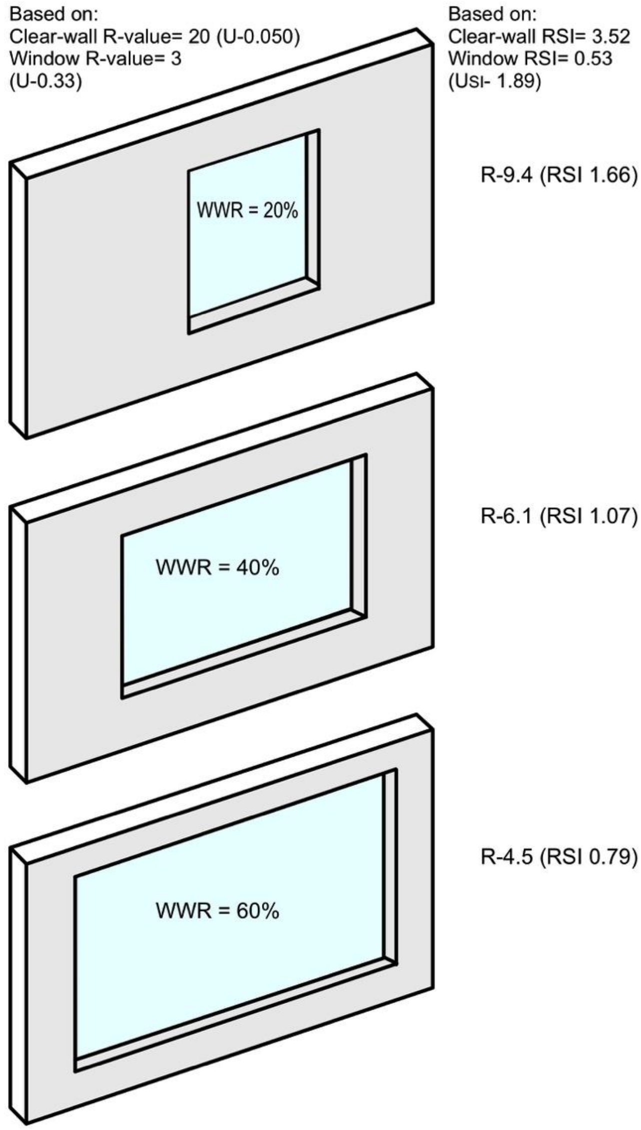


Figure 9: Impact of windows on overall enclosure R-value.

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-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 practise, 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.

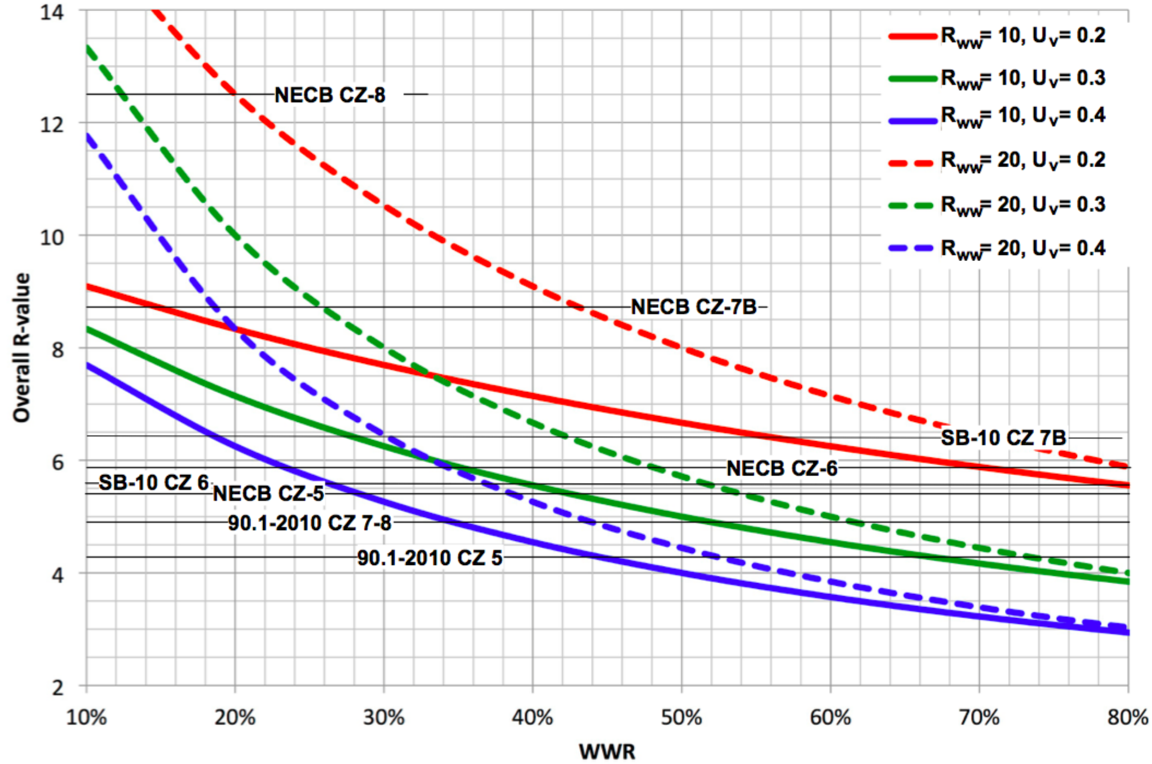


Figure 10: Overall R-value of mass walls and metal windows and the WWR (Note: CZ= climate zone, R_{ww} is whole-wall R-value, and U_v is window U-value).

4 Calculating the Thermal Performance of Concrete Enclosures

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

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 modeller 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 Concrete Enclosures

The wall types considered in this guide are limited to those where concrete is cast onsite. These commonly include cast-in-place, sandwich, and insulated concrete form (ICF) wall systems.

Conventional Cast-in-Place (CIP) construction uses reusable formwork to create solid walls that usually also act as the primary structure. Tilt-up construction techniques can also be employed. These enclosures can be insulated on the interior or exterior surface. The interior insulation solutions employ a combination of continuous and batt insulation between studs. A rendering or paint is usually applied directly to the concrete as an exterior finish. Exterior insulation solutions use a wide range of insulation and cladding systems, ranging from brick and natural stone veneers to lightweight panels and thin synthetic stucco. The primary air, water, and vapour control for these systems is typically accommodated at the exterior face of the CIP wall. The interior can be concrete, laminated gypsum wallboard (GWB), or light-gauge metal framing and GWB.

Insulated Concrete Form (ICF) walls are comprised of two layers of thermal insulation (typically expanded polystyrene), which act as left-in-place formwork for cast-in-place concrete walls and floors. The layers of insulation are connected with ties (often low-conductivity composite polymers). The thermal, air, and vapour control can be provided by ICF components, but the exterior finish, interior finish, fire control layers are typically added afterwards.

Cast-in-Place Integrally Insulated (Sandwich) walls are comprised of an interconnected exterior and interior concrete wythe with an insulated core (typically rigid plastic foam). The concrete wythes are connected with ties (usually stainless steel or composite polymer) that maintain the structural integrity of the panel and provide the degree of composite action desired. These systems may be constructed as tilt-up walls. Exterior finish and waterproof coatings may be applied to the exterior face. These systems provide a complete enclosure, with integral fire resistance and air, water, vapour, and thermal control.

The following sections provide example calculations to estimate the thermal performance of each of these systems. The examples provide a comparison to some example building code requirements.

4.2 Cast-in-Place (CIP) Concrete

Cast-in-place concrete walls are common structural components especially for taller buildings and institutional buildings demanding exceptional durability. They also have the potential to economically provide very high thermal performance building enclosures as they can achieve excellent airtightness and, when used with continuous exterior insulation, also provide excellent control of thermal bridging.

Figure 11: Cast-in-place concrete building under construction.

There is a significant difference between the performance of interior insulated versus exterior insulated. Hence, the following sections consider the two approaches separately.

For internally insulated CIP wall systems it is critical that:

1. some form of continuous insulation be installed outside of the stud bays of any steel framing to ensure good thermal performance (and meet even the least demanding Canadian codes),
2. the insulation *be in tight contact* with the back of the concrete to avoid cold-weather condensation caused by convective loops, and
3. the insulation itself (or an adhered facer) be sealed to provide continuous airtightness and an appropriate amount of vapour diffusion resistance.

The insulation used as continuous insulation in contact with the concrete can be semi-rigid mineral fiber (with airtight facer), rigid board foam (XPS, EPS, or polyiso) or spray polyurethane foam (SPF). Light-gauge steel stud framing is normally installed inboard of this continuous insulation layer and the stud cavities can be left uninsulated or insulated with fibrous or spray insulation[11].

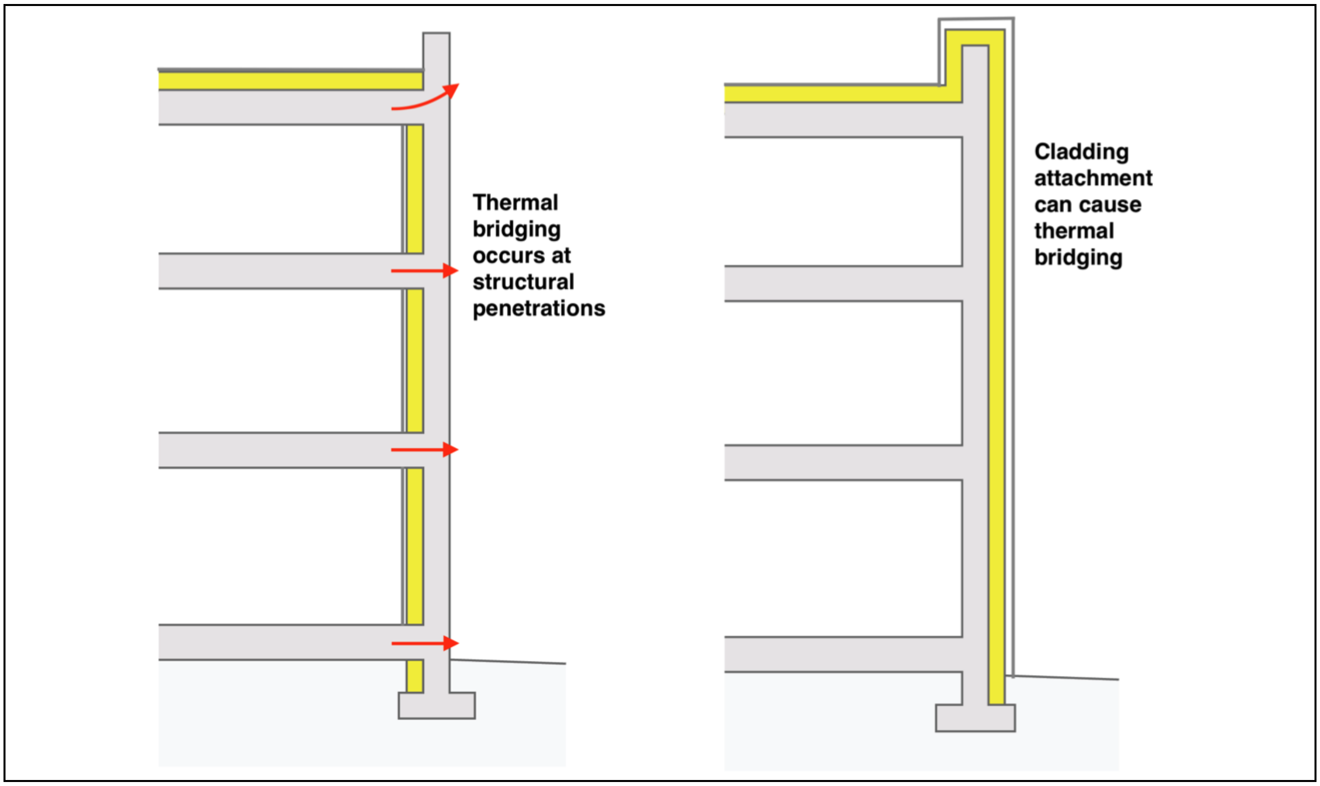


Figure 12: Exterior vs. interior insulated CIP enclosure walls.

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**: A CIP concrete enclosure is comprised of an 8" (200 mm) reinforced concrete panel, 2" (51 mm) of closed cell Spray Polyurethane Foam (ccSPF) continuous insulation, 3.5" (89 mm) steel stud framing at 16" (406 mm) on center, and 5/8" (16 mm) GWB on the interior (Figure 13). What is the clear-wall R-value if the stud space is left empty or if an R-13 batt is added?

[11] Due to thermal bridging through the steel studs, the addition of insulation to the stud space 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 stud space insulation always increases the risk of cold weather condensation. For buildings with low or moderate relative humidity levels in the winter, the increased risk of condensation is often acceptable; high humidity buildings will require special consideration.

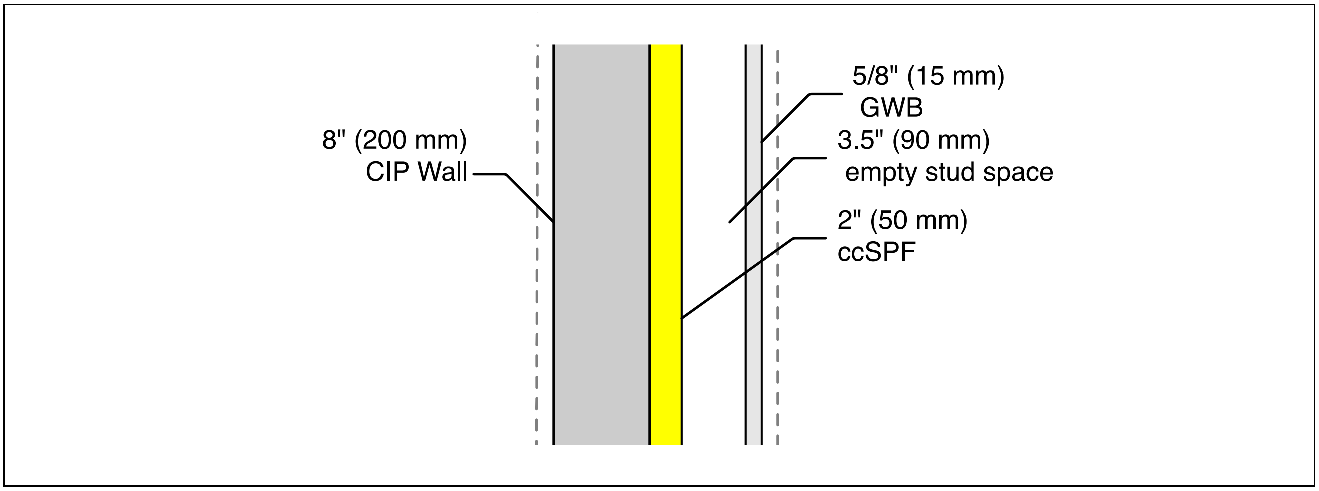


Figure 13: Example interior insulated CIP assembly.

The R-value of all finish components is R-2.19 (Table 7), 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 (RSI-2.50). The R-value provided by the concrete (about R-0.4) has been ignored.

If R-13 batt were to be added to the stud space, the calculation would be R-7.4 plus R-12, for a total of R-19.4 (RSI-3.41) or U-0.052 (U-0.293).

Reference to Table 2 shows that the example system with no batt insulation (R-14.2) would be compliant with:

- ASHRAE 90.1-2010 for all building occupancies up to Climate Zone 7.

The system with batt insulation (R-19.4) would be compliant with:

- NECB Climate Zone 4,
- Ontario SB-10 requirements up to Climate Zone 5, and Climate Zone 6 with the addition of only R-2 to the continuous insulation layer, and
- all climate zones and all building types of ASHRAE 90.1-2010, except for residential buildings in Zone 8.

Of course, if thermal bridging of the floor slabs were to be included, as is required by some AHJs, LEED Canada, and Ontario’s SB-10, the thermal performance of the example wall system would be much lower.

The previous example was an interior insulated wall system: the calculation of clear-wall R-value for exterior insulated systems is exactly the same. To demonstrate, an example is provided.

Example. An 8” CIP wall is to be insulated on the exterior with 3” of stonewool (a mineral wool product) and finished with a masonry veneer (Figure 14). Calculate the clear-wall R-value.

Referencing Table 7 and Table 8, one can sum the contributions made by the air films (R-0.68 and R-0.16 respectively), the air gap (R-1), masonry veneer (R-0.45), 3” of stonewool (R-12), and the concrete itself (R-0.48). This totals to a clear-wall R-value of R-14.8 (of which a rather insignificant R-2.8 is provided by all non-insulation layers).

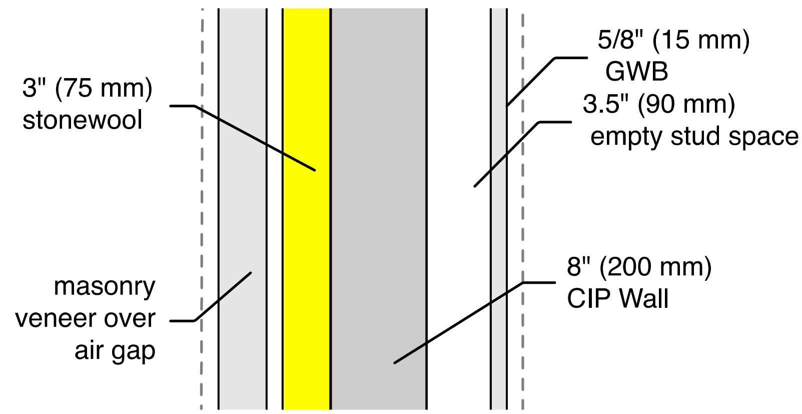


Figure 14: Example exterior insulated CIP wall with masonry veneer.

Masonry ties and flashing rarely need to be considered when calculating clear-wall R-values in today's code environment (they are explicitly exempted in Ontario's SB-10, but must be considered for Passive House projects).

4.2.2 Interior Insulated Whole-wall R-values (Accounting for Floor Slabs)

While the calculation demonstrated above is simple and sufficient for a clear-wall R-value calculation, a whole-wall R-value must include the floor slab intersection. As described in Section 2.5 many codes and energy programs do not allow the floor slabs to be ignored. The approach for accounting for these thermal bridges has only recently begun to appear in practise and depends on the code in force and which thermal bridging effects may be ignored.

The most important potential thermal bridge for an internally insulated CIP concrete enclosure system is the floor-to-wall intersection (Figure 15).

The whole-wall R-value for a CIP wall system including the impact of a through-penetrating floor system can be calculated by recognizing that the floor slab has much lower thermal resistance than the clear wall. Using the parallel path method (see Section 3.4 Calculating Thermal Bridging Impacts) can be used to approximate heat flow:

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

where

R_{ww} is the whole-wall R-value of the opaque enclosure (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)

Based on 2-D computer models the R-value of a typical concrete slab in this application can be assumed to be approximately R-1.2 (RSI0.264).

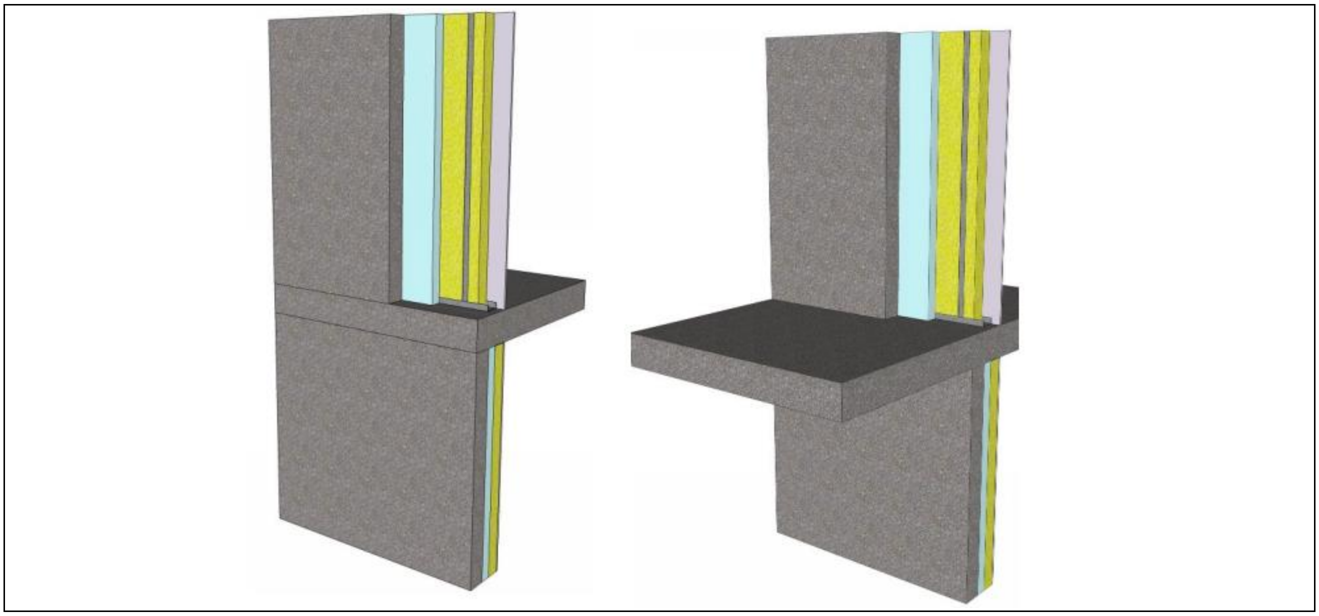


Figure 15: Isometric view of floor slab penetration of interior insulation.

Example: An internally insulated CIP wall (Figure 16) 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 concrete 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 provides 3 x R-4/inch (from Table 7) = R-12, and the 8" (203 mm) of concrete provides 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 R-1.2 for the slab, as:

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

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

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.

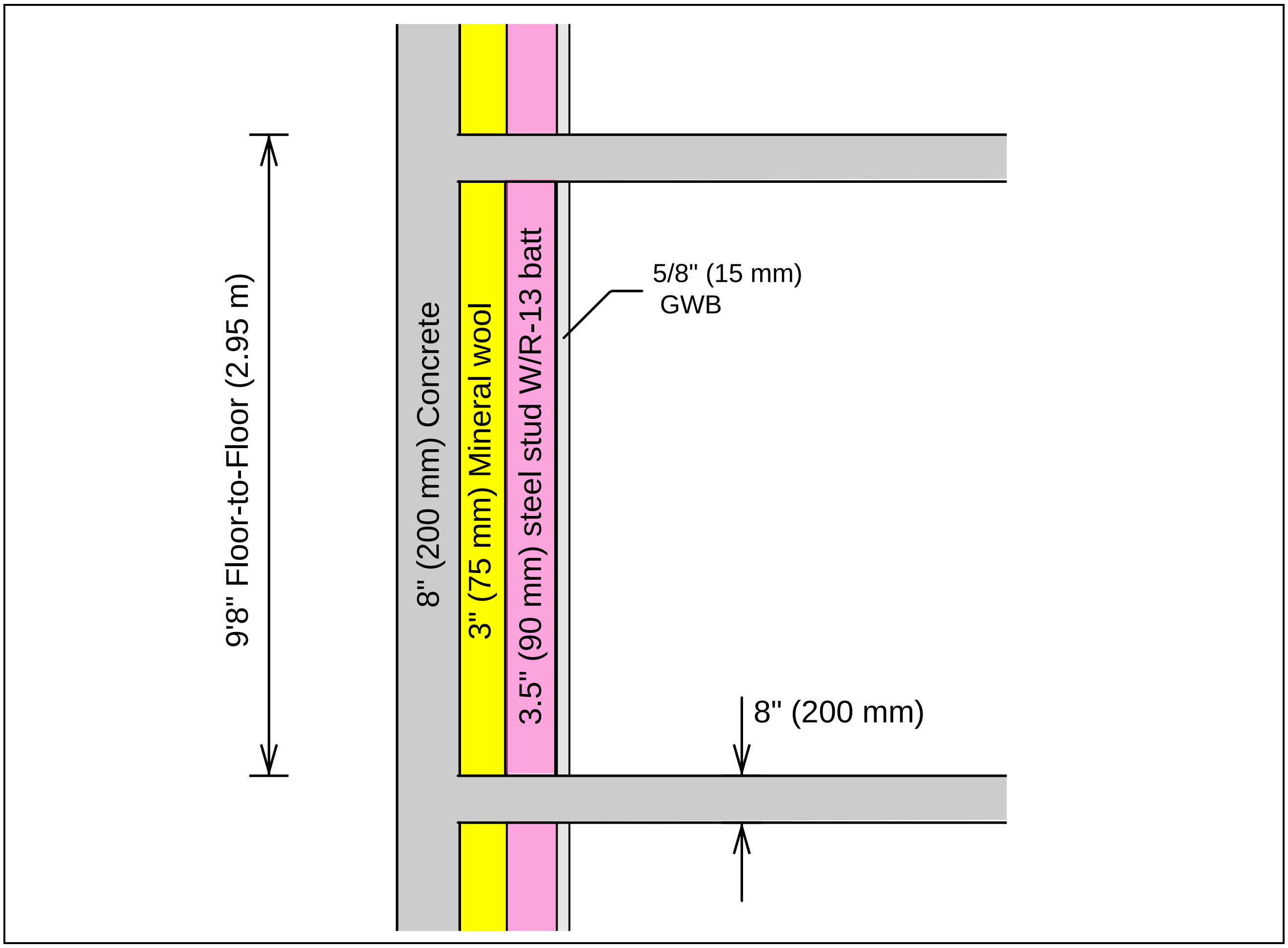


Figure 16: Example interior insulated CIP wall.

Such a system may be code compliant if the window area is reduced, or the window performance is improved, so that the overall R-value is still compliant via the simple trade-off method. 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 with a U-value of 0.3 were specified,
- Ontario's SB-10 up to Climate Zone 6 if windows with a U-value of 0.3 were specified, and
- NECB 2011 Climate Zone 6 if a window U-value of 0.3 and WWR of 0.35 were specified.

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.

The whole-wall R-value for a CIP wall 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, and a range of different floor-to-floor heights and clear-wall R-values. The results are shown in Table 9.

Table 9: Approximate Whole-Wall R- and RSI-values for Interior Insulated CIP Walls

	floor-to-floor (ft)				
R_{cw}	**9**	**10**	**11**	**12**	**16**
5	4.0	4.1	4.2	4.3	4.4
7.5	5.4	5.6	5.7	5.8	6.2
10	6.5	6.7	6.9	7.1	7.7
12.5	7.4	7.7	8.0	8.2	9.0
15	8.1	8.5	8.8	9.2	10.1
17.5	8.7	9.2	9.6	10.0	11.2
20	9.3	9.8	10.3	10.7	12.1
25	10.1	10.8	11.4	11.9	13.7
30	10.8	11.5	12.2	12.9	15.0
35	11.3	12.2	12.9	13.6	16.1
40	11.8	12.7	13.5	14.3	17.0

	floor-to-floor (m)				
RSI_{cw}	**2.74**	**3.05**	**3.35**	**3.66**	**4.88**
0.88	0.71	0.73	0.74	0.75	0.78
1.32	0.95	0.98	1.00	1.02	1.08
1.76	1.1	1.2	1.2	1.3	1.3
2.20	1.3	1.4	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

As can be seen from Table 9, the impact of floor slabs is significant for interior insulated CIP systems. Code compliance is usually best achieved by improving window performance and/or reducing window area via the simple trade-off method, or conducting whole-building energy modeling to account for improvements over code-minimum values for heating, cooling and ventilation equipment, lighting, and controls.

4.2.3 Exterior Insulated Whole-wall R-values

An important benefit of exterior insulated CIP systems is that there is no thermal bridging at floor slabs and shear wall intersections. Hence, the whole-wall R-values are the same as the clear-wall R-values.

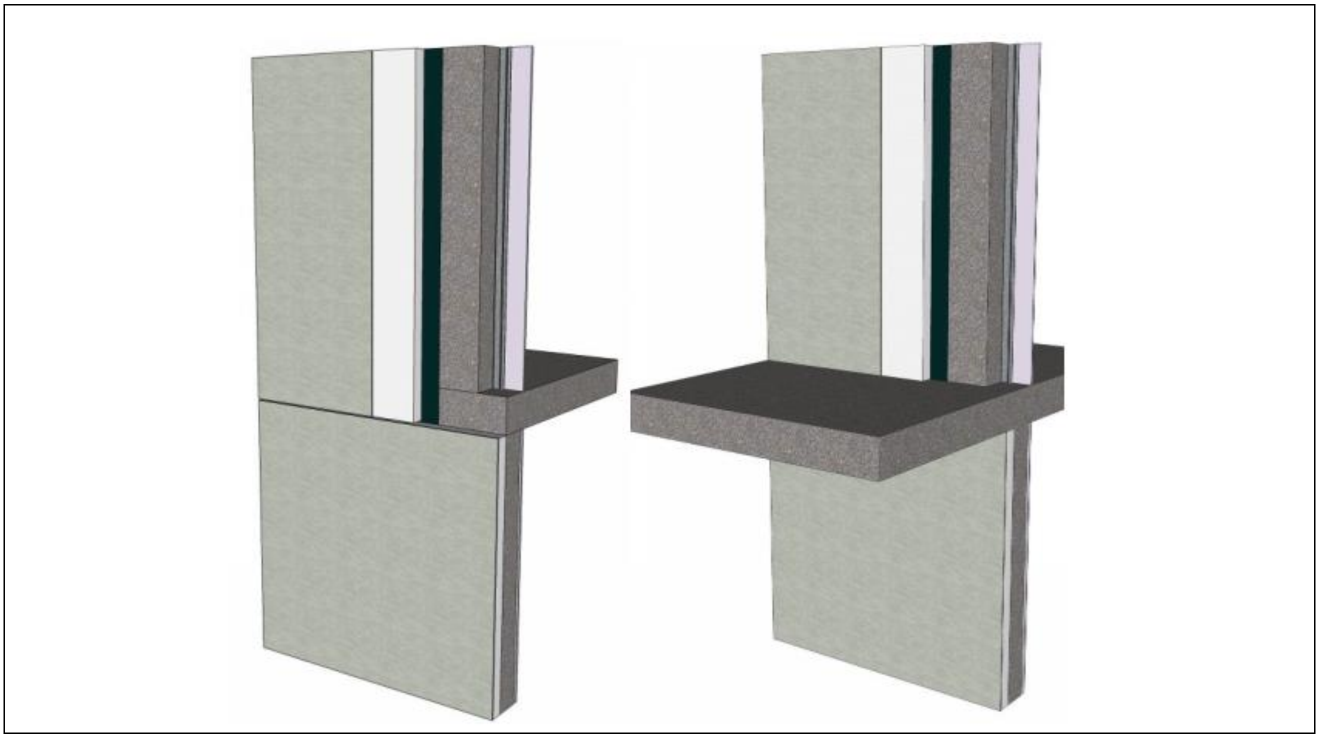
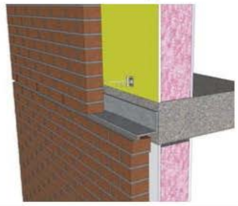
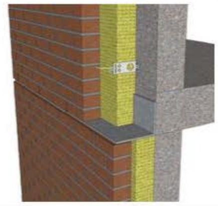
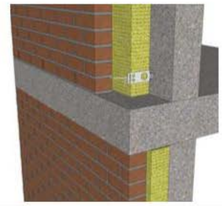
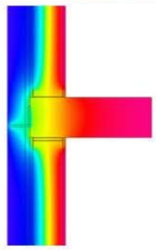
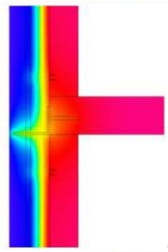
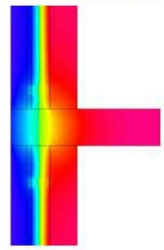


Figure 17: Exterior insulated CIP wall system at floor slab intersection (RDH 2013).

The thermal bridging of concern for all exterior insulated systems is the method of cladding attachment. There are dozens of products and techniques in use for cladding attachment, some of which can reduce the clear-wall R-value by more than 50%. Most energy codes and standards do not explicitly require consideration of cladding attachments, and Ontario's SB-10 explicitly exempts these, but the AHJ in some regions are beginning to require this. Although covering all of the common attachment methods is beyond the scope of this guide, a useful summary of common cladding attachments and their thermal impact can be found on-line (Finch & Higgins, 2016).

A special case of cladding attachments involves the use of shelf angles to support masonry veneers outboard of a continuous exterior insulation layer. An important change in practise over the last decade has been the emergence of stand-off attachment of shelf angles: this not only reduces thermal bridging effects, it eases the installation of water control membranes, accommodates dimensional variations and is usually less expensive than the use of large angles. The thermal bridge impacts are demonstrated in Figure 18, including psi-factors for the calculation of other scenarios.

	Steel Stud Backup	Poured Concrete Backup	Exposed Slab Edge
			
			
Nominal Insulation R-Value/U-Value	R-20 (RSI 3.52) U-0.05 (USI 0.284)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)
Effective Assembly R-Value/U-Value	R-7.3 (RSI 1.29) U-0.137 (USI 0.777)	R-10.5 (RSI 1.84) U-0.096 (USI 0.543)	R-9 (RSI 1.58) U-0.112 (USI 0.634)
Effective Reduction	63.5%	37.5%	46.4%
Linear Transmission	-	ψ = 0.339 IP (0.586 SI)	ψ = 0.478 IP (0.827 SI)

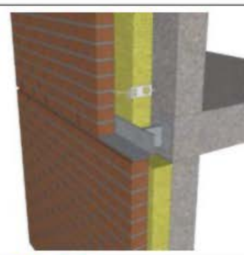
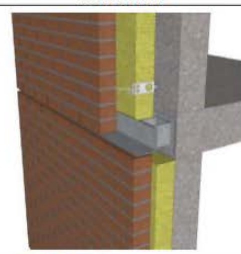
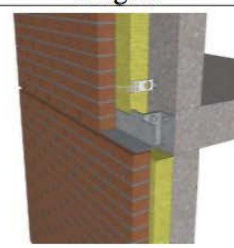
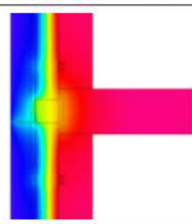
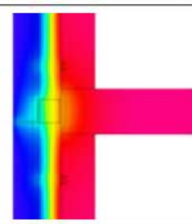
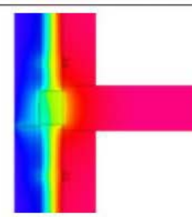
	Knife Plate	HSS Structural Section	Overlapping Angles
			
			
	shelf angle: 4"x4"x1/4" outside of insulation. 4"x4"x3/4" stand-off knife plates welded to embed plates at 48" o.c.	shelf angle 4"x4"x1/4" outside insulation. 4"x4"x1/4" HSS tube welded to embed plates at 48" o.c.	shelf angle 4"x4"x1/4" outside insulation. 2-6"x4"x5/16" angles bolted to slab edge at 48" o.c.
Nominal Insulation R-Value/U-Value	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)
Effective Assembly R-Value/U-Value	R-14.8 (RSI 2.6) U-0.068 (USI 0.384)	R-14.8 (RSI 2.6) U-0.068 (USI 0.385)	R-15.0 (RSI 2.64) U-0.067 (USI 0.379)
Effective Reduction	16.4%	16.5%	15.3%
Linear Transmission	ψ = 0.096 IP (0.166 SI)	ψ = 0.097 IP (0.168 SI)	ψ = 0.089 IP (0.153 SI)

Figure 18: Thermal bridging examples of traditional (top) and improved (bottom) masonry veneer shelf angles (Wilson, 2013).

4.3 Integrally Insulated Sandwich Walls

Double-wythe insulated (sandwich) panels provide a continuous layer of insulation encapsulated during the casting process between two layers of concrete. This type of wall 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 under construction is shown in Figure 19. The integrated insulation layer and composite polymer ties are clearly visible.

Figure 19: Close-up view of integrally insulated wall system during forming.

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 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[12].

[12] 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 Sandwich Wall Clear-wall R-value

The clear-wall R-value of an integrally insulated sandwich 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 10 below as a function of insulation type and thickness.

Table 10: Approximate Whole-Wall Thermal Resistance of Integrally Insulated Sandwich Panels

	Insulation Type		
Insulation Thickness (in)	R4/in (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 (EPS)	k=0.029 W/mK (XPS)	k=0.026 W/mK (PIC)
50.8	1.65	2.00	2.18
63.5	2.00	2.44	2.66
76.2	2.35	2.88	3.14
88.9	2.70	3.32	3.63
101.6	3.06	3.76	4.11
114.3	3.41	4.20	4.60
127	3.76	4.64	5.08
152.4	4.46	5.52	6.05
203.2	5.87	7.28	7.99

4.3.2 Sandwich Wall Whole-wall R-value: Accounting for Floor Slabs

One advantage of sandwich wall construction is that penetrating floor slabs and shear walls do not cause thermal bridging. This assumes that the insulation remains continuous throughout.

Example: What is the whole-wall R-value and U-value for a sandwich wall system (Figure 20) comprising a 3" concrete outer-wythe, 4" of XPS insulation, and 6" 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.

A simple estimate, using Table 7, would be R-20 (RSI 3.52), as 4" of XPS is specified. Table 10 provides an estimate of R-21.4 (RSI 3.76) as it includes the benefit of air films and concrete. In practise, many such systems will have slightly lower R-values because of inter-wythe ties, and slightly higher R-values because of interior GWB finishes.

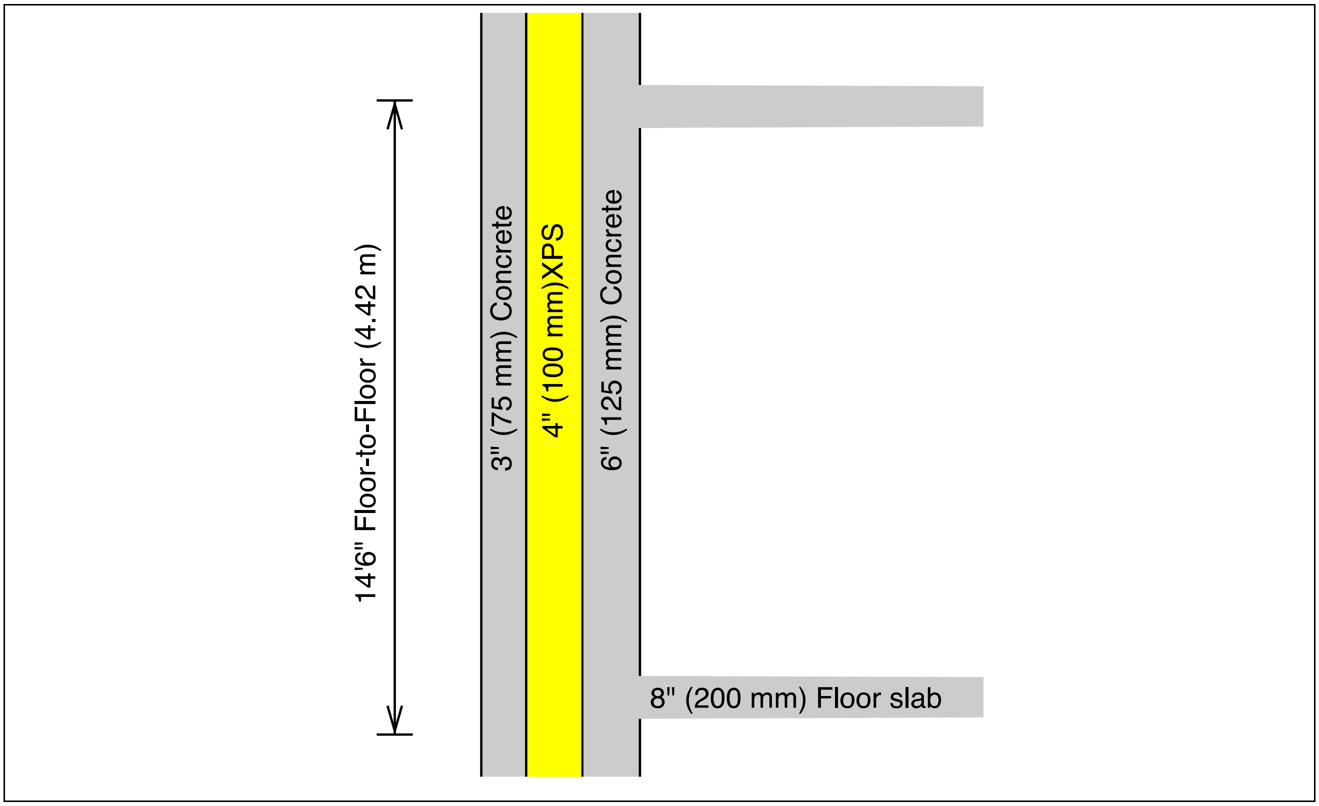


Figure 20: Example double-wythe (sandwich) panel.

Such a system would meet the *prescriptive* requirements of:

- all ASHRAE 90.1-2010 climate zones (up to and including Zone 8),
- up to Climate Zone 6 of Ontario's SB-10, and
- up to NECB Climate Zone 5.

To achieve higher performance using the prescriptive compliance path, thicker insulation must be used. For example, increasing the insulation from 4" (100 mm) of XPS to 6" (150 mm) would increase the whole-wall R-value to R-31.4 (RSI 5.52) and thus would meet the *prescriptive* requirements of all climate zones for the NECB.

Using simple trade-off analysis, better windows can be used to target a true overall R-value for the vertical enclosure (see Section 3.5 and Figure 10). For example, the example system would:

- exceed the requirements of Ontario's SB-10, Climate Zone 6 if windows with code-minimum U-value of 0.35 were specified in a building with a WWR of 40%, and
- meet NECB Climate Zone 7B buildings, either by using a 25% WWR ratio and U=0.30 windows, or U=0.20 windows and 42% WWR.

4.4 Insulated Concrete Forms

Insulated concrete forms are produced by numerous manufacturers and take on a wide range of forms. The thickness of the concrete core that is formed is critical for structural performance. However, the thermal resistance of the concrete can be conservatively ignored in approximate calculations.

Figure 21: ICF apartment building under construction.

4.4.1 ICF Clear-wall R-value

The clear-wall R-value of an ICF can be calculated from the sum of the R-value provided by the EPS insulation facers and the interior and exterior finishes. Table 4 through Table 8 summarize most practical options. Many ICF products have an inner and outer layer of EPS that is about 2.5" (65 mm) thick. For the most common type of EPS[13], the insulation provides an R-value of 4/inch (0.036 W/mK). However, as the market evolves and demands even higher R-values, newer types of EPS (with higher R-value/inch) and thicker EPS facers are becoming more common. Variations in insulation thickness and type provide designers access to products with clear-wall R-values that range from around R-20 (RSI-3.5) to over R-40 (RSI-7.0).

[13] The CAN/ULC-S701 standard governs the minimum properties of expanded polystyrene. Type 2 EPS is the most commonly used for ICF's.

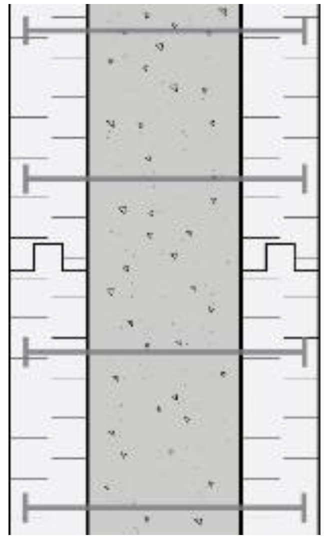


Figure 22: Generic cross-section through an ICF wall.

In early-stage design, the specific ICF product has often not yet been chosen. Thus, a designer will often wish to estimate the performance rather than be limited by the value of a specific manufacturer's product. The calculated clear-wall U-values and R-values, assuming Type 1 EPS insulation, are given for a range of thicknesses including interior GWB and air films (Table 11).

Table 11: Calculated Clear-wall U-values and R-values for ICF Walls for a Range of Insulation Thicknesses including Air Films and ½" GWB (concrete and exterior finishes not included)

EPS Type 2	I-P		SI	
Thickness	R_{cw}	U_{CW}	R_{cw}	U_{CW}
100mm (4")	17.3	0.0579	3.0	0.329
125mm (5")	21.3	0.0470	3.7	0.267
150mm (6")	25.3	0.0396	4.5	0.225
175mm (7")	29.3	0.0342	5.2	0.194
200mm (8")	33.3	0.0300	5.9	0.171
225mm (9")	37.3	0.0268	6.6	0.152
250mm (10")	41.3	0.0242	7.3	0.138

As the design of a building project matures, the R-value of the actual product can often be taken from manufacturer's literature. For greater precision, it is important to confirm if the R-value quoted includes concrete, air films, interior finishes or just the insulation.

Example. An ICF system with a 6" core and two 2.5" EPS facers is proposed as an enclosure system (Figure 23). Estimate the clear-wall R-value.

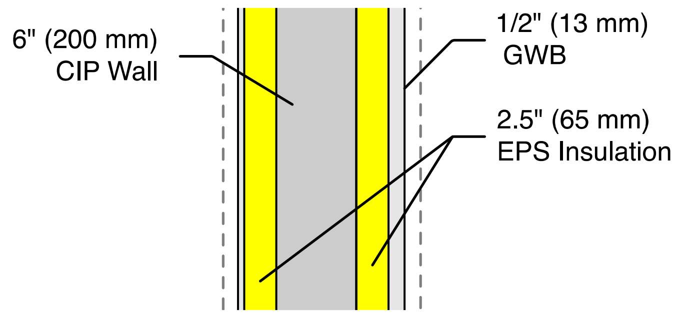


Figure 23: Example ICF wall system.

The total thickness of EPS insulation is 5" (125 mm) and hence Table 11 can be used. The clear-wall R-value would be 21.3 (RSI 3.7) or U-0.047 (U_{SI}-0.267). The synthetic stucco will provide no meaningful R-value improvement.

This assembly could be used to meet the *prescriptive* requirement (i.e. assuming the WWR was less than 40%) for:

- ASHRAE 90.1-2010 in all climate zones for all building types,
- Ontario SB-10 for Climate Zone 5, and for residential buildings only in Climate Zone 6,
- NECB in only Climate Zones 4 and 5.

Of course, other compliance paths could be used for a building in other NECB climate zones, such as improving window performance, reducing window area, increasing mechanical system efficiencies, etc.

The use of cladding systems other than direct-applied stucco will provide a small increase in thermal performance: for example, a 4" masonry veneer over a nominal 1" air space would add R-1.6 to the assembly, whereas a metal panel system would add only about R-1. In the former case the increase in R-value might be sufficient to allow the system to meet the prescriptive requirements of NECB Climate Zone 6.

4.4.2 ICF Whole-wall R-value: Accounting for Floor Slabs & Balconies

Floor slabs, either CIP concrete, topped metal deck, or precast, pass through the inner layer of ICF insulation and thereby increase heat flow in this location. In almost every practical case, the amount of insulation provided by the exterior insulation is sufficient to limit the impact significantly. These thermal bridges can often be ignored as their impact is small. However, some more advanced energy programs (such as Passive House International or PHIUS) may require accounting of these thermal bridges.

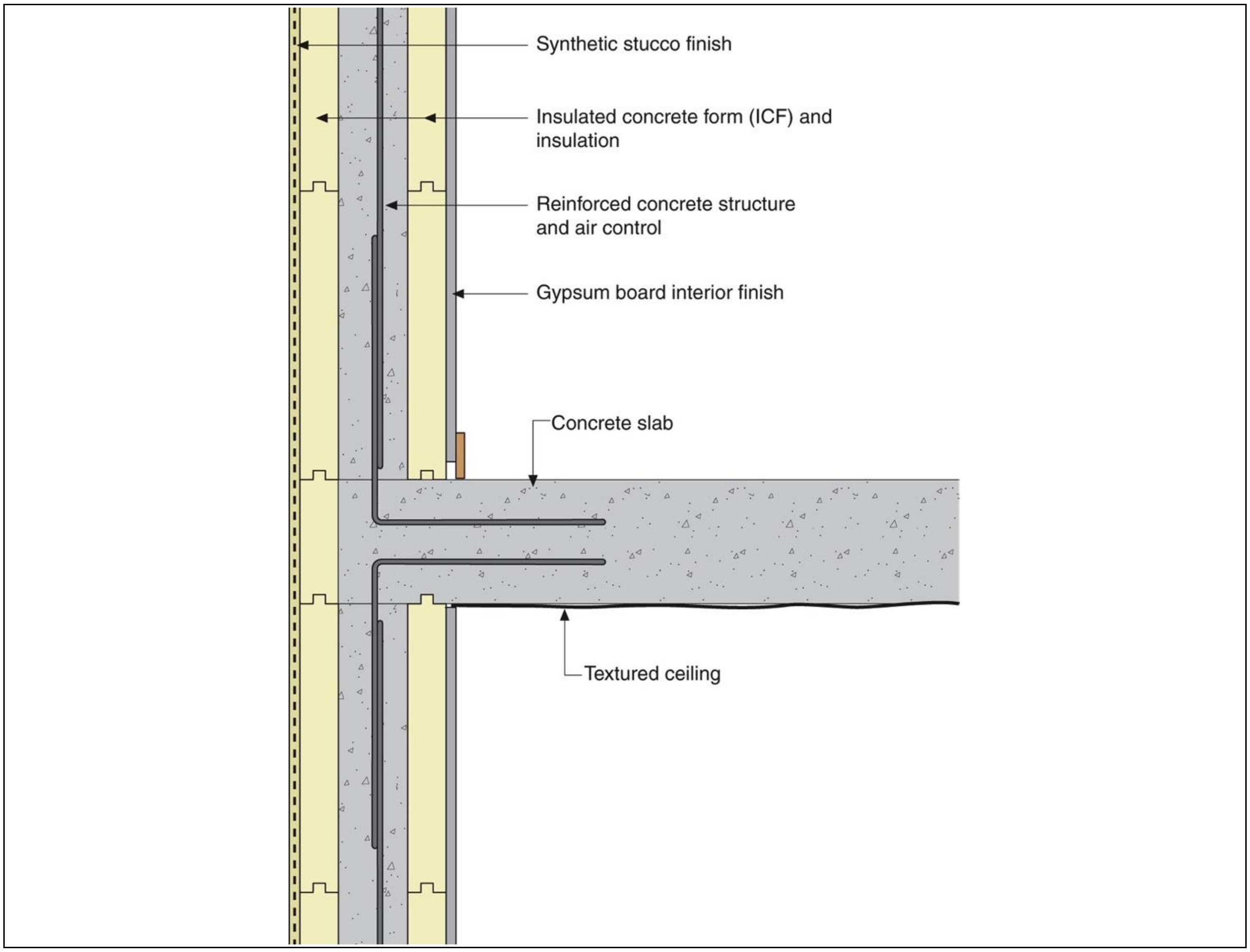


Figure 24: Example floor slab intersection for an ICF with CIP floor.

To estimate the whole-wall R-value for an ICF enclosure, including the impact of the floor system, the following equation can be used[14]:

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

where

R_{ww} is the whole-wall R-value of the ICF wall (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 the R-value of the ICF wall assembly (R-value or RSI) at the floor penetration

The R-value of the floor slab interface with the wall is strongly affected by the amount of continuous insulation at the slab edge. Computer modeling of two common thicknesses was conducted to assess appropriate R_{fl} values, and it was found that the R-value was approximately equal to the R-value of the exterior insulation. The recommended R-values for use in early-stage design calculations are provided in Table 12.

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

Table 12: Total R-value of Floor Slab (R_{fl}) Intersections

Slab Edge Insulation Thickness		R_{fl}-value	
(in)	(mm)	R-value	RSI
2.5	64	11	1.94
3	76	13.1	2.31
3.5	89	15.15	2.67
4	102	17.2	3.03
>4	>102	4.0*t+1.2	0.70*t+0.21

Using the parallel path method approach, the whole-wall R-value, including the effect of floor slab penetrations, was calculated for a range of ICF R-values, slab edge insulation thickness, and floor-to-floor heights with an 8" deep concrete floor slab. The results are tabulated in Table 13 for easy use. It can be seen that the impact of the floor slab is modest, and only reduces the clear-wall values by 5 to 10%.

Example. An ICF wall system is proposed for a high-rise residential apartment building. It is assumed the ICF will have two 2.5" (65 mm) EPS faces, and be finished on the inside with GWB and on the exterior with a thin synthetic stucco. The floor-to-floor height is 10' (3.05 m) and the floor slab is 8" (200 mm) deep.

The clear-wall R-value was found to be R-21.4 in the previous example. Using Table 13, the whole-wall R-value can be estimated using the second row (R_{cw}-22) and second column (10 ft floor-floor). The R-value is about R-20.6, which is a slight reduction from the clear-wall value. This level of thermal bridging would have little impact on either mechanical system design or code compliance.

Cantilevered balconies that penetrate from interior to exterior will have a significant impact on thermal performance of an ICF wall. In general, a reduction of about half of the wall's R-value should be expected. To calculate the impact, the techniques described in Section 4.2.2 Interior Insulated Whole-wall R-values (Accounting for Floor Slabs) can be used.

Table 13: Whole-wall ICF R-values including Floor Slab Penetrations

8" floor slabs		Floor-to-floor height (ft)					
R_{cw}	**slab edge insulation (in)**	**9**	**10**	**12**	**16**	**20**	**24**
20	2.5	18.9	19.0	19.1	19.3	19.5	19.6
22	2.5	20.5	20.6	20.8	21.1	21.3	21.4
24	2.5	22.1	22.2	22.5	22.9	23.1	23.2
30	2.5	26.6	26.9	27.4	28.0	28.4	28.6
35	2.5	30.1	30.6	31.2	32.1	32.6	33.0
40	2.5	33.5	34.0	34.9	36.0	36.8	37.3
20	4.0	19.8	19.8	19.8	19.9	19.9	19.9
22	4.0	21.6	21.6	21.7	21.7	21.8	21.8
24	4.0	23.3	23.4	23.5	23.6	23.7	23.7
30	4.0	28.4	28.6	28.8	29.1	29.3	29.4
35	4.0	32.5	32.7	33.1	33.6	33.8	34.0
40	4.0	36.4	36.8	37.3	37.9	38.3	38.6

203 mm floor slabs		Floor-to-floor height (m)					
RSI_{cw}	**Slab edge insulation (mm)**	**2.7**	**3.0**	**3.7**	**4.9**	**6.1**	**7.3**
3.52	64	3.32	3.34	3.37	3.41	3.43	3.44
3.87	64	3.61	3.63	3.67	3.72	3.75	3.77
4.23	64	3.89	3.92	3.97	4.03	4.07	4.09
5.28	64	4.68	4.74	4.82	4.93	5.00	5.04
6.16	64	5.31	5.38	5.50	5.65	5.75	5.81
7.04	64	5.89	5.99	6.14	6.35	6.48	6.56
3.52	102	3.48	3.48	3.49	3.50	3.50	3.51
3.87	102	3.80	3.80	3.82	3.83	3.84	3.84
4.23	102	4.11	4.12	4.14	4.16	4.17	4.18
5.28	102	5.01	5.03	5.07	5.12	5.16	5.18
6.16	102	5.73	5.77	5.83	5.91	5.96	5.99
7.04	102	6.41	6.47	6.56	6.68	6.75	6.79

5 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 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 will 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 concrete enclosure systems to deliver high levels of effective insulation, often more easily and more economically than other types of enclosure systems. Although the benefits of durability, fire resistance, moisture tolerance, and airtightness of concrete enclosure systems are very significant, they have not been the focus of this guide.

6 References and Guidance Documents

Anon. *Building Envelope Thermal Bridging Guide*. Version 1.1. Morrison Hershfield Limited / BC Hydro, Vancouver, 2016.

Anon. *The Importance of Slab Edge & Balcony Thermal Bridges*, RDH, Vancouver, BC, September 2014.

ASHRAE *Handbook of Fundamentals*, ASHRAE, Atlanta, 2013.

Axy Pagan-Vazquez, Dahtzen Chu, John Straube, Robert Ryan, and Mark Lawton. *Development of Thermal Bridging Factors for Use in Energy Models*. U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL, 2015.

Carmody, J., Selkowitz, S., Arasteh, D., Lee, E. S., Willmert, T. *Window Systems for High- Performance Buildings.* Norton & Co., 2004.

Christian, J.E., and Kosny, J., "Toward a National Opaque Wall Rating Label". *Proc Thermal Performance of the Exterior Envelopes VI*, ASHRAE, Clearwater Beach,1995.

Finch, G., Higgins, J. *Cladding Attachment Solutions for Exterior Insulated Commercial Walls*. Technical Bulletin 11, RDH.com, 2016.

ISO 10077:2012. *Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 2: Numerical method for frames.* International Organization for Standardization, Geneva, 2012.

ISO 10211:2007. *Thermal bridges in building construction Heat flows and surface temperatures Detailed calculations*. International Organization for Standardization, Geneva, 2007.

ISO 14683:2007. *Thermal bridges in building construction -- Linear thermal transmittance -- Simplified methods and default values*. International Organization for Standardization, Geneva, 2007.

ISO 6946:2015. *Building components and building elements — Thermal resistance and thermal transmittance — Calculation method*. International Organization for Standardization, Geneva, 2015.

Johnson, R, Sullivan, R., Selkowitz, S., Nozaki, S., Conner, C., Arasteh, D. “Glazing energy performance and design optimization with daylighting”. *Energy and Buildings*, Vol. 6, No. 4, pp. 305-317, 1984.

LEED. www.cagbc.org.

Love J., Tian W., Tian Z, "Window-to-Wall Ratios and Commercial Building Environmental Control in Cold Climates", *Proc. 3rd SBRN and SESCI 33rd Joint Conference*, Fredericton, 8 pp., 2008.

Morrison Hershfield Limited. *ASHRAE 1365-RP Thermal Performance of Building Envelope Construction Details for Mid- and High-Rise Buildings*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers Inc., 2012.

National Building Code of Canada, Ottawa, 2011 .

National Energy Code for Buildings, Ottawa, 2011 and 2015.

NCMA. *Thermal Catalog of Concrete Masonry Assemblies*, Second Edition. National Concrete Masonry Association, NCMA Publication Number TR233A, Hendon, VA, December 2012.

Poirazis, H., Blomsterberg, A., Wall, M., “Energy simulations for glazed office buildings in Sweden”, *Energy & Buildings*, Vol 40, pp. 1161-1170, 2008.

Ross, B., Straube, J.F., “Enclosure Performance vs Building Form in Cold-Climate Commercial Buildings—What really Drives Energy Use?”, *Proc. 14th Can Bldg Sci & Tech Conf.*, Toronto, Oct 2014, pp. 161-171.

Straube, J.F., *High Performance Enclosures: Design Guide for Institutional Commercial and Industrial Buildings in Cold Climates*. Building Science Press, Somerville, Massachusetts, 2012. 320 pp.

Wilson, M., Finch, G., Higgins, J.,”Masonry Veneer Support Details: Thermal Bridging”, *Proc. of 12th Canadian Masonry Symposium*, Vancouver, British Columbia, June 2-5, 2013.

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 the 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 air spaces 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: 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 recognized procedures including ASHRAE handbooks, standard, and guidelines. Typically, the calculation procedures in the ASHRAE 90.1 standard are used.

Table B1: NECB 2011 (and NECB 2015) Above-grade Opaque Wall Thermal Performance Requirements

Climate Zone	Max. U-value SI (W/m^2 °C)	U-value (I-P) (BTU/ h ft^2 °F)	R-value (I-P) (BTU/ h ft^2 °F)
4	0.315	0.055	18.2
5	0.278	0.049	20.4
6	0.247	0.044	22.7
7	0.210	0.037	27.0
8	0.183	0.032	31.3

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 given 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 the “Other Walls – Steel Framed” subheading in the table.

Table B2: 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)	3.4 RSI (R19)	2.4 RSI (R14)	2.8 RSI (R16)
B	3.1 RSI (R18)	3.6 RSI (R20)	2.6 RSI (R15)	3.0 RSI (R17)
C	3.3 RSI (R19)	3.8 RSI (R22)	2.8 RSI (R16)	3.2 RSI (R18)
D	3.5 RSI (R20)	4.0 RSI (R23)	3.0 RSI (R17)	3.5 RSI (R20)
E	3.7 RSI (R21)	4.2 RSI (R24)	3.2 RSI (R18)	3.8 RSI (R22)
F	3.9 RSI (R22)	4.5 RSI (R26)	3.5 RSI (R20)	4.1 RSI (R23)

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 B3: ASHRAE 90.1-2010 Building Envelope Requirements for Walls, Above Grade - SI (IP)

Climate Zone	Nonresidential			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 are 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 B4: Supplemental Bulletin-10 Amended Requirements for Above Grade Walls – SI (I-P) units

Climate Zone	Nonresidential			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 requires. It is not commonly used and is not summarized here.

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RDH Building Science Inc.
167 Lexington Court, Unit 5
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Tel: 519.342.4731

www.rdh.com

Canadian Ready-Mixed Concrete Association
365 Brunel Road, Unit 3
Mississauga, ON, Canada
L4Z 1Z5
Tel: 905.507.1122

www.crmca.ca

Insulating Concrete Forms Manufacturers Association
Suite 460, 11-300 Earl Grey Drive
Ottawa, ON, Canada
K2T 1C1
Tel: 613.290.6869

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