Quantifying the Energy Impacts of Thermal Bridges in Commercial Buildings and Implications for ASHRAE 90.1-2022 Application

Eric Martin, Pacific Northwest National Laboratory
Paula M. Zimin, Pacific Northwest National Laboratory
Michael Tillou, Pacific Northwest National Laboratory

ABSTRACT

The ASHRAE 90.1 committee expanded the definition and quantification of thermal bridges—components in the building envelope that conduct heat more readily than surrounding materials, reducing overall thermal resistance—in ASHRAE 90.1-2022. Thermal bridges are common in typical construction and can appreciably increase heating and cooling related energy use. These changes in 90.1-2022 substantially improve the detailed modeling of building envelopes and as such affect how energy modelers, designers, and permit applicants must characterize envelope systems for compliance. This paper investigates two primary research questions:

1. What is the modeled energy impact of newly defined thermal bridges when incorporated into DOE's commercial prototype building models, and
2. How can practitioners efficiently document and implement the new requirements during design and permitting?

Using updated Psi- and Chi-factor data adopted by the ASHRAE 90.1 Envelope Subcommittee, Pacific Northwest National Laboratory (PNNL) developed an updated modeling methodology for incorporating thermal bridges into commercial prototype building models and evaluated resulting changes in building energy performance across climate zones. This analysis is followed by a discussion of energy implications and documentation strategies, identifying pathways likely to be used by design teams and code officials. Together, the modeling analysis and documentation discussion provide a bridge between the technical rigor of the updated standard and the practical needs of the building design community.

Introduction

Thermal bridges—localized regions of increased heat flow caused by conductive materials penetrating or bypassing insulation layers—have long been recognized as a significant source of envelope heat loss in commercial buildings. While modern assemblies increasingly rely on continuous insulation and advanced wall systems, real-world construction still incorporates numerous elements that interrupt insulation continuity, including parapets, balconies, shelf angles, intermediate floor edges, window interfaces, and structural attachments. These details can meaningfully degrade the effective thermal performance of building envelopes, especially in colder climates. Over the past two decades, growing research has highlighted the gap between idealized assembly U-factors used in energy modeling and the true performance of envelope systems that include common linear and point thermal bridges (ASHRAE 2011; BC Housing, 2018; BC Hydro Power Smart, 2021).

Responding to this need for more realistic modeling, ASHRAE Standard 90.1-2022 introduces expanded requirements for identifying, quantifying, and mitigating thermal bridges in commercial building envelopes. The 2022 edition adds prescriptive mitigation measures for common conditions, references standardized Psi- and Chi-factors for linear and point thermal bridges, and introduces an allowance mechanism for “other” thermal bridges not specifically addressed in the prescriptive provisions. These updates represent a significant shift for energy modelers, architects, engineers, and code officials, as thermal bridges become an explicit component of both documentation and performance simulations.

Pacific Northwest National Laboratory (PNNL) develops and maintains the U.S. Department of Energy (DOE) commercial prototype building models that underpin many national analyses, including evaluations of incremental savings across code cycles. To assess the effect of the new thermal bridge requirements, PNNL integrated thermal bridges into all prototype vintages using standardized Psi- and Chi-factors used by the ASHRAE 90.1 Envelope Subcommittee. This integration provides, for the first time, a consistent basis for comparing energy impacts with and without explicit thermal bridge accounting.

Accordingly, this paper addresses two research questions central to both the analytical community and the code-compliance ecosystem:

1. What is the impact of newly defined and quantified thermal bridges on heating and cooling energy use in DOE’s commercial prototype building models?
2. How can practitioners—design teams, permit applicants, and code officials—effectively document and implement the new ASHRAE 90.1-2022 thermal bridge requirements in design and permitting workflows?

The first portion of the paper focuses on PNNL’s methodology for integrating thermal bridges into the prototype models and evaluates resulting impacts on heating, cooling, and total energy use in modeled results across climate zones and building types. The second portion provides a practitioner-oriented synthesis of documentation strategies drawn from the new standard, highlighting practical approaches for meeting these new requirements with prescriptive, equivalence-based, and performance-based pathways. Together, these two dimensions—energy impact analysis and documented implementation—offer a unified look at the technical and procedural implications of the 90.1-2022 updates, supporting both more accurate energy modeling and more consistent code application.

Background

Thermal bridging has been widely recognized in building science literature as a significant factor in negatively impacting building thermal envelope performance, yet it has historically been underrepresented in energy codes and simulation practices. A thermal bridge occurs where conductive materials—such as steel framing members, concrete slabs, masonry ties, shelf angles, or structural penetrations—interrupt or bypass insulation layers. These conditions create localized zones of elevated heat transfer that are not captured by conventional clear-field U-factors alone. Over several decades, numerous research efforts have quantified the resulting performance degradation in wall, roof, and floor assemblies, showing that even relatively small conductive elements can reduce overall R-values and increase heating loads, particularly in cold climates.

Earlier editions of ASHRAE 90.1 acknowledged certain types of thermal bridges indirectly. Clear-field framing effects were accounted for through assembly U-factor tables and Appendix A methods, which incorporate framing members, sheathing fasteners, and similar repeating elements. However, other common thermal bridges—such as parapets, balcony slabs, window-to-wall transitions, and cladding support systems—were not explicitly included in envelope requirements. As insulation levels increased across code cycles, the discrepancy between idealized assembly performance and actual field conditions widened, underscoring the need for a more comprehensive approach.

These thermal bridge assumptions are also applied in the DOE commercial prototype building models. To evaluate the impact of the new mitigation requirements in the 2022 prototypes, earlier prototype editions must likewise be updated to reflect unmitigated thermal bridging conditions. Because the prototypes represent minimally code-compliant buildings, all pre-2022 models use unmitigated thermal bridge factors, while the 2022 prototypes use the mitigated factors required by ASHRAE 90.1-2022. This effort captures the effect of the new requirements but also substantially reduces the assumed envelope performance in pre-2022 models.

Parallel to code development, research from utilities, universities, industry, and government agencies has produced detailed quantification of linear (Psi-factor) and point (Chi-factor) thermal bridges. Studies have shown that these non-repeating details can have first-order impacts on envelope performance, in some cases exceeding the impact of improvements to insulation thickness or material selection (ASHRAE, 2011). These findings prompted the ASHRAE 90.1 Envelope Subcommittee to expand thermal bridge considerations in the 2022 edition, integrating the latest research into standardized factors and prescriptive mitigation pathways (Sciarra, 2023).

The resulting framework introduces clearly defined categories of thermal bridges—clear-field, linear, and point—and provides methods for adjusting assembly transmittance values to reflect real-world construction practices. For the first time, a wide range of common envelope intersections are explicitly regulated through prescriptive requirements or quantified through Appendix A Psi- and Chi-factors. These developments represent a significant evolution in how thermal performance is characterized and likely result in improved alignment between modeled and actual building behavior.

For practitioners, the expanded framework means that design teams must move beyond single-value U-factors and consider how detailing decisions influence thermal continuity. For energy modelers, the changes require new workflows for adjusting envelope U-factors and interpreting simulation results. For code officials, they introduce new documentation requirements and review considerations. Understanding the historical context and technical basis for these changes is therefore essential for consistent compliance and effective implementation of ASHRAE 90.1-2022.

Evaluating Thermal Bridges in Commercial Prototype Building Models

Methodology

Table A10.1 in ASHRAE 90.1-2022 Normative Appendix A lists Psi- and Chi-Factors for common linear and point thermal bridge components, respectively (Table 1). The table lists “Unmitigated” and “Default” (i.e. mitigated) factors for each of the eight thermal bridge types, with different factors listed for steel-framed and metal buildings, mass, and wood-framed walls. The factors in Table A10.1 are similar in magnitude to those listed in previous research projects that studied the effects of thermal bridging in building envelopes (BC Housing, 2018; BC Hydro Power Smart, 2021). Example figures illustrating the different thermal bridge types listed in Table 1 are shown in ASHRAE 90.1 Informative Appendix K. While the prescriptive path requires thermal bridge mitigation, the envelope trade-off option offers flexibility for thermal bridges that do not meet the prescriptive requirements. For non-compliant designs following the building envelope trade-off compliance path (ASHRAE 90.1 Section 5.6), thermal bridges can be modeled either using the unmitigated factors from Table A10.1 or using thermal bridge factors from another recognized source as outlined in Section A.10.1.

Table 1. Thermal Bridging Psi-Factors and Chi-factors for common thermal bridges in steel framed and metal buildings (from Table A10.1)

	Unmitigated		Mitigated / Default	
Thermal Bridge Type	Psi-Factor Btu/(h-ft-°F)	Chi-Factor Btu/(h-°F)	Psi-Factor Btu/(h-ft-°F)	Chi-Factor Btu/(h-°F)
Parapet	0.289		0.151	
Intermediate floor balcony or overhang to opaque *wall* intersection	0.487		0.177	
Intermediate floor balcony in contact with *vertical fenestration*	0.974		0.177	
Cladding support	0.314		0.217	
Wall to *vertical fenestration* intersection	0.262		0.112	
Other element and assembly intersections		1.730		0.910

Normative Appendix A provides guidance on how to calculate assembly U-factors that incorporate the effects of thermal bridges in simulations. Equation A10.2 in ASHRAE 90.1-2022 (1) can be used to modify clear-field U-factors of modeled assemblies, using the Psi- and Chi-factors listed in Table A10.1.

$$U_{tot} = \left\{ \frac{\left[\left(\sum \psi_i \times L_i \right) + \left(\sum \chi_j \times n_j \right) \right]}{A_{total}} + U_O \right\} \quad (1)$$

Where:

U_{tot} = overall thermal transmittance, including the effect of linear thermal bridges and point thermal *bridges* not included in the *construction* assembly U_O-factor (Btu/h-ft^2-°F)

U_O = clear-field *thermal transmittance* of the *construction* assembly as determined in accordance with Section 5 (Btu/h-ft^2-°F)

A_{total} = total *opaque* projected surface area of the *construction* assembly (ft^2)

ψ_i = psi-factor, thermal transmittance for each type of linear thermal bridge (Btu/h-ft^2-°F)

L_i = length of a particular *linear thermal bridge* as measured on the outside surface of the *building* envelope (ft)

χ_j = chi-factor, thermal transmittance for each detail type of point thermal bridge (Btu/h-°F)

n_j = number of occurrences a particular type of *point thermal bridge*

Equation A10.2 offers flexibility in its application to building models, enabling varying degrees of granularity when accounting for the effects of thermal bridges in simulations. The most detailed approach involves calculating U_{tot} individually for each exterior surface containing a thermal bridge. In this case, each surface could have a unique U_{tot} value, as surface-specific differences such as thermal bridge types and surface areas would be considered. The drawback of this approach is the significant effort required to calculate and evaluate U_{tot} for each surface, as well as the challenge of ensuring that the correct U_{tot} is consistently applied to the corresponding surface.

At the other extreme, U_{tot} could be calculated for the entire exterior wall area of a building, where A_{total} represents the total exterior wall surface area, and the bracketed term in Equation A10.2 accounts for the sum of all thermal bridge elements across all exterior wall surfaces. In this approach, all exterior walls are modeled using the same U_{tot} value. A disadvantage of this simplified approach is that the thermal effects of bridging elements are distributed across a larger area, rather than being concentrated in the thermal zones most directly impacted. For instance, thermal bridges at roof edges with parapets would realistically affect only the thermal loads in zones directly beneath the roof edge (e.g., top-floor zones). Extending this impact to ground-floor zones is unrealistic, as HVAC systems and other aspects of thermal separation (e.g., insulation, infiltration, and internal gains) would largely mitigate any thermal effects from the top floor on the lower floors.

A balanced approach that is both detailed and manageable involves calculating U_{tot} on a floor-by-floor basis for relevant construction assemblies. This method was developed and adopted in the commercial prototype models through collaborative efforts between PNNL and industry experts, including the ASHRAE 90.1 envelope subcommittee.

Previous editions of ASHRAE 90.1 prescriptively require exterior insulation to remain continuous at floor-to-wall intersections, including at roof edges and intermediate floor to wall intersections; consequently, this thermal bridge type is not represented in the prototypes. Furthermore, the prototype geometries do not include elements that would constitute point thermal bridges. Of the eight thermal bridge types in Table A10.1, the remaining six were identified as present within the prototypes and subject to prescriptive mitigation requirements, including:

- Cladding support
- Intermediate floor balcony in contact with vertical fenestration
- Intermediate floor balcony or overhang to opaque wall intersection
- Wall to vertical fenestration intersection
- Parapet
- Roof edge

The above thermal bridge types were evaluated for each prototype model by accounting for dimensions of relevant components in the prototype geometry and applying the appropriate thermal transmittance factors from Table A10.1. Detailed thermal bridge adjustment calculations and overall thermal transmittance values are calculated for each prototype, by floor, in the Thermal Bridge Calculator workbook (U.S. Department of Energy, 2026).

To illustrate the process of calculating the overall transmittance values used in PNNL’s commercial prototypes, the following is a detailed example of how thermal bridges are accounted for in the Medium Office prototype in climate zone 4A (New York, NY) including vertical fenestration to wall intersections and cladding supports; other thermal bridges meet prescriptive requirements. All the commercial prototypes have windows, so the wall to vertical fenestration intersection thermal bridge type is addressed in all prototypes. This thermal bridge involves the interface between an insulated exterior wall and a vertical window. The intersections between the opaque walls and vertical fenestrations were measured in each prototype and multiplied by the appropriate Psi-factor in Table A10.1. The Medium Office has a window-wall intersection length of 1,410.9 ft on the first floor and is constructed with steel-framed walls. Therefore, the mitigated heat flow (the numerator in Equation (1)) associated with the window-wall intersection on the first floor is equal to:

$$0.112\ Btu/(h \cdot ft \cdot {}^{\circ}F) \times 1{,}410.9\ ft = 158.0\ Btu/(h \cdot {}^{\circ}F) \qquad (2)$$

Where:
0.112 Btu/(h·ft·°F) is the default/mitigated Psi-factor for wall to vertical fenestration intersections in steel-framed walls from table A10.1.

The window-wall intersection length of the middle and top floors is 1398.2 ft. Therefore, mitigated heat flow associated with the window-wall intersection on the middle and top floors is equal to:

$$0.112\ Btu/(h \cdot ft \cdot {}^{\circ}F) \times 1{,}398.2\ ft = 156.6\ Btu/(h \cdot {}^{\circ}F) \qquad (3)$$

Some of the thermal bridge types apply only to certain prototypes. For example, cladding support is only relevant for buildings with shelf angles or girts supporting exterior cladding. A brick masonry veneer is assumed for the Medium Office, Secondary School, Hospital, Outpatient, Large Hotel, Small Hotel, Midrise Multifamily, and Highrise Multifamily. For these prototypes, metal shelf angles supporting the exterior brick cladding are assumed as linear thermal bridges occurring over a portion of the building's exterior walls. For the Medium Office prototype, 20 percent of the 546-ft building perimeter is assumed to be the length of the shelf angle cladding support. Therefore, the total mitigated heat flow associated with cladding support is equal to:

$$20\% \times 546\ ft \times 0.217\ Btu/(h \cdot ft \cdot {}^{\circ}F) = 23.7\ Btu/(h \cdot {}^{\circ}F) \qquad (4)$$

Where:
0.217 Btu/(h-ft-°F) is the default/mitigated Psi factor for cladding support in steel-framed walls from table A10.1.

The cladding support and window-wall intersection lengths are the same for each floor of the Medium Office prototypes. However, the denominator in Equation (1), A_{total} (the total opaque surface area of the construction assembly), varies by floor. The ground floor has six doors totaling 84 ft^2, so the total opaque surface area on the ground floor is 84 ft^2 less than floors two and three. Therefore, the thermal bridge adjustment U-factor $\frac{[(\sum \psi_i \times L_i)+(\sum \chi_j \times n_j)]}{A_{total}}$ for the **first (bottom/ground) floor** is:

$$(23.7 + 158.0\ Btu/(h \cdot {}^{\circ}F))/(4{,}754.2 - 84\ ft^2) = 0.039\ Btu/(h \cdot ft^2 \cdot {}^{\circ}F) \qquad (5)$$

The thermal bridge adjustment U-factor for the **second (middle) floor** is:

$$(23.7 + 156.6\ Btu/(h \cdot {}^{\circ}F))/(4{,}754.2\ ft^2) = 0.038\ Btu/(h \cdot ft^2 \cdot {}^{\circ}F) \qquad (6)$$

The third floor of the Medium Office prototype is also the top floor, where an additional thermal bridge type is assumed for the parapet. The parapet length is assumed to be the building's roof perimeter. The Medium Office roof perimeter is 166.4 m (546 ft). Therefore, the total mitigated heat flow associated with the parapet is equal to:

$$546\, ft \times (0.151\, Btu/(h \cdot ft \cdot {}^\circ F)) = 82.4\, Btu/(h \cdot {}^\circ F) \quad (7)$$

Where:
0.151 Btu/(h·ft·°F) is the default/mitigated Psi-factor for parapets in steel-framed walls from table A10.1.

The thermal bridge adjustment U-factor for the **third (top) floor** is the sum of the heat flows associated with the parapet, cladding support, and window-wall intersection, divided by the opaque wall area on the top floor:

$$(82.4 + 23.7 + 156.6\, Btu/(h \cdot {}^\circ F))\ /\ 4{,}754.2\, ft^2 = 0.055\, Btu/(h \cdot ft^2 \cdot {}^\circ F) \quad (8)$$

Per Equation (1), the overall thermal transmittance of the opaque walls on each floor (U_{tot}) is the sum of the clear-field thermal transmittance (U_O) and the thermal bridge adjustment U-factors calculated in (4), (5), and (7). For example, per Table 5.5-4 in ASHRAE 90.1-2022, the assembly maximum U-factor for a steel-framed wall in climate zone 4A is 0.064 Btu/hr-ft²-°F. Accounting for the mitigated thermal bridging types summarized above, the top, middle, and ground floor overall thermal transmittance values for the Medium Office prototype model in New York, NY (climate zone 4A) are:

$$U_{tot_{top}} = 0.064 + 0.055 = 0.119\, Btu/(h \cdot ft^2 \cdot {}^\circ F) \quad (9)$$

$$U_{tot_{mid}} = 0.064 + 0.038 = 0.102\, Btu/(h \cdot ft^2 \cdot {}^\circ F) \quad (10)$$

$$U_{tot_{ground}} = 0.064 + 0.039 = 0.103\, Btu/(h \cdot ft^2 \cdot {}^\circ F) \quad (11)$$

The thermal transmittance values in Equations (9), (10), and (11) match the U-factors listed in the Envelope Summary output report for the 90.1-2022 Medium Office prototype model in climate zone 4A as well as those calculated in the Thermal Bridge Calculator workbook on energycodes.gov (U.S. Department of Energy, 2026).

Energy Impacts

Figure 1 shows the overall exterior wall U-factors assumed for the Medium Office prototype models in climate 4A (New York, NY) before and after accounting for thermal bridging. Prior to the 2022 set, the wall U-factors were equivalent to the assembly maximum U-factor for a steel-framed wall listed in Section 5.5. The 2022 set derates the U-factors from the assembly maximum requirement by accounting for unmitigated thermal bridging in vintages prior to 2022 and mitigated thermal bridging in the 2022 prototypes.

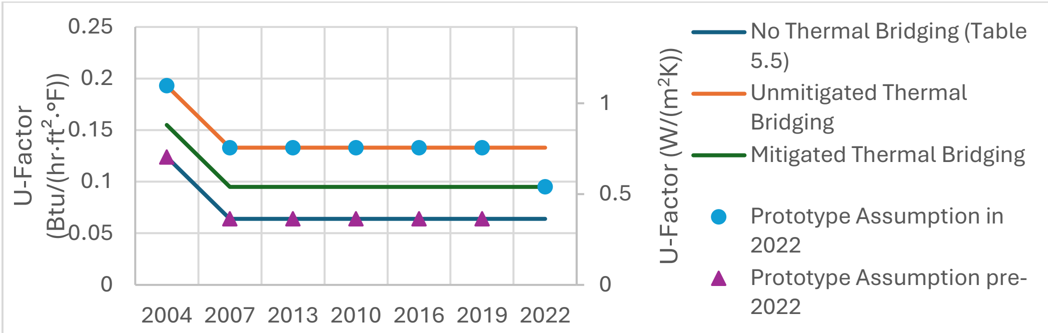

Figure 1. Exterior wall U-factors in Medium Office prototype in New York, NY (4A) before (green) and after (blue) the 2022 release

Accounting for thermal bridging increases the overall energy use intensity (EUI) of the buildings because, in almost all cases, reduced wall performance leads to higher HVAC energy consumption, especially in cold climates. Figure 2 shows the impact on EUI that the thermal bridging assumptions have on the Medium Office prototype in New York, NY. While the overall EUIs increased due to the thermal bridging assumption, relative savings between subsequent editions of ASHRAE 90.1 remained similar in magnitude, except for the savings increase between 2019 to 2022 (Figure 3). The savings increase between 2019 and 2022 is expected since the models reflect unmitigated thermal bridges in 2019 and mitigated thermal bridges in 2022.

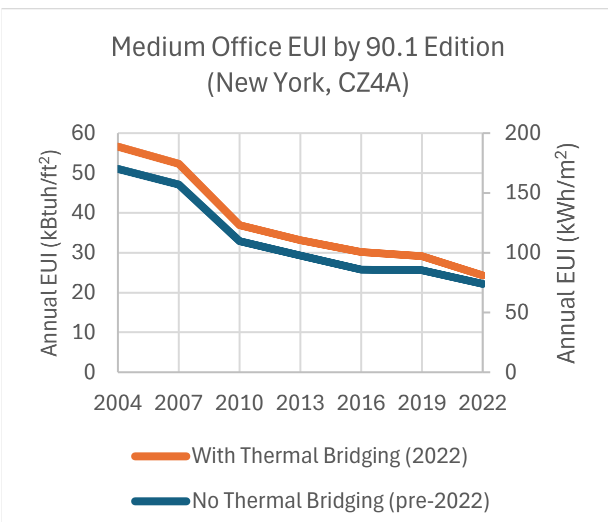

Figure 2. Thermal bridging impact on Medium Office EUI in New York, NY

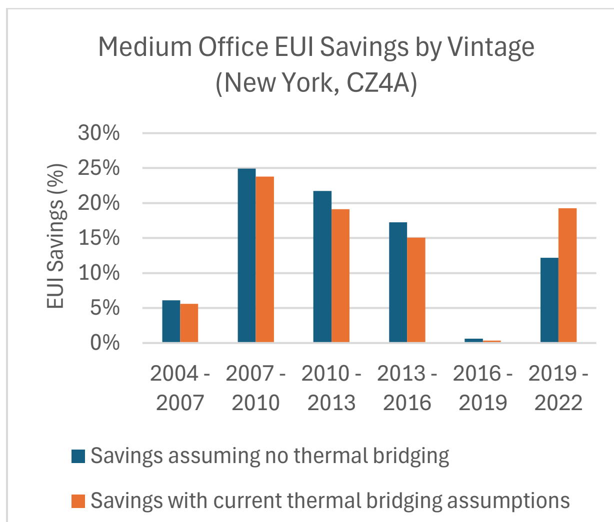

Figure 3. Thermal bridging impact on Medium Office Savings in New York, NY

Tables 2 and 3 show the energy impacts of accounting for thermal bridging across all building prototypes, expressed as percent change in total EUI, for the warmest and coldest climate zones (0A and 8, respectively). A comparison of these two tables highlights that the energy impacts of thermal bridging are more pronounced in colder climates, where the greater heating demand amplifies the effect of conductive heat loss through bridged assemblies. This trend is further illustrated in Tables 4 and 5, which show the relative impacts on cooling and heating energy, respectively, for a mixed-humid climate representative of New York, NY (climate zone 4A). Collectively, these results demonstrate both the energy savings potential of the thermal bridge mitigation requirements introduced in ASHRAE 90.1-2022 for climate zones 4 through 8, as well as the energy penalties associated with unmitigated thermal bridging in climate zones where such requirements are not mandated.

While the impact of accounting for thermal bridging almost always increases overall EUI, there are a few examples where accounting for thermal bridging improves energy performance. For example, the Hospital shows the smallest EUI impacts from thermal bridging across all climates, and in some climates and vintages—such as Climate Zone 0A (Table 2)—accounting for thermal bridging can actually improve the building's EUI, even though it effectively reduces envelope thermal performance. This is due to the Hospital's significant internal gains and high ventilation rates, which dampen the impacts of envelope performance.

Table 2. Total Energy impact of applying thermal bridge assumptions in Climate Zone 0A (% EUI Increase)

Climate 0A							
Prototype	2004	2007	2010	2013	2016	2019	2022
ApartmentHighRise	2%	2%	2%	2%	2%	2%	2%
ApartmentMidRise	2%	2%	2%	2%	2%	2%	2%
Hospital	-3%	-3%	-2%	-1%	-2%	-1%	-1%
HotelSmall	1%	1%	1%	1%	1%	1%	1%
HotelLarge	0%	0%	0%	0%	0%	0%	0%
OfficeMedium	2%	2%	2%	2%	5%	3%	3%
OfficeLarge	-7%	-7%	-5%	-1%	-1%	-2%	-2%
OfficeSmall	3%	3%	3%	2%	2%	2%	2%
OutPatientHealthCare	1%	1%	1%	1%	1%	1%	1%
RestaurantFastFood	0%	0%	0%	0%	0%	0%	0%
RestaurantSitDown	0%	0%	1%	0%	0%	0%	0%
RetailStandalone	0%	0%	0%	0%	0%	0%	0%
RetailStripmall	1%	1%	1%	1%	1%	1%	1%
SchoolPrimary	1%	1%	1%	1%	1%	1%	1%
SchoolSecondary	1%	1%	1%	1%	0%	1%	1%
Warehouse	0%	0%	0%	5%	1%	1%	1%

Table 3. Total Energy impact of applying thermal bridge assumptions in Climate Zone 8 (% EUI Increase)

Climate 8							
Prototype	2004	2007	2010	2013	2016	2019	2022
ApartmentHighRise	11%	12%	12%	13%	13%	14%	6%
ApartmentMidRise	9%	10%	11%	12%	12%	13%	6%
Hospital	1%	1%	2%	1%	2%	1%	1%
HotelSmall	4%	4%	4%	5%	5%	6%	3%
HotelLarge	2%	2%	2%	3%	2%	2%	2%
OfficeMedium	9%	10%	11%	15%	18%	18%	9%
OfficeLarge	5%	6%	6%	6%	8%	9%	7%
OfficeSmall	15%	17%	19%	20%	22%	24%	11%
OutPatientHealthCare	2%	5%	5%	4%	6%	7%	3%
RestaurantFastFood	2%	2%	2%	2%	2%	2%	1%
RestaurantSitDown	1%	2%	2%	3%	3%	3%	1%
RetailStandalone	1%	3%	3%	4%	4%	4%	3%
RetailStripmall	4%	4%	4%	5%	5%	5%	3%
SchoolPrimary	15%	10%	6%	8%	11%	11%	5%
SchoolSecondary	4%	5%	6%	7%	10%	9%	5%
Warehouse	0%	2%	3%	4%	4%	4%	2%

Table 4. Cooling energy impact of applying thermal bridge assumptions in Climate Zone 4A (% Cooling Energy Increase)

Climate 4A							
Prototype	2004	2007	2010	2013	2016	2019	2022
ApartmentHighRise	2%	2%	1%	0%	-2%	-2%	-1%
ApartmentMidRise	2%	2%	2%	0%	0%	0%	0%
Hospital	0%	0%	0%	0%	0%	0%	0%
HotelSmall	0%	-1%	-1%	-1%	-2%	-2%	-1%
HotelLarge	0%	0%	0%	0%	-1%	0%	0%
OfficeMedium	2%	2%	2%	2%	5%	3%	1%
OfficeLarge	1%	1%	0%	0%	0%	0%	3%
OfficeSmall	1%	1%	1%	-1%	-1%	0%	1%
OutPatientHealthCare	2%	2%	2%	1%	2%	1%	0%
RestaurantFastFood	0%	0%	0%	0%	0%	0%	0%
RestaurantSitDown	5%	0%	0%	0%	0%	0%	0%
RetailStandalone	0%	0%	1%	0%	1%	1%	1%
RetailStripmall	1%	0%	1%	1%	1%	1%	1%
SchoolPrimary	1%	1%	2%	1%	2%	2%	1%
SchoolSecondary	1%	1%	1%	1%	1%	1%	0%
Warehouse	1%	1%	1%	2%	2%	2%	1%

Table 5. Heating energy impact of applying thermal bridge assumptions in Climate Zone 4A (% Heating Energy Increase)

Climate 4A							
Prototype	2004	2007	2010	2013	2016	2019	2022
ApartmentHighRise	21%	24%	32%	37%	55%	60%	26%
ApartmentMidRise	17%	20%	25%	33%	45%	51%	23%
Hospital	2%	2%	3%	3%	3%	5%	4%
HotelSmall	9%	16%	17%	22%	34%	31%	14%
HotelLarge	4%	4%	12%	15%	11%	11%	9%
OfficeMedium	12%	17%	17%	24%	44%	22%	10%
OfficeLarge	7%	9%	15%	21%	25%	15%	128%
OfficeSmall	12%	15%	15%	29%	25%	23%	18%
OutPatientHealthCare	9%	12%	17%	19%	18%	15%	9%
RestaurantFastFood	1%	2%	2%	2%	2%	2%	1%
RestaurantSitDown	-6%	6%	6%	6%	6%	6%	3%
RetailStandalone	3%	5%	5%	10%	5%	5%	3%
RetailStripmall	5%	10%	10%	11%	10%	10%	6%
SchoolPrimary	11%	15%	20%	24%	25%	25%	11%
SchoolSecondary	9%	18%	21%	29%	27%	29%	13%
Warehouse	1%	2%	2%	2%	2%	2%	1%

Other anomalies in the results arise from load changes induced by thermal bridging adjustments that trigger unrelated ruleset requirements. In some cases, accounting for thermal bridging causes heating or cooling loads to cross capacity thresholds defined ASHRAE 90.1, shifting equipment into different size categories that carry different efficiency requirements. Depending on the direction of the threshold exceedance, this can result in either more or less stringent efficiency requirements being applied to the equipment, producing outsized energy impacts that are not directly attributable to the thermal bridging adjustment itself. Examples of this are observed in the 2013 vintage of the Warehouse in climate zone 0A and the 2022 vintage of the Large Office in climate zone 4A, among others. Similar anomalies arise from threshold exceedances related to a variety of code requirements, including those governing heating and cooling efficiency, economizer operation, fan power, and pump power. These types of interactions between load changes and code-defined thresholds should be considered when interpreting results, as they can obscure the direct relationship between thermal bridging and energy performance.

The simulation results underscore the critical role of accurately modeling thermal bridging in building energy analyses. Although the magnitude of the impact can vary considerably depending on building types and climate zones, the findings reinforce the necessity of accounting for thermal bridging to enhance the accuracy and reliability of energy models.

Discussion

The analysis presented in this paper demonstrates that incorporating linear and point thermal bridges into commercial prototype models has a measurable influence on building energy performance. With this shift toward more realistic envelope characterization in ASHRAE 90.1-2022, design teams and code officials are now responsible for documenting thermal bridges more explicitly than in previous editions of the standard. This section interprets what the modeling results mean for practice, how the new requirements will be implemented in real projects, and what challenges practitioners may face as these provisions enter the permitting and compliance workflow.

Implications for Design and Modeling Practice

The expanded requirements in ASHRAE 90.1-2022 formalize a long-recognized disconnect between idealized, clear-field envelope performance and real-world thermal behavior. For energy modelers, incorporating thermal bridges means that envelope performance becomes more sensitive to geometric configuration and detailing, particularly where parapets, cladding supports, intermediate floors, and fenestration interfaces are prevalent. This change elevates the importance of understanding Psi- and Chi-factor values, their appropriate use, and the correct application of adjusted U-factors in simulation tools.

The modeling results indicate that even modest thermal bridges can meaningfully increase heating loads in cold and mixed-humid climates. This reinforces the need for designers to involve building envelope specialists earlier in project development—particularly for buildings with high envelope-area-to-floor-area ratios, large fenestration systems, or prominent architectural features such as cantilevered balconies. Clear documentation of intersection details will also facilitate modeling accuracy, as energy modelers depend on documented conditions rather than assumptions.

Implications for Code Application and Permitting

Because thermal bridge mitigation is now a prescriptive requirement for several common envelope conditions, permit applicants must produce documentation that demonstrates either:

- Prescriptive compliance through specific insulation placement, alignment with fenestration, or continuous insulation at floor-wall intersections,
- Performance-based equivalence using Psi-/Chi-factor calculations, or
- A thermal bridge allowance calculation under Section 5.5.5.5 for "other" conditions not addressed in prescriptive text.

These pathways are technically straightforward but represent a procedural shift. Design and permitting teams will need to coordinate more closely, as envelope details—often considered later in the design process—now have direct consequences. For example, cladding support systems or fenestration attachment details may require documentation of cross-sectional area limits, thermal break materials, or mitigation strategies consistent with the standard.

From the code official's perspective, the required level of transparency improves enforceability but may increase review time, particularly during the early years of adoption. To support efficient review, construction documents must clearly identify each thermal bridge condition, note whether mitigation or equivalence is used, and reference appropriate sections of the standard. Schedules that quantify lengths, areas, Psi/Chi values, and exemption claims enable reviewers to quickly verify compliance. To improve transparency, similar to a door or window schedule, design teams can assemble a Thermal Bridge Schedule. An example Thermal Bridge Schedule is shown in Table 6.

Table 6. Example Thermal Bridge Schedule

Thermal Bridge Location	Applicable Code Section	Point Thermal Bridge Area (in.^{2}) (Total Qty)	Linear Thermal Bridge Length (lin.ft.)	Thermal Bridge Material	Table A10.1 Default psi- / chi-value	Design psi- / chi-value*	Detail Reference
Parapet on Mass Wall	Psi-Factor Equivalence (Section 5.5.5(b))	n/a	2,500	Concrete	0.125	0.115	X/A-XXX
Floor Edge	Insulation Placement Sections 5.5.5.2)	n/a	n/a	n/a	n/a	n/a	X/A-XXX
Entry Canopy	Exempt (5.5.5.2.2)	n/a	n/a	n/a	n/a	n/a	X/A-XXX
Brick Shelf Angles	Psi-Factor Equivalence (Section 5.5.5(b))	n/a	5,000	Carbon Steel	0.186	0.150	X/A-XXX
Punched Windows	Fenestration and Insulation Placement and Alignment (Section 5.5.5 4)	n/a	n/a	Wood Blocking	n/a	n/a	X/A-XXX

Thermal Bridge Location	Applicable Code Section	Point Thermal Bridge Area (in.^{2}) (Total Qty)	Linear Thermal Bridge Length (lin.ft.)	Thermal Bridge Material	Table A10.1 Default psi- / chi-value	Design psi- / chi-value*	Detail Reference
Sunshade Attachments	Unmitigated Thermal Bridge Allowance Calculation* (Section 5.5.5.5)	32 (96)	n/a	Stainless Steel	n/a	0.91	X/A-XXX

* Unmitigated Thermal Bridge Allowance Calculation should be provided if referenced in a schedule.

Interpretation of the Prescriptive and Performance Pathways

Three prescriptive pathways—insulation placement, Psi/Chi-factor equivalence, and derated assembly equivalence—allow flexibility for varying architectural and structural conditions. In practice:

- Insulation placement will be the most common strategy because it aligns with typical detailing and requires the least supplemental calculation.
- Psi- and Chi-factor equivalence will be used when innovative or nonstandard detailing is required, or when manufacturers provide third-party-tested values for specialized assemblies.
- Derated assembly equivalence offers flexibility for designs that cannot meet dimensional or alignment requirements but can still demonstrate acceptable performance through modified U-factors.

Section 5.5.5.5—the “other thermal bridges” allowance—provides a mechanism for handling penetrations not explicitly listed in the prescriptive text, such as dunnage, complex canopy supports, or structural steel elements. While the calculation is mathematically simple, its correct use requires careful identification of applicable conditions and materials. Most projects are expected to have a small number of such elements, and design teams will benefit from including a short summary of each condition in the permit drawings.

Thermal bridge accounting must also be considered when utilizing performance-based pathways, using either the envelope tradeoff calculation (Section 5.6 and Appendix C), the Energy Cost Budget (Section 12), or the Performance Rating Method (Normative Appendix G). These strategies allow for design flexibility within the whole of ASHRAE 90.1. The three strategies themselves are not new to ASHRAE 90.1, but their application does have some differences:

- Envelope tradeoff calculation (Section 5.6 and Appendix C) requires inclusion of all applicable linear and point thermal bridges covered by Sections 5.5.5.1–5.5.5.5 within the calculation. Any thermal bridge that meets prescriptive requirements should be identified by location, type, and unit dimension. Any thermal bridge that does not meet prescriptive requirements must be included in the trade-off calculations using psi- and chi-factors per Appendix C (often through the DOE’s COMcheck software). For these noncompliant bridges, projects may either calculate custom psi/chi values or use the “unmitigated” values from Table A10.1.

- Whole-building performance modeling calculations, using either the Energy Cost Budget Method (Section 12) or the Performance Rating Method (Normative Appendix G), projects must also account for thermal bridges in the simulation analysis. Both performance approaches are required to demonstrate building envelope compliance either prescriptively or through Section 5.6 "Building Envelope Trade-Off Compliance Option" (per Section 5.2.2). The Envelope Trade-off guidance above may be used for envelope system documentation for these projects. Further, the requirements for the baseline building design are different for each pathway.
    - Proposed Design Model (both Section 12 and Appendix G): Where included in a building design, each linear thermal bridge and point thermal bridge identified in ASHRAE 90.1 Section 5.5.5 needs to be modeled as shown on the construction documents by either adjusting the clear-field wall u-factor as described in Appendix A10.2 or using a separate model of the assembly within the energy simulation program.
    - Baseline Building Design:
        - Energy Cost Budget (Chapter 12): Where included in the proposed design model, each linear thermal bridge and point thermal bridge needs to be modeled so that it meets the minimum prescriptive criteria in ASHRAE 90.1 Section 5.5.5 by adjusting the clear-field wall u-factor in accordance with Appendix A10.2. This requirement only applies to thermal bridges that exceed any of the allowances or limits for unmitigated thermal bridges in Section 5.5.5, such as an allowance for "other" thermal bridges in Section 5.5.5.5 (including an exemption based on cross-section area of individual "other" elements) and in Section 5.5.5.2 allowing for a certain percentage of building perimeter length to have unmitigated balcony thermal bridges depending on climate zone.
        - Performance Rating Method (Appendix G): Where linear thermal bridges and point thermal bridges are included in the proposed design, they shall not be included in the baseline building design. The baseline building assembly U-factors must reflect the prescriptive requirement by Climate Zone as listed in Tables 5.5-0 through 5.5-8.

Design–Review Workflows and Documentation Needs

A key takeaway from this study is that documentation quality strongly influences compliance clarity. Many practitioners historically omitted thermal bridges from energy modeling and code documentation because they were implicitly covered by clear-field U-factor assumptions. ASHRAE 90.1-2022 changes that dynamic, and project teams will need workflow adjustments to ensure compliance materials are both accurate and verifiable.

Common strategies include:

- Incorporating thermal bridge schedules that list all linear and point bridges, lengths/areas, mitigation strategies, Psi/Chi values (where applicable), and detail references.
- Embedding annotated drawings that clearly show continuous insulation paths, fenestration alignment, and parapet/floor-wall transitions.

- Providing supporting calculations or manufacturer data for equivalence-based compliance options.
- Using per-floor quantification for energy modeling inputs to ensure consistency between documents and simulations.

As with other code changes, early integration into schematic and design-development phases will reduce downstream effort and uncertainty.

Broader Significance and Practical Challenges

The enhanced treatment of thermal bridges in ASHRAE 90.1-2022 represents an important step toward aligning modeled and actual building performance. For organizations using DOE's commercial prototypes to estimate national savings potential or evaluate cost-effectiveness, the updated modeling approach provides a more accurate basis for comparison across code cycles.

However, several challenges may arise during early adoption:

- Familiarity: Many practitioners may be learning Psi-/Chi-factor concepts for the first time.
- Detail availability: Structural and facade systems are often designed late in the process, making it difficult to fully document thermal bridges at the time of permit submission.
- Review complexity: Code officials must evaluate new types of documents and calculations not previously required.
- Variation in real-world detailing: Projects differ more substantially in geometry and envelope systems than prototypes do, which may lead to wider performance variation than shown in the modeling results.

These challenges underscore the importance of guidance documents, calculation tools, and example details—the types of supplemental resources that PNNL has already begun developing.

Connecting the Modeling and Documentation Findings

Taken together, the modeling results and documentation insights highlight how thermal bridges affect both energy performance and compliance processes. The expanded technical rigor of ASHRAE 90.1-2022 requires project teams to quantify conditions that were previously unmodeled, while also offering multiple pathways to mitigate or justify these conditions. The modeling results emphasize the energy significance of thermal bridges, particularly in colder climates, reinforcing why detailed accounting and careful documentation are essential for achieving intended energy savings.

Conclusion

This work evaluates the energy impacts of newly defined thermal bridges in ASHRAE Standard 90.1-2022 and examines how the updated requirements will be implemented in practice. By integrating standardized Psi- and Chi-factors into DOE's commercial prototype models, the impact of thermal bridges on envelope transmittance and building energy use has been quantified. The results show that accounting for thermal bridges can substantially increase heating loads, particularly in cold and mixed-humid climates, while producing smaller but measurable effects elsewhere. These impacts help explain why the 2022 edition introduces explicit mitigation requirements and why code documentation will require more comprehensive envelope characterization.

In addressing the second research question, we found that successful implementation of the new requirements will depend on integrating thermal bridge considerations into the design and permitting process earlier and more systematically than in previous code cycles. The prescriptive options—insulation placement, Psi-/Chi-factor equivalence, and derated assembly equivalence—provide flexible pathways for compliance, while the Section 5.5.5.5 allowance calculation helps address project-specific conditions. However, effective use of these pathways requires clearly documented details, consistent quantification of linear and point thermal bridges, and coordination between design teams, energy modelers, and code officials.

More broadly, the expanded treatment of thermal bridges in 90.1-2022 represents an evolution in energy code development toward modeling practices that more faithfully capture the thermal performance of constructed assemblies. Incorporating thermal bridges reduces the gap between idealized assumptions and real construction conditions, improving the accuracy of both energy modeling and code-savings estimates. As the industry adapts to these changes, tools such as thermal bridge calculators, prototype model documentation, and example detailing guidance will play a vital role in ensuring consistent and efficient compliance.

References

ASHRAE. 2011. RP-1365, Thermal Performance of Building Envelope Details for Mid- and High-Rise Buildings. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2021. ASHRAE Handbook—Fundamentals. Peachtree Corners, GA. ASHRAE. https://technologyportal.ashrae.org/Handbook.

ASHRAE. 2022. ANSI/ASHRAE/IES Standard 90.1-2022, *Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings*. Peachtree Corners, GA: ASHRAE.

BC Housing. 2018. *Guide to Low Thermal Energy Demand for Large Buildings*. https://tinyurl.com/33kjnnb6.

BC Hydro Power Smart. 2021. *Building Envelope Thermal Bridging Guide*. https://tinyurl.com/39h5n3vd.

Sciarra, L., R. Athalye, J. Humble, C. Mathis, B. Meyer, M. Tillou, and R. Zabcik. 2023. "Thermal Bridging Requirements in Standard 90.1-2022." *ASHRAE Journal* 65 (6): 42–46.

U.S. Department of Energy. (2026). *Thermal bridging calculator: Excel workbook*. Energy Codes website. Retrieved in 2026, from https://www.energycodes.gov/prototype-building-models