Building Envelope Characteristics in Cold Climates

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ABSTRACT

Prescriptive guidelines for thermal insulation in the design of buildings in cold climates have traditionally been derived by a holistic consideration of climatic factors, energy policy, environmental policy, and economics. The differences in thermal barrier requirements in buildings across the arctic and subarctic regions of the world are influenced as much by the differing priorities of the governing bodies that set these requirements as by actual physical demands and conditions. Usually, national requirements for building envelope characteristics such as thermal insulation values, building envelope airtightness, vapor permeability, building mass, and detailing are based on economics, durability, and environmental considerations. Consideration of thermal energy system resilience provides a new paradigm through which to view the optimization of these parameters.

The paper describes specifics of construction in cold climates; summarizes best practice requirements for the building envelope characteristics for buildings located in cold and arctic climate of the United States, Canada, and Scandinavian countries; provides some details illustrating how to implement these requirements; and compares the effects of different levels of building envelope efficiency and building mass on indoor air temperature decay when heat supply is interrupted. The paper also presents results from experts' discussions during the consultation forum "Thermal Energy Systems Resilience in Cold/Arctic Climates" (ERDC 2020) and research conducted under the IEA EBC Annex 73, the Environmental Security Technology Certification Program (ESTCP) Project "Technologies Integration to Achieve Resilient, Low-Energy Military Installations," and U.S. Army Program project 633734T1500 under Military Engineering Technology Demonstration. The paper complements the Cold-Climate Design Guide *(ASHRAE 2015) with a focus on the resilience of thermal energy systems.*

TRADITIONAL PARAMETERS OF COLD-CLIMATE CONSTRUCTION

The U.S. Department of Energy (DOE) classifies locations with more than 3000 HDD18 (5400 HDD65) as "cold" (zone 6), and any area with more than 5000 HDD18 (9000 HDD65) as "very cold" (zone 7). Places with more than 7000 HDD18 (12,600 HDD65) are considered "subarctic" (zone 8). The problem with using these climate zones to discuss "cold climates" is that the "cold" designation applies to both Des Moines, IA, (3570 HDD18 [6426 HDD65]) and Utqiagvik (Barrow), AK (10,553 HDD18 [18,996 HDD65]). The climate-specific construction requirements for Utqiagvik, AK, are significantly different from those of Des Moines, IA. Codes for cold climates are often diluted by the warmer end of "cold" climate. This paper focuses on the colder end of the cold-climate spectrum, i.e., areas with greater than 4500 HDD18 (8000 HDD65).

Alaska is the case study for cold climates; it encompasses all three DOE cold climate zones (Figure 1a). Because Alaska is an arctic state, Alaskans add a fourth climate zone, zone 9, or "arctic," which includes areas with more than 9300 HDD18 (16,800 HHD65) (AFHC 2018).

Weather Considerations

Very cold temperatures drive building design in cold climates. For people to survive in the cold, buildings that are warm and comfortable are essential. A tight, warm building envelope goes a long way toward mitigating the effects of cold,

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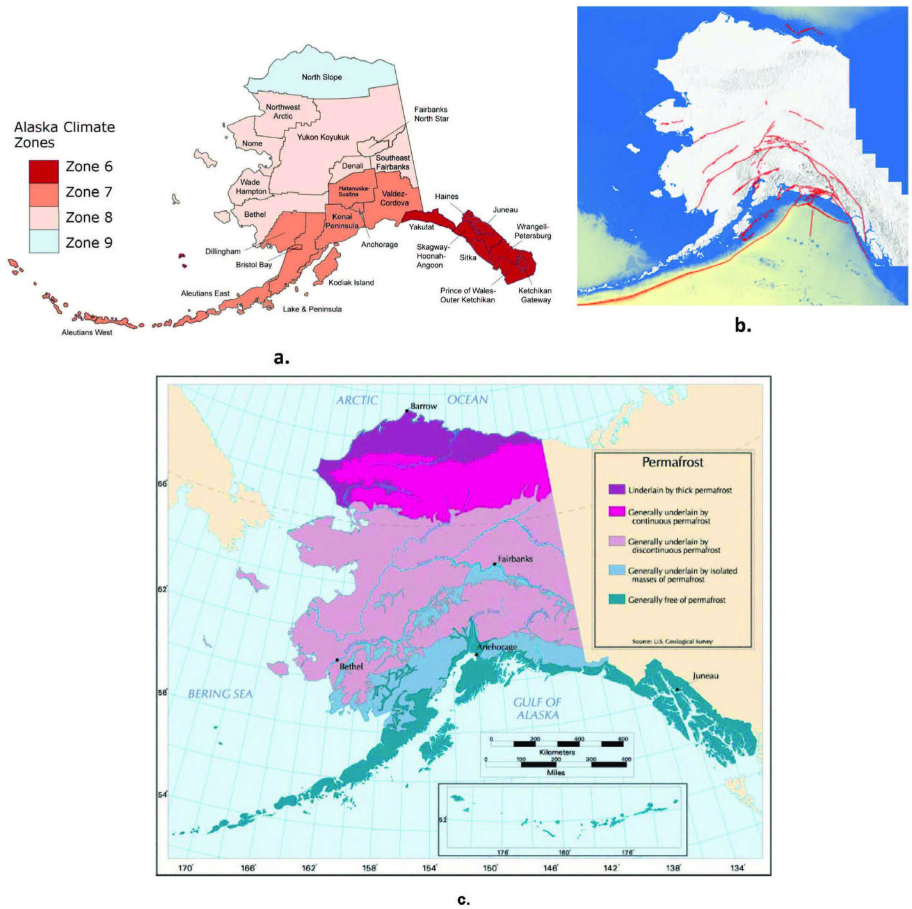


Figure 1 *Alaskan Climate: (a) climate zones (AFHC 2018), (b) fault lines,[4] and (c) permafrost distribution (Alaska History).*

harsh weather. Quality building envelopes are also imperative for resiliency; if there is a disruption in services (which can be quite common in the remote arctic), the building envelope is the first defense against facility failure. Tight building envelopes create extra requirements for ventilation (ASHRAE 2015; Winfield et al. 2021) and may necessitate heat recovery. Ventilation with heat recovery capability is important in cold regions as it lowers heat loss and improves building efficiency. The use of operable windows or "natural ventilation," though code compliant, is not a viable solution during the winter months.

Mechanical systems must be able to handle the effects of freezing temperatures: automatic defrost cycles in ventilators are necessary to prevent frost buildup; the location of exterior exhaust hoods must be carefully chosen to limit ice buildup on and above walkways; and personnel doors, vehicle entries, and intake and exhaust penetrations must have adequate screen opening sizes and configurations to prevent frost and blowing snow from blocking them. Tight, heavily insulated buildings often have enough internal heat gain to require cooling in the warmer months; well-water cooling, ammonia absorption, and vapor compression refrigeration are all options.

Extreme cold exterior temperatures create low relative humidity inside buildings. Ten percent relative humidity is not uncommon in commercial buildings that are not humidified. Low humidity (i.e., less than 35%) can create human health problems like increased bacteria and virus spread, respiratory infection, allergic rhinitis, and asthma (Sterling et al. 1985). Low humidity also creates excess static electricity, which is dangerous to sensitive electronics. Proper humidification is energy-intensive, requires regular maintenance, and is difficult to achieve at low outdoor temperatures but often necessary. Humidification must be coupled with appropriate building envelope design, including inspection and/or envelope commissioning during construction. Systems design should include controls that offset the indoor relative humidity set point based on outdoor air temperature (ASHRAE 2015). Many warm climate conventional wall and roof designs fail in cold climates due to the extreme vapor drive at low winter temperatures (Craven and Garber-Slagh 2012). Thermal bridges through walls and ceilings need to be avoided as higher indoor humidity can result in dew or frost on surfaces where thermal bridging is occurring. It is highly recommended that facilities or portions of facilities that are actively humidified have a detailed hygrothermal analysis completed by a design professional for all building envelope components. Building indoor positive pressure should be kept to a minimum to avoid forcing warm humidified air into wall or ceiling cavities where condensation and frost buildup can occur. Where facilities have isolated rooms that are humidified, such as operating rooms or data centers, humidity migration to the surrounding spaces should be limited through the use of internal vapor barriers, sealed vestibules, or using a box-within-box design layout. This will not only reduce the energy used in the humidification process but also limit humidity exposure to the exterior envelope. Humidification in improperly designed and/or installed envelopes can lead to the generation of mold, which can have a significant negative impact on indoor air quality.

In addition to very cold temperatures, frozen and freezing precipitation are also building design drivers. Local snow depth and potential snow drifting should determine the structural design of the roof. The amount of snow and prevailing winds along with wind speed can complicate the location of exterior penetrations. Ventilation hoods need to be specially designed for use in environments with blowing snow. Snowflakes fracture when transported by winds and become small particles that can penetrate small openings in building envelopes and accumulate in ventilation hoods. Strong winds in far northern (i.e., tundra) areas of Alaska only enhance the need for strict airtightening requirements for buildings in the Arctic.

Extreme weather events in arctic locations can exacerbate failures. Rapid climatic warming in the Arctic is leading to more extreme weather events (U.S. Climate Resilience Toolkit. 2017). Many locations in Alaska are receiving more precipitation, which as a result calls into question the current snow load design code for building roofs. Other locations are much drier, leading to more wildfires and the need to design and redesign buildings and sites to be resilient to fast and large wildfires (FEMA 2008). River and coastal locations are prone to flooding and erosion due to increases in precipitation, loss of vegetative cover from wildfires, and loss of winter sea ice. Site selection and building planning should consider the flood potential of a specific location (Jones 2017).

Challenges Specific to Remote Locations

Many locations in Alaska are very remote; this isolation creates unique challenges. The logistics of construction and maintenance in such remote locations is unique and can be daunting. For example, most remote locations in Alaska have only one or two barge deliveries in the summer and access by airplane, snowmobile, or not at all the rest of the year. Even in locations that are normally accessible by road and airplane, extreme weather events (i.e., winter storms and avalanches) can make these locations inaccessible for several days at a time. Ice roads are annually constructed to move materials and equipment during the winter to some remote communities and industrial areas. Heavy construction equipment is not often available on site and must be shipped by barge. Room and board can be difficult to find for construction crews in smaller communities, often leading to the need to bring in construction camps for larger projects.

The transportation of replacement parts and equipment can affect the original system design. For instance, it may be more desirable to use a cast-iron sectional boiler or a series of smaller boilers rather than a large water-tube boiler.

Fuel to provide electricity and heat is expensive at remote sites due to shipping costs. The use of static resiliency measures, such as a robust building envelope design, not only makes sense from a mission operational standpoint but also significantly reduces long-term operational costs. Balancing energy efficiency with robustness in all building system designs will reduce the need for costly fuel, making for more resilient remote facilities.

Seismic Considerations

The very foundation of Alaska is in constant movement. Most of central and southern Alaska is underlain with seismic faults (Figure 1c). These faults have produced some of the largest earthquakes in the world in the past 100 years and the majority of U.S. earthquakes greater than magnitude 5 have occurred in Alaska (Alaska Earthquake Center 2020). Buildings designed for Alaska need to conform to strict structural codes and guidelines so that they can resist most earthquakes (Municipality of Anchorage 2018).

Permafrost Considerations

Alaska has seasonally frozen and permafrost soils—soils colder than 32°F (0°C). Permafrost soils occur when the soil remains frozen for two or more years. Discontinuous permafrost is laterally discontinuous, meaning it includes numerous permafrost-free areas that decrease in size and number from south to north. Continuous permafrost is present almost everywhere below the land surface except under the lakes and rivers that do not freeze to the bottom. In Alaska, there is a transition from seasonally frozen soils to discontinuous permafrost (subarctic) to continuous permafrost (arctic) from the southern coastal areas of Alaska to Alaska's north slope (see Figure 1b). For both seasonally frozen and permafrost soils, the surface layer that undergoes an annual freeze-thaw cycle is referred to as the active layer. In seasonal frost locations, it is the depth of freeze, and for permafrost locations, it is the depth of thaw. Construction in permafrost zones requires special care to keep the soils frozen; thawed permafrost can lose its structural integrity leading to failure of the structure built on it.

PARAMETERS FOR THERMAL ENERGY SYSTEM RESILIENCE

In addition to traditional cold-climate building parameters, thermal resilience is a parameter of growing importance,

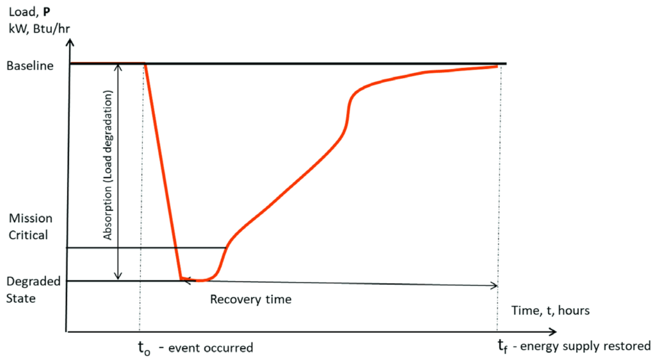


Figure 2 *System response to a disruptive event (Zhivov et al. 2021).*

especially for medical, university campuses, and military and government installations that house mission-critical operations. Resilient energy systems (both electric and thermal) are those that can prepare for and adapt to changing conditions and recover rapidly from disruptions including deliberate attacks, accidents, and naturally occurring threats (OPS 2013). A quantitative approach described in Zhivov et al. (2021) allows for evaluation of both the ability of a system to absorb the impact of a disruption (i.e., robustness) and its ability to recover. Figure 2 shows a system performance disturbance which occurs without warning, such as a seismic event. Immediately following the event, there is a sharp drop in the load available to mission. For electric energy systems, the duration of phase one is much shorter than for thermal energy systems, unless thermal systems are used for processes using steam or hot water. This change from the baseline to the degraded state represents the robustness of the system to that particular event. The time required to restore the system to its baseline state is referred to as *recovery*. The smaller the change in load available to mission and the shorter the recovery time, the more robust the system. The robustness R of the system to any particular event can be quantified using Equations 1 and 2.

The smaller the area between the baseline and the curve, the more resilient the system (Equations 1 and 2). Robustness will be measured on the scale between 0 and 1, where 1 is the most resilient system:

$$R_{m.c.} = \frac{E_{event}}{E_{m.c.}} \quad (1)$$

$$R_{baseline} = \frac{E_{event}}{E_{baseline}} \quad (2)$$

where, $R_{m.c.}$ and $R_{baseline}$ are system robustness measured against the mission critical load and the baseline load, E_{event}, $E_{m.c.}$, and E_{event} are energy supplied to the building during the period of time between t_o and t_f with the baseline load, mission-critical load, and degraded due to event load and can be illustrated by the area between the line showing the baseline mission availability and the curve representing the actual mission performance over time:

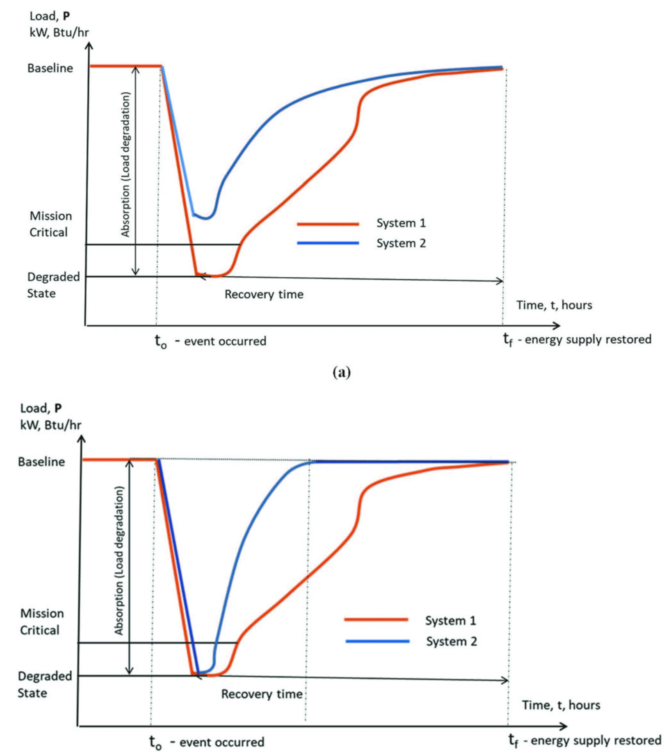


Figure 3 *Two systems with different levels of resilience: (a) different robustness and (b) different recovery time (Zhivov et al. 2021).*

$$E = \int_{t_o}^{t_f} P(t)dt \quad (3)$$

Depending on mission needs, it may be more important to prioritize either absorption or recovery. For example, Figure 3a shows two systems with different levels of absorption. The two systems have the same recovery time, but System 2 has a lower initial decrease in power available to the building. System 2 is more resistant to the postulated event and is more robust than System 1, despite having the same recovery time.

In other cases, it may be more important to prioritize recovery from an event as opposed to absorption. Figure 3b shows two systems with similar absorption to an event but different recovery times. Though both systems have the same ability to absorb the shock from the event, the shorter recovery time for System 2 yields a larger area under the curve. Accordingly, System 2 can be said to be more resilient than System 1.

Following a contingency event, the facility or site should have a plan in place to adapt to and recover quickly from its effects. Due to limitations of personnel, resources, and logistics, repairs for all components cannot occur simultaneously. It may also be required that some assets be restored in sequence. The priority shall be given to restoring power to the level satisfying needs of mission-critical loads. In this case, the maximum time to repair the system providing the mission-critical load shall be smaller than the maximum allowable downtime assigned based on the configuration and storage capacity of the building level system.

While there have been more discussions and research related to the resilience of electric energy systems, the resilience of thermal energy systems is especially important for extreme climate locations. Resilience requirements for a thermal system comprised of energy conversion, and for distribution and storage components, depends on thermal energy availability required by the production process, the level of environmental conditions degradation allowed by the process, and the environmental threshold limit values dictated by people such as habitability and sustainability of the shelter/building/housing.

The maximum time to repair a thermal system serving a building can be defined in terms of how long the process can be maintained or the building remains habitable or protected against damage to water pipes, sewer, fire suppression systems, sensitive content, or mold damage during an extended loss of energy supply from extreme weather events. The analysis presented in Zhivov et al. (2021) shows that major factors affecting the time, when the internal temperature reaches the threshold of building habitability or sustainment, include:

- Difference between indoor and outdoor air temperature.
- Building envelope leakage rate
- Building envelope insulation properties, including insulation levels of its components, and thermal bridging
- Internal thermal load (people and appliances/equipment connected to electric power)

Also, the thermal mass of building structures composed of concrete, masonry, or stone materials that constitute high levels of embodied energy enables the building to absorb and store heat to provide "inertia" against temperature fluctuation and allows an increase in the time allowed for the thermal system to be repaired. Figure 4 shows how these factors will influence the time of building temperature degradation from the comfortable level t_o to the habitability t_h and sustainability t_s temperature thresholds.

Usually national requirements for building envelope characteristics, e.g., thermal insulation values of its components, building envelope air tightness, vapor permeability, building mass, detailing, and so on, are based on economic and environmental considerations. Thermal energy system resilience consideration brings another dimension to the optimization process of these parameters.

THERMAL INSULATION VALUE

Various methods for establishing minimum insulation values in buildings exist. The simplest guidelines are those that establish a single minimum insulation value for buildings by climate zone, differentiating only between the walls, roof, and floor, with additional guidelines for windows and doors (Tables 1 and 2).

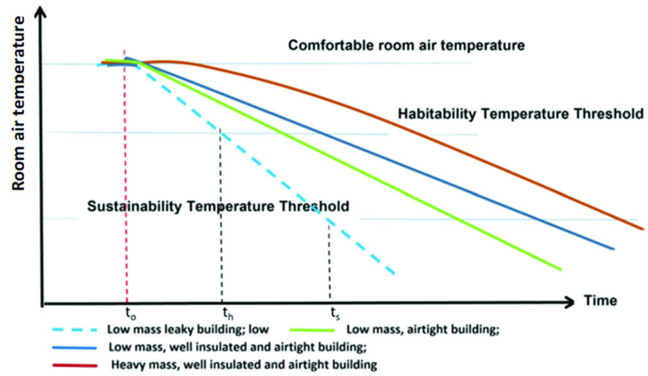


Figure 4 *Notional example of temperature decay rate for different types of building envelope: comfortable level* t_o, *habitability* t_h *and sustainability* t_s *temperature thresholds.*

Changes to insulation requirements over time are less likely to be a result of a change in climate (e.g., more or fewer degree days per year over time) as they are to be as a result of a change in priorities associated with environmental, energy, comfort, economic, or societal parameters. As a general trend, guidelines for minimum insulation values have trended upwards, and continue to do so. This increase in insulation values impacts both new construction and major retrofits.

The U.S. Federal Government bases standards for thermal insulation in buildings on the Unified Facility Criteria, which are in turn based on variations of the existing ANSI/ASHRAE/IES Standard 90.1-2013 (ASHRAE 2013). (See Table 3). This method of determining minimum insulation value considers the construction typology of the building as well as its size and cost, in an attempt to address economic and energy factors. Air Force projects use ASHRAE Standard 90.1-2013 as a standard, while the other branches of the military use ASHRAE Standard 189.1-2014, which represents a 10% nominal improvement over ASHRAE Standard 90.1-2013. New construction projects over 10,000 ft^2 (930 m^2) and \$3 million in cost are required to achieve a reduction in total building energy consumption of 30% over the ASHRAE Standard 90.1-2013 baseline building.

Some regulatory entities employ a different approach to the thermal barrier of buildings in cold climates. Multiple methods are allowed to satisfy code requirements. In Greenland, for instance, there are three allowable methods to meet the regulations:

- U-factors for building components (only possible if the area of windows and doors does not exceed 22% of the heated floor area).
- Maximum allowable heat loss from a given building.

Table 1. Window Insulation Standards

Country/ Region	Window Insulation Standards Standard	Window Maximum U-Factor, Btu/(°F•ft^2•h) (W/[m^2•K])	Source
Alaska	Alaska Building Energy Efficiency Standard climate zone 7	0.30 (1.70)	(AHFC 2018)
	Alaska Building Energy Efficiency Standard climate zone 8	0.22 (1.25)	(AHFC 2018)
	Military Construction (MILCON) Initial Compliant Standards	0.33 (1.87)	(Nygaard 2019)
Canada	Window Specifications for Cost Optimized Housing	0.17 (0.99)	(RDH 2016a)
	National Energy Code of Canada for Buildings 2017 climate zone 7	0.33 (1.90)	(NRCC 2017)
	National Energy Code of Canada for Buildings 2017(AHFC 2018) climate zone 8	0.25 (1.40)	(NRCC 2017)
Finland	Decree of the Ministry of the Environment on the Energy Performance of New Building	0.18 (1.00)	(Finland's Ministry of the Environment. 2017)
Norway	Norwegian Regulations	0.21 (1.20)	(NBA 2017)
Greenland	Greenlandic Building Regulations^	0.32 (1.80)	(DHI 2006)

- Calculation of total energy use based on a method dictated by the building regulations and dependent on location (north or south of the Arctic Circle).

While various codes provide alternate compliance paths, pursuing energy modeling approaches and prescriptive thermal insulation values typically provide a good starting point for design. Excluding the highest and lowest outliers, the prescriptive values for insulation in climate zone 7 ranges between R-28 and R-45 in walls, between R-48 and R-60 in roofs, and approximately 0.30 for windows. In climate zone 8, prescriptive values range between R-38 and R-50 for walls, between R-59 and R-75 for roofs, and 0.22 for windows.

The range of prescriptive thermal insulation values described above considers energy guidelines, economic factors, and construction realities. Thermal resilience as an input variable in the setting of insulation guidelines is a relatively new field that brings its own priorities.

Thermal Bridging Metrics and Mitigation

Thermal bridging occurs when highly conductive elements partially or fully penetrate the insulated building envelope. Common examples include studs, fasteners, shelf angles, exposed slab edges, and structural steel beams, but can also include geometric thermal bridges and thermal bridges created at the transitions between envelope elements such as at window perimeters or roof-to-wall interfaces (Figure 5, top).

While thermal transmittance (U-factor) and thermal resistance (R-value) are most commonly used to quantify the thermal performance of assemblies, a set of additional metrics is required to quantify the impact of thermal bridging elements.

Point thermal bridges are typically described using a point thermal transmittance, or Chi-value χ (W/K [Btu/(h•°F)]). A χ-value is the additional amount of heat flow through an assembly caused by a point thermal bridging detail such as a screw, clip, fastener, tie, and so on. It is calculated by subtracting the heat flow through a building envelope assembly with no thermal bridge from the heat flow through the same assembly but including the point thermal bridge. In some cases, it can be more practical to include repetitive point thermal bridges such as fasteners and cladding attachment clips within the U-factors or R-values so that they can be applied to an area of the building envelope rather than counted individually.

Linear thermal bridges such as flashings, parapets, or window perimeter installation details are typically described using linear thermal transmittance, Psi-value Ψ, W/(m•K) (Btu/[ft•h•°F]). Similar to a χ-value, Ψ-values are calculated by subtracting the heat flow through an assembly (or pair of assemblies) with no thermal bridge from the heat flow through the same assembly but including the linear thermal bridge.

These thermal bridging metrics can be thought of as correction factors, which can be used to correct the clear field U-factor or R-value such that it also accounts for thermal bridging. In addition to these metrics that quantify the energy transfer characteristic of a thermal bridge, an additional metric is required to assess the risk of condensation or frost accumulation on a cold surface as a result of thermal bridging. Typically, either the surface temperature itself is used for this purpose or temperature index *I* can be used as a metric independent of the boundary condition temperature.

Table 2. Insulation Standards for Cold Regions

Country/ Climate Zone	Standard/Guideline	Walls Minimum Insulation Value °F•ft²•h/Btu (W/(m²•K))	Roof Minimum Insulation Value °F•ft²•h/Btu (W/[m²•K])	Source
Alaska	Deep Energy Retrofit climate zone 7	R-50 (U-0.11)	R-65 (U-0.09)	(Zhivov and Lohse 2020)
	Deep Energy Retrofit climate zone 8	R-50 (U-0.11)	R-75 (U-0.08)	(Zhivov and Lohse 2020)
	Alaska Building Energy Efficiency Standard climate zone 7	R-25 (U-0.23)	R-54 or 48* (U-0.11 or 0.13)	(AFHC 2018)
	Alaska Building Energy Efficiency Standard climate zone 8	R-30 (U-0.19)	R-59 or 48* (U-0.10 or 0.12)	AFHC 2018)
	MILCON Initial Compliant Standards	R-45 (U-0.13)	R-60 (U-0.09)	(Nygaard 2019)
Canada	Nunavut Good Building Practices	R-28 (U-0.20)	R-40 (U-0.14)	(RDH 2016b)
	Northwest Territories Good Building Practices	R-32 (U-0.18)	R-50 (U-0.11)	(RDH 2016b)
	Yellowknife - Existing Buildings	R-30 (U-0.19)	R-40 (U0.14)	(RDH 2016b)
	Yukon Housing Corporation	R-28 Whitehorse R-21-9 Elsewhere (U-0.20 Whitehorse U-0.26 Elsewhere)	R-59 (U-0.10)	(RDH 2016b)
	General Passive House Guidelines	R-60 to R-80+ (U-0.09 to 0.07)	R-60 to R-100+ (U-0.09 to 0.06)	(RDH 2016b)
	National Energy Code of Canada for Buildings 2017—climate zone 7	R-27 (U-0.210)	R-41 (U-0.138)	(NRCC 2017)
	National Energy Code of Canada for Buildings 2017—climate zone 8	R-31 (U-0.183)	R-47 (U-0.121)	(NRCC 2017)
Finland	Decree of the Ministry of the Environment on the Energy Performance of New Building	R-35 (U-0.16)	R-65 (U-0.09)	(Finland's Ministry of the Environment 2017)
Norway	Norwegian Regulations	R-26 (U-0.22)	R-32 (U-0.18)	(DHI 2006)
Greenland^	Greenlandic Building Regulations	R-28 for weight<100 kg/m² or R-19 for weight>100 kg/m² (U-0.20 for weight<100 kg/m² or U-0.30 for weight>100 kg/m²)	R-38 (R-28 flat roofs) (U-0.15 [0.20 flat roofs))	(NBA 2017)

* The smaller value may be used with a properly sized, energy-heel truss.
^ Greenlandic codes offer three different ways in which to fulfill the building regulations: U-value, heat loss, or energy use.

There are various standards for calculating (and aggregating) these metrics for the purpose of energy calculations. While the building industry is generally familiar with large thermal bridges that occur in locations such as parapets, balconies, and intermediate floors, one thermal bridge that has largely been neglected is the window-to-wall interface. Conventional window frames and the associated detailing are often one of the worst thermally performing elements of a building, from both an energy and an interior surface temperature perspective. While window selection has a significant impact, detailing the window installation can significantly impact its performance. For example, optimizing the window placement within the rough-opening and over-insulating the window frames on the exterior are two strategies that can

Table 3. Climate Zone 8 Thermal Resistance Requirements

	R-Value: (°F•ft^2•h/Btu) [U-Value: W/(m^2•K)]						
	Roof			Above-Grade Walls			
Standard	Insulation Entirely above Deck	Metal Building	Attic	Mass (Concrete Masonry Unit [CMU])	Metal Building	Steel Framed (Metal Stud)	Wood Framed and Other (SIPS)
ASHRAE Standard 90.1-2013	R-35.7 (U-0.16)	R-38.5 (U-0.15)	R-58.8 (U-0.10)	R-21.8 (U-0.26)	R-25.6 (U-0.22)	R-27.0 (U-0.21)	R-31.3 (U-0.18)
ASHRAE Standard 90.1-2013 +30% Minimum R-Value	R-46.4 (U-0.12)	R-50 [U-0.11]	R-76.5 (U-0.07)	R-27.1 (U-0.21)	R-33.3 (U-0.17)	R-35.1 (U-0.16)	R-40.6 (U-0.14)

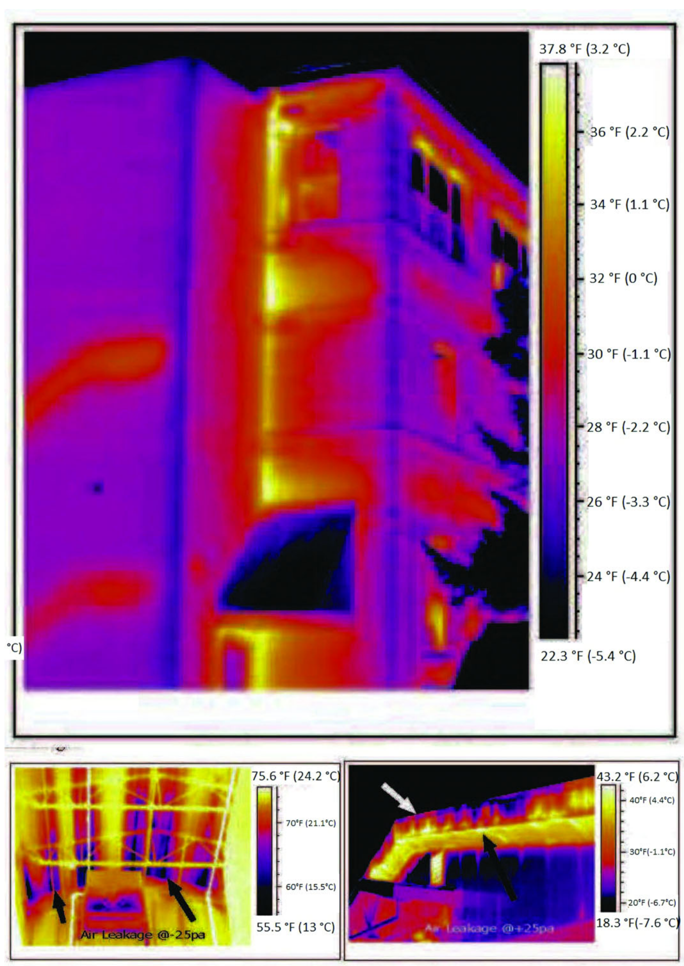


Figure 5 *Infrared thermographic image of typical thermal bridge in cold climates; Bottom: Infrared (IR) Images of air leakage at roof-to-rake wall joints. The building was tested to achieve air leakage rate of 0.25 cfm/ft^2 at 75 Pa (3.5 m^3/h/m^2 at 50 Pa) (Leffel 2021).*

effectively reduce the thermal bridging typically associated with window-to-wall interfaces.

Vapor Diffusion

Insulated building assemblies often require vapor diffusion resistance protection to reduce the risk of elevated humidity levels and condensation within interstitial spaces, which can lead to mold growth, decay, and corrosion. However, the vapor-retarding properties of materials that are typically used to provide this protection also prevent the assembly from drying out in response to incidental wetting that may occur from other, more significant sources of moisture such as air leakage and water intrusion. In cold climates, where indoor-to-outdoor vapor pressure differences are typically significant, it is common to use exterior insulation to reduce thermal bridging and increase the temperature of moisture-sensitive elements such as the building structure and sheathing. In some cases, relatively impermeable insulations are used in these arrangements, such as extruded polystyrene, while in other situations, semipermeable or permeable insulations such as expanded polystyrene or mineral wool are used. Additional insulation inside the structure is typically vapor permeable, such as fiberglass, mineral wool, or cellulose, though other options do exist, such as closed-cell polyurethane spray foam.

Hygrothermal modeling was completed to assess the vapor-diffusion-related performance of generic split-insulated wall assembly arrangements potentially appropriate for use in cold climates. In this modeling, the critical material layer was plywood/oriented strand board (OSB). These products are considered sensitive to mold growth and serve critical structural functions. Many buildings may have structural layers of metal or masonry that would have different mold growth characteristics due to the less sensitive nature of these substrates. Under undesirable conditions, frost, condensation, or corrosion may appear on masonry or metal surfaces, and mold growth can also occur on dirt/dust accumulated on the surface of these materials. Moderate amounts of frost will melt in warmer periods and either be absorbed within the materials (to dry later) or puddle at the base of the assembly. These effects are not included in this analysis. The strategies presented here to reduce mold growth on wood substrates are likely also to be effective at reducing the likelihood of frost accumulation at a surface; however, the difference in vapor permeability of these alternate substrates should be considered.

With Humidity Class 2 taken as the interior humidity (25% to 35% wintertime relative humidity, depending on the climate), no interior vapor control membrane (i.e., polyethylene sheet) included, and with mold-sensitive materials such as plywood in the structure, hygrothermal modeling has found that:

- In climate zone 6, vapor diffusion alone will not cause problems if at least 20% of the total insulation thermal resistance is installed to the exterior of the wood sheathing.
- In climate zone 7, vapor diffusion alone will not cause problems if at least 33% of the total insulation thermal resistance is installed to the exterior of the wood sheathing.
- In climate zone 8, vapor diffusion alone will not cause problems if at least 50% of the total insulation thermal resistance is installed to the exterior of the wood sheathing.

The modeled hybrid walls contain no interior membrane (polyethylene) vapor barriers, so they have maximum drying potential from the building cavity toward the indoors.

It is important to note that while these hygrothermal models focus specifically on the subject of diffusion, they do not consider a complete view of envelope design as it relates to longevity and resilience. It is known that from the standpoint of mold growth and other concerns, the ratios modeled above may be insufficient in real-world cases in cold and arctic climates, largely as a result of alternative, and often more substantial, wetting mechanisms such as exfiltration. For this reason, in actual practice the proportion of exterior insulation would likely need to either be higher than the models predict, or if that is not economical or practical, the wall should use permeable insulation on the exterior. More permeable exterior insulation and sheathing membranes in conjunction with an interior vapor control membrane will also work to improve the overall durability of these wall assemblies with respect to the potential for interstitial condensation and subsequent related damage. Hygrothermal modeling, including consideration of air leakage and incidental wetting, should be completed if a split-insulated wall system is to be used. This analysis is especially critical for humidified buildings and should be used to determine the amount of interior insulation that can be safely used without creating moisture damage risks.

In summary, most moisture damage to building assemblies occurs from water leaks or air leaks carrying humid air. Prevention of these forms of damage hinges on good management—by design, construction, and operation—of water and air. Thermal insulation choices are made based on code and project requirements. Vapor-control measures (described above) are implemented to control the relatively small amounts of moisture associated with vapor diffusion. Thermal insulation measures and vapor-control measures should not be considered as appropriate for preventing or resolving water leakage or air leakage problems.

Airtightness

Airtightness of the building envelope assists in providing various important building functions. The control of exfiltration to reduce the risk of interstitial condensation, and the control of infiltration to reduce building energy consumption, are typically of the highest importance, and are of particular importance in cold climates. Airtightness can also impact thermal comfort, indoor air quality, resistance to chemical attack, acoustic separation, and mechanical ventilation performance.

Of increasingly noted importance is also the contribution of airtightness to thermal resiliency.

Historically, the building industry has taken a component approach to airtightness, typically specifying the airtightness of individual materials, systems, or products which form part of the building air barrier systems. It is now well recognized that while the airtightness of these elements is important, this alone is not sufficient to ensure that an airtight building envelope is achieved. This is because critical air leakage locations are typically found at the interfaces between these elements and are highly dependent on design coordination and quality control through the construction process. As a result, more modern codes and standards have developed a preference for whole-building airtightness testing as a quality assurance measure to evaluate the adequacy of the installed air barrier system.

Airtightness testing of large buildings in cold-climate regions has been utilized for research purposes since the early 1970s in Canada by the National Research Council, and later in the mid-1980s in the United States by the National Bureau of Standards, and in Great Britain by the Building Services Research and Information Association (Proskiw and Phillips 2001). Since then, airtightness testing, called air permeability testing in Europe, has developed into a robust building envelope commissioning industry and is used in conjunction with other commissioning tools to verify airtightness of the building envelope components and assemblies.

Whole-building airtightness testing is a great way to determine the building's air leakage rate and, by extension, thermal resiliency. However, air leakage testing only reveals the air barrier's overall performance, so individual air leaks that can cause localized moisture damage can still be present in a building that receives very good airtightness test results. Therefore, airtightness testing should be used as only one part of a comprehensive quality control/quality assurance program, which also includes air barrier design review, air barrier inspections, and infrared thermography.

Air barrier design reviews should be performed to ensure that the construction documents are complete and correct regarding the construction of a continuous air barrier across the entirety of the building envelope. Missing, incomplete, incorrect, or unconstructable air barrier details are very common and lead to poor air barrier installations. Air barrier inspections should occur during construction to ensure that proper materials and installation techniques are being used, and they should follow Air Barrier Association of America (ABAA) guidelines. They should include the observation and testing of a significant sample of details that cover the typical weaknesses in the air barrier, including all transitions in geometry and materials. Finally, infrared thermography should be used to locate and qualitatively ascertain the magnitude of air leaks. While it is not possible to have a perfect air barrier, a high-performance air barrier (necessary for thermal resiliency) is very much possible with proper design and construction quality control measures.

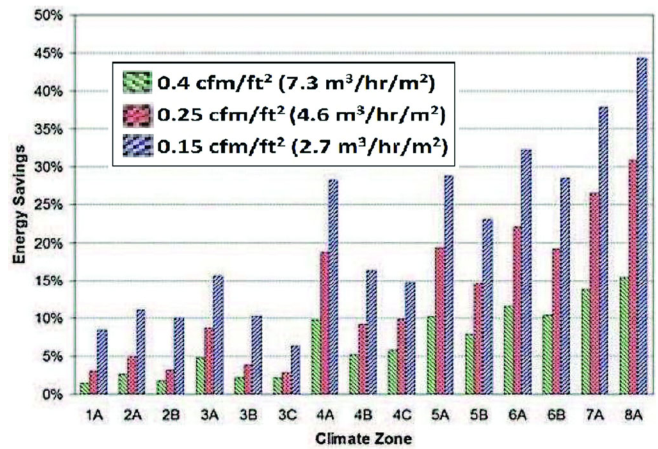


Figure 6 *Percent annual energy savings in a barracks building due to airtightness improvement for U.S. climate zones (Zhivov et al. 2014).*

Since 2009, the U.S. Army Corps of Engineers (USACE) has implemented an airtightness requirement in all new construction and building envelope renovation projects. Engineering and Construction Bulletin (ECB) 2012-16 (USACE 2014) set levels of airtightness for building envelopes at the material, assembly, and system level as having a maximum air leakage of 0.25 cfm/ft^2 at 75 Pa (3.5 m^3/h/m^2 at 50 Pa) for the six-sided building envelope (Zhivov et al. 2014). This airtightness requirement is comparable to England's HM Government's Non-Dwelling Building Code Regulation (HM Government 2013), which currently requires 0.21 cfm/ft^2 at 75 Pa (3.0 m^3/h/m^2 at 50 Pa). USACE (2014) references many ASTM, International Organization for Standardization (ISO), and other related publications as the basis for how USACE projects are to use air leakage testing and thermal imaging for building envelope commissioning requirements. The implementation of these building envelope airtightness requirements over the past several decades for U.S. Department of Defense (DOD) projects has drastically improved the level of understanding, design considerations, and construction methods of air barriers in the United States. Improvements in design, air barrier products, and installation practices have occurred during each construction cycle since 2009, resulting in a progressive learning curve for all parties involved (Leffel 2021).

In a 2012 published report, the average for the first 200 USACE building envelope tests was reported as low as 0.17 cfm/ft^2 at 75 Pa (2.38 m^3/h/m^2 at 50 Pa) (Zhivov et al. 2014). Modeled energy savings in the arctic climates indicate that upwards of a 40% to 45% energy savings are possible with an airtightness requirement of 0.15 cfm/ft^2 at 75 Pa (2.10 m^3/h/m^2 at 50 Pa). (See Figure 6). The next goal in meeting stringent national fossil fuel and GHG goals for arctic and subarctic regions will have to include more airtight building envelopes.

A review of test results conducted in Alaska (Leffel 2021) shows examples of projects with air leakage results at or below 0.25 cfm/ft^2 at 75 Pa (3.5 m^3/h/m^2 at 50 Pa) that had significant air leakage pathways uniformly at major air barrier joints. Figure 5(bottom) shows thermal images of a building that tested at 0.25 cfm/ft^2 at 75 Pa (3.5 m^3/h/m^2 at 50 Pa), which still experiences significant air leakage signatures at the roof-to-rake wall joints. By comparison, projects below 0.15 cfm/ft^2 at 75 Pa (2.1 m^3/h/m^2 at 50 Pa) had substantially less air leakage pathways at major air barrier joints based on infrared thermography.

The need to improve building durability, indoor air quality, energy savings, and thermal resilience in cold-climate regions creates a companion need for more airtight building envelopes. By far the most damaging mechanism of moisture deposition in walls in cold climates is air leakage (ASHRAE 2015). A review of average published test results and airtightness levels shown to be achievable in building envelope airtightness testing around the world reveals a missed opportunity in building airtightness. For these reasons, it is recommended that airtightness requirements for cold-climate regions be increased to 0.15 cfm/ft^2 at 75 Pa (2.10 m^3/h/m^2 at 50 Pa) for normal indoor wintertime relative humidity conditions, and 0.10 cfm/ft^2 at 75 Pa (1.41 m^3/h/m^2 at 50 Pa) for buildings humidified to 30% relative humidity or higher.

Wall and Roof Assemblies

The building envelope is a system of materials, components, and assemblies that physically separates the exterior and interior environments. It comprises various elements including roofs, above-grade walls, windows, doors, skylights, below-grade walls, and floors, which in combination must control water, air, heat, water vapor, fire, smoke, and sound. Additionally, the building envelope is an aesthetic element of the building. Each of these functions must be included in the design of the building envelope assemblies and components.

Roofs. For cold climates, an exterior-insulated roof is recommended. Typically, this is provided in the form of a conventional roof assembly with slope to drains provided by a tapered insulation package or by the structure itself. A key consideration for these assemblies is to reduce thermal bridging as much as possible, and consequently, a fully adhered system is typically recommended over a mechanically fastened system. Membrane compatibility with extreme cold should also be considered, as some roofing membranes (such as thermoplastic olefin [TPO] and PVC) are known to fail in extreme cold temperatures. Airtightness and vapor control in this assembly are both provided by a membrane installed on the roof deck. This assembly is suitable for all types of building structural systems. Illustrations of common approaches to this assembly are shown in Figure 7.

Sloped roofs should pursue similar exterior-insulated strategies to reduce thermal bridging through the assemblies, and often techniques applicable to walls are also generally

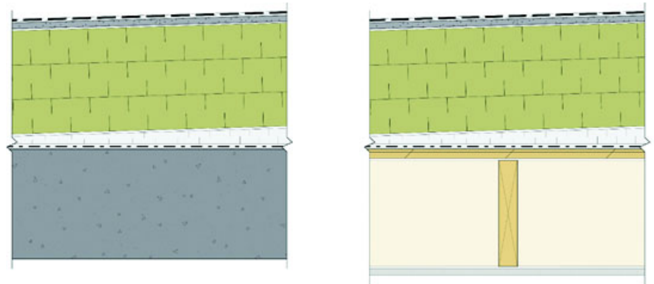


Figure 7 *Conventional roof assembly on a concrete structure (left) and on a wood structure (right). From exterior (top) to interior (bottom) these assemblies include roof membrane, cover board, insulation, tapered insulation, air and vapor control membrane, and structure.*

applicable to sloped roofs. Due to high snow loads and potential concerns with thermal bridging from continuous fastener cladding attachment techniques, it can often be practical to introduce a plywood or OSB shear layer within in the insulation thickness to allow for increased strength and shorter offset fasteners.

Walls. For cold climates, an exterior-insulated wall assembly is recommended. A key consideration for these assemblies is the support of the exterior finish (i.e., cladding). In some cases, this can be incorporated as part of insulation products (i.e., exterior-insulated finish system [EIFS] or insulated metal panel [IMP]), and in others, specific cladding support designs will need to be considered, such as thermally broken cladding attachment clips or long fasteners through the insulation.

Airtightness in this assembly can be achieved using a membrane applied to the sheathing. This membrane, which also acts as the water-resistive barrier, can be selected to be relatively vapor impermeable to control vapor diffusion, if needed. In systems with cladding independent of the insulation, a drained and vented cavity should be provided behind the cladding. In alternative systems, similar provisions should be provided as appropriate, including at joints in panel type systems. This assembly is suitable for all types of building structural systems. Figure 8 shows a common approach for this assembly.

Sometimes due to economic or structural constraints, a split-insulated wall is recommended to make efficient use of the cavity space created by the wall structure. This approach can be particularly beneficial when using structural systems with relatively low thermal conductivity (i.e., wood), where the insulation effectiveness is better realized. Similar to the exterior insulated wall described above, a variety of insulation and cladding attachment strategies are available. For wood construction, long fasteners through insulation are more common and constructability of this approach can be improved through the use of ¾-in. (19 mm) sheathing. Figure 8b shows a common approach for this assembly.

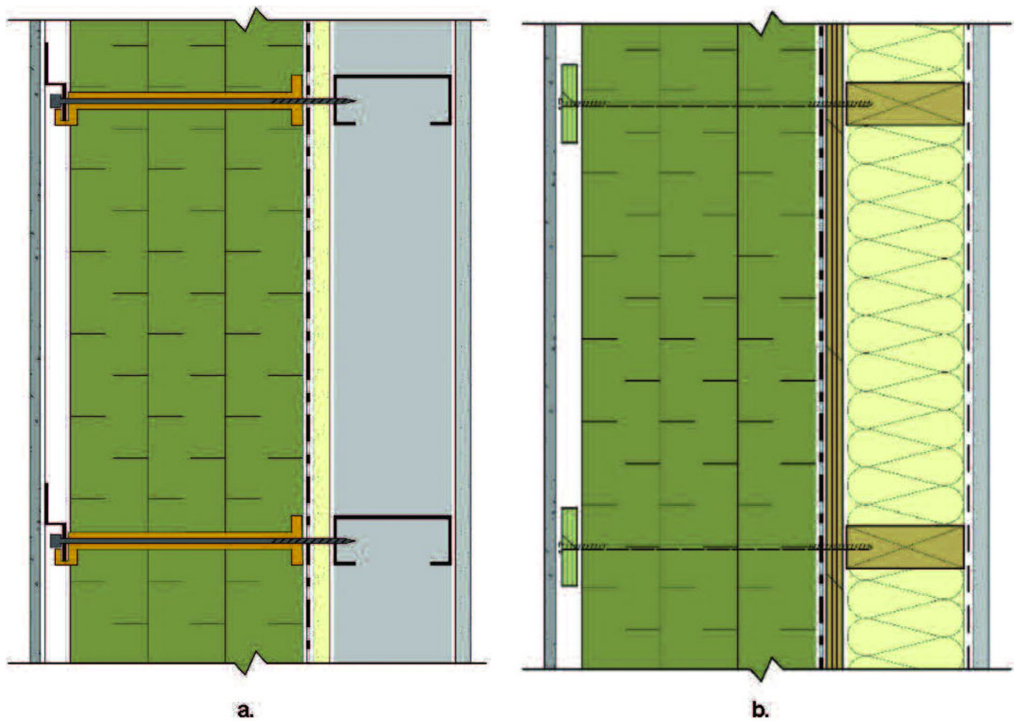


Figure 8 *Examples of exterior insulation: (a) Steel stud wall assembly, and similar approaches are appropriate for other back-up wall structures including wood and CMU. From exterior (left) to interior (right), this assembly consists of cladding, continuous girts exterior of the insulation to receive cladding fasteners, thermally efficient intermittent cladding attachment clips fastened to structure, air/water/vapor control membrane on the sheathing, exterior grade gypsum sheathing, structure (steel studs), and interior finish. (b) Wood stud wall assembly. From exterior (left) to interior (right), this assembly consists of cladding, wood furring attached with long fasteners, exterior insulation, air/water control membrane on the sheathing, wood sheathing, wood studs with insulation, interior vapor barrier membrane, and interior finish.*

While interior air barrier systems are possible with a split-insulated assembly, for best practice air leakage control, an exterior air barrier system such as sealed sheathing or a sheathing membrane are recommended. This layer would typically also be the primary water control layer. Depending on the split between interior and exterior insulation and the vapor permanence of the insulation, vapor control should be provided on the interior, often by a polyethylene sheet.

Fenestration. The selection of fenestration systems for cold climates is of particular importance as these are typically the lowest performing element of the building envelope from the perspective of thermal control, and thus the most likely cause of energy, comfort, and durability challenges. Key performance considerations include structural capacity, water penetration resistance, airtightness, thermal conductance (U-factor), solar heat gain coefficient (SHGC), visual light transmittance (VLT), and temperature index (I). There are two primary components of any fenestration system that must be considered: the frame and the glazing.

The frame of a window has a significant impact on the thermal performance and is the most common location for condensation or frost accumulation issues. Additionally, the air and water tightness of the frame and associated dry (i.e., gasket) and wet (i.e., sealant) seal components are fundamental to the fenestration product's overall performance.

All window materials are potentially applicable to cold climates; however, care must be taken when using thermally conductive base materials such as aluminum to achieve other design objectives to also ensure that a well thermally broken product is selected. While high-performing aluminum products exist, many products typically used in warmer climates are not likely to be appropriate for cold climates.

Other frame considerations include the durability of finishes, internal water control strategy (pressure moderated and drained strategies recommended), hardware type and durability (i.e., multipoint locking hardware improves compression on air seal gaskets for operable units), and integration with the surrounding building envelope. Many high-performance installation details call for exterior insulating the frame (Zhivov and Lohse 2020), and this should be considered in the design of the frame, including operable vents.

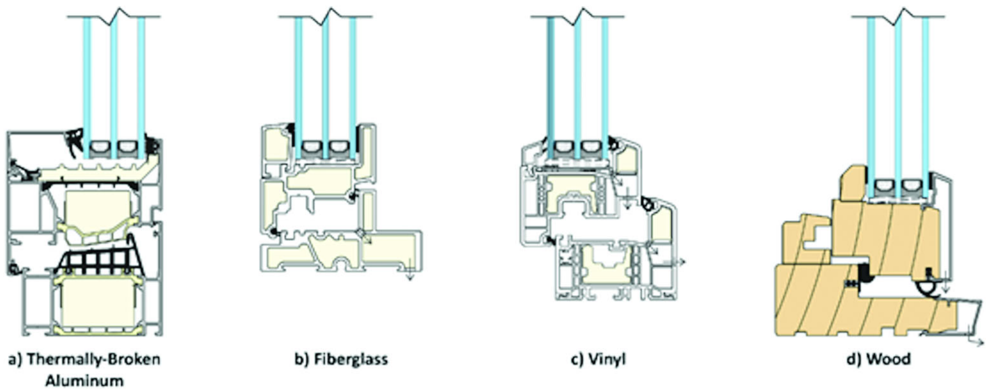


Figure 9 *High thermal performance window frame types, (a) thermally broken aluminum, (b), fiberglass, (c) vinyl, and (d) wood.*

Figure 9 shows examples of different window frame technologies appropriate for use in cold climates.

Glazing. In cold climates, a minimum of triple-glazing is recommended (AHFC 2018, Nygaard 2019, RDH 2016b, NRCC 2017, Finnish Ministry of the Environment 2017, NBA 2017, Zhivov and Lohse 2020) in conjunction with a combination of low emissivity coatings and gas fills to optimize thermal conductance, solar heat gain, VLT, and interior surface temperatures. Technologies such as suspended films, electrochromic glazing, and vacuum-insulated glazing are less common, but with appropriate due diligence may also be suitable for some applications.

Spacer bar systems should be selected to reduce thermal bridging. Dual seal stainless steel, silicone, and thermally broken spacer bars often perform well from this perspective. In all cases, the durable long-term performance of the insulated glazing units is essential. Insulated glazing units designed and tested in accordance with applicable standards such as ASTM E2190, *Standard Specification for Insulating Glass Unit Performance and Evaluation* (ASTM 2019) are recommended.

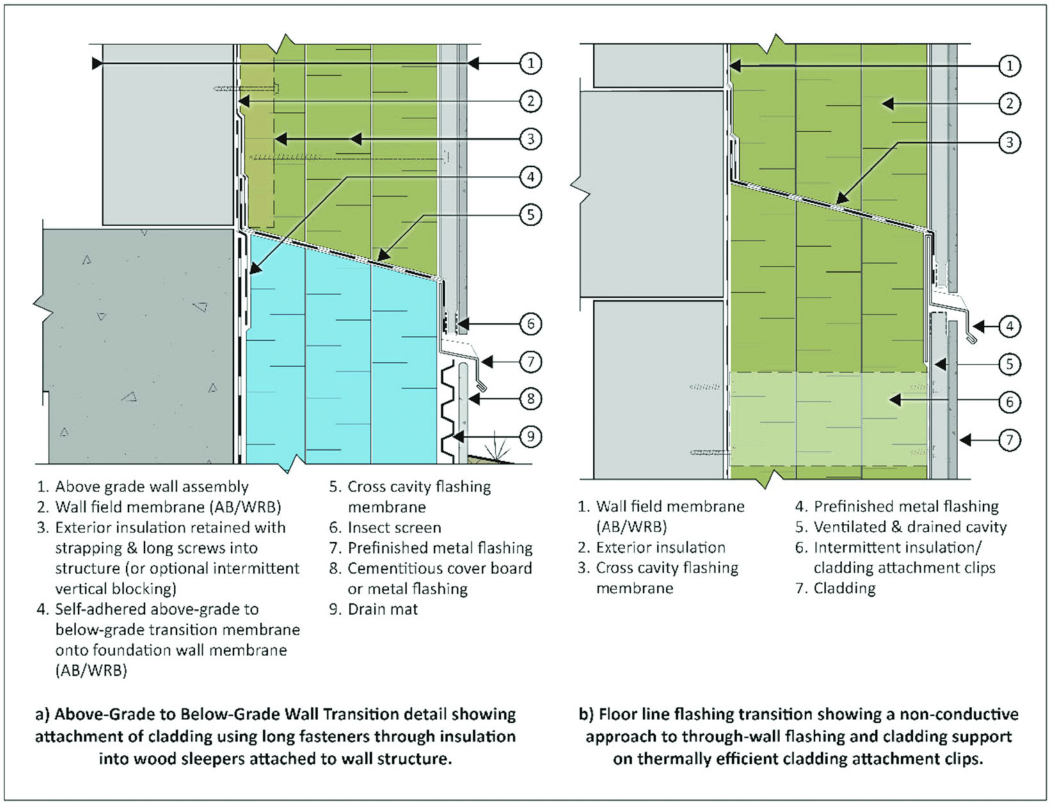
Pertinent Details

The continuity of the building envelope control layers described in the preceding sections (air, thermal, water, and vapor diffusion) is critical to the performance of the building envelope and heavily dependent on proper detailing. Each transition in plane or material represents an opportunity for the building envelope to be improperly installed, discontinuous, or naturally vulnerable to damage. The continuity of the air and thermal barriers are especially critical to support the building's thermal resiliency in cold/arctic climates, as has been demonstrated in previous sections. Localized areas of air leakage or thermal bridging can cause significant heat loss and interstitial condensation, which can impact indoor air quality, increase energy consumption, and lead to damage in the form of mold, decay, or corrosion. This section highlights a few of the most important details of a high-performance building envelope in support of thermal resiliency in cold/arctic climates.

Structural Support of Exterior Finishes. The extreme thickness of exterior insulation in cold/arctic climates typically requires structural supports for exterior finishes, introducing another layer of potential thermal bridging. Several strategies exist to minimize the resulting thermal and moisture impacts. Adhesive-based systems such as EIFS and fully adhered membrane roofs avoid highly conductive structural supports or fasteners and thereby reduce thermal bridging. Depending on wind loads, cladding weight, and insulation thickness, exterior wall finishes can often be supported by mechanical fasteners alone as shown in Figure 10a. Each fastener acts as a thermal bridge, reducing the wall's thermal resistance, but the relatively small percentage of area covered by fasteners makes this a better option than structural support members that penetrate the insulation plane. For exterior-insulated sloped roof systems, partial-depth mechanical fasteners can transfer structural loads through a plywood layer embedded within the large insulation layer, while avoiding direct transfer of thermal loads between the interior and exterior spaces.

When the fastener-only approach is not feasible for wall cladding support, then metal furring can be supported by low-conductivity (fiberglass) and/or thermally broken clips that penetrate the insulation layer as shown in Figure 10b. While these proprietary systems perform well, they often do not survive value engineering efforts.

Another option that does not perform as well, but often fits within project budgets and can be used with greater insulation depths, is a two-layer furring system. Ideally, the two layers of furring would be oriented at 90 degrees from each other, so direct thermal bridging is limited only to the small areas of contact between the furring members. While orienting the two layers perpendicular to each other does reduce the thermal bridging created by these steel elements, typically this approach is on the order of 30% to 40% less effective than thermally efficient clips or long fasteners. Whenever possible, the



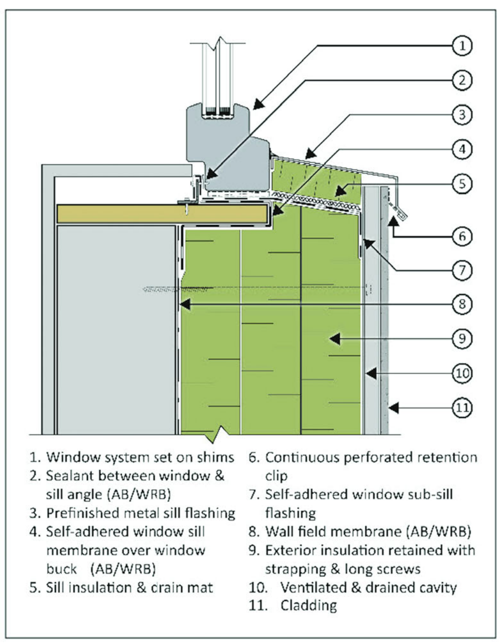


Figure 10 *Top: schematics of building envelope control layers in cold and arctic climates: (a) floor line details for exterior-insulated wall assemblies, (b) windowsill detail showing key design elements for high-performance detailing. In particular, this detail includes a membrane upturn on a back dam angle for enhanced water penetration resistance, continuity of the air barrier from the wall system to the window product, over-insulation of the window frame to reduce thermal bridging, and sub-sill drainage to direct any water which penetrates to the sub-sill area out to the exterior of the wall assembly. Bottom: roof-to-wall details showing key design elements for high-performance detailing. In particular, note the continuity of control layers including the air barrier systems and the insulation in each of the details.*

first layer of furring should be lumber, which assists in reducing this thermal bridging effect due to its lower thermal conductivity.

Window Openings. Window openings present several challenges to control layer continuity. In addition to properly draining the wall above the window and flashing the sill to prevent water intrusion, the air barrier must connect the wall to the window, preventing leakage through the shim space. Full-depth injection of low-expansion foam and a bead of sealant around the entire perimeter of the window frame is used to prevent interior air from escaping and causing condensation in this relatively weaker portion of the building's thermal barrier (Figure 10, bottom). The water-resistive barrier (often doubling as an air barrier) needs to maintain its shingle-lapped installation sequence across the opening, and rain screen furring should be intentionally gapped to allow for ventilation air to flow around horizontal furring at the windowsill. A schematic windowsill detail is provided in Figure 10.

Penetrations. Mechanical and electrical penetrations through building envelope surfaces are common locations for air leakage and water penetration, and as such, require proper detailing. The cavity around all penetrations should be fully insulated with injection foam to make sure that the full depth of the space is filled. In particular, drain box cavities (for roof drains) are large voids that need to be insulated in the same fashion as the rest of the roof. The penetrating member itself can also be a good conductor of heat (thermal bridge), causing condensation to form on the interior side of the penetration. In arctic climates, pipe lagging with vapor-retardant coating should be installed on the first 10 ft (3 m) of the pipe on the inside of the building.

Wall-to-Roof Transitions. As discussed in previous sections, the wall-to-roof transitions typically represent the largest source of air leakage and can present opportunities for thermal bridging if not properly detailed. This area of the building envelope involves transitions in materials, geometry, and often subcontractors, so there is often confusion over responsibility and sequencing between the different trades. Maintaining continuity of the thermal insulation and air barrier at this transition is paramount to the performance of the building envelope.

For low-slope roofs, the parapet framing needs to be completely surrounded by exterior insulation on all three sides to avoid thermal bridging. The wall air barrier needs to be sealed to the roof air barrier, but this connection can be challenging to construct, especially if the wall air barrier is on the interior side of the wall. When exterior air barriers are used, the interior air that is in the parapet framing space is in a narrow "cold peninsula" surrounded by cold wall construction on three sides. Relatively high humidity air from the interior may form condensation on cold surfaces within this space if it falls below the dew-point temperature of the interior air. To avoid this, it is sometimes prudent to provide an air seal at the interior of these "cold peninsulas." Closed-cell spray foam or a prestripped membrane can be used to provide this air seal. The most appropriate air sealing strategy depends on a number of factors, including the structural design, the length of parapet of overhang projection, and the adjacent assemblies.

Figure 11a provides a schematic detail for a low-slope roof-to-wall transition detail at a parapet. Similar considerations need to be applied to rake and eave details for exterior-insulated sloped roofs, ensuring both air barrier and thermal continuity. A schematic detail for a standing seam metal roof rake is provided in Figure 11b, and a sloped wood-frame roof-to-wall transition (i.e., eave) detail is provided in Figure 11c.

Thermal Resiliency Impact and Recommendations

Increased thermal insulation, improved thermal bridge detailing, and whole-building airtightness have significant potential to impact the thermal resiliency of buildings in cold climates. In a study of the effect of different levels of building envelope energy efficiency (e.g., thermal insulation, airtightness) and mass, an indoor air temperature decay study was conducted to simulate interruption of the mechanical heating supply during outdoor temperature conditions of –40°F (–40 °C) (Liesen et al. 2021). This study found that in a building with a mass structure (concrete masonry unit [CMU], poured slab) and a more energy-efficient building envelope design, the indoor air temperature approached the habitability level of 60°F (16°C) (Zhivov et al. 2021) seven hours later than a similar building with a less energy-efficient building envelope, and six hours later than a similar building with a framed (i.e., lower thermal mass) building structure. The intersection of the indoor air temperature decay line with the building sustainability threshold of 40°F (4°C) occurs 31 hours and 27 hours later, respectively, for the same scenarios. When mass high-performance buildings are compared to buildings built using typical 1980 code (i.e., buildings that constitute the majority of existing buildings), and the difference in the mean time to repair (MTTR) is calculated until the building air temperature reaches habitability and sustainability threshold values, the difference in MTTR is much more significant. These results are illustrated in Figures 12a and 12b. Table 4 lists the parameters and corresponding results associated with the different buildings.

Based on these findings, it is evident that a more energy-efficient building envelope and a higher thermal mass structure improves thermal resiliency and, and at an exterior temperature of –40°F (–40°C), allows approximately eight more hours to reach the habitability threshold and 26 more hours to reach the sustainability threshold during which the heating system can be repaired. Therefore, more thermally resilient designs for buildings in cold climates should include consideration of increased thermal resistance of the building envelope, improved whole-building airtightness, and higher thermal mass.

Air tightness of 0.15 cfm/ft^2 at 75Pa in cold climate is achievable and results in significant energy use reduction and

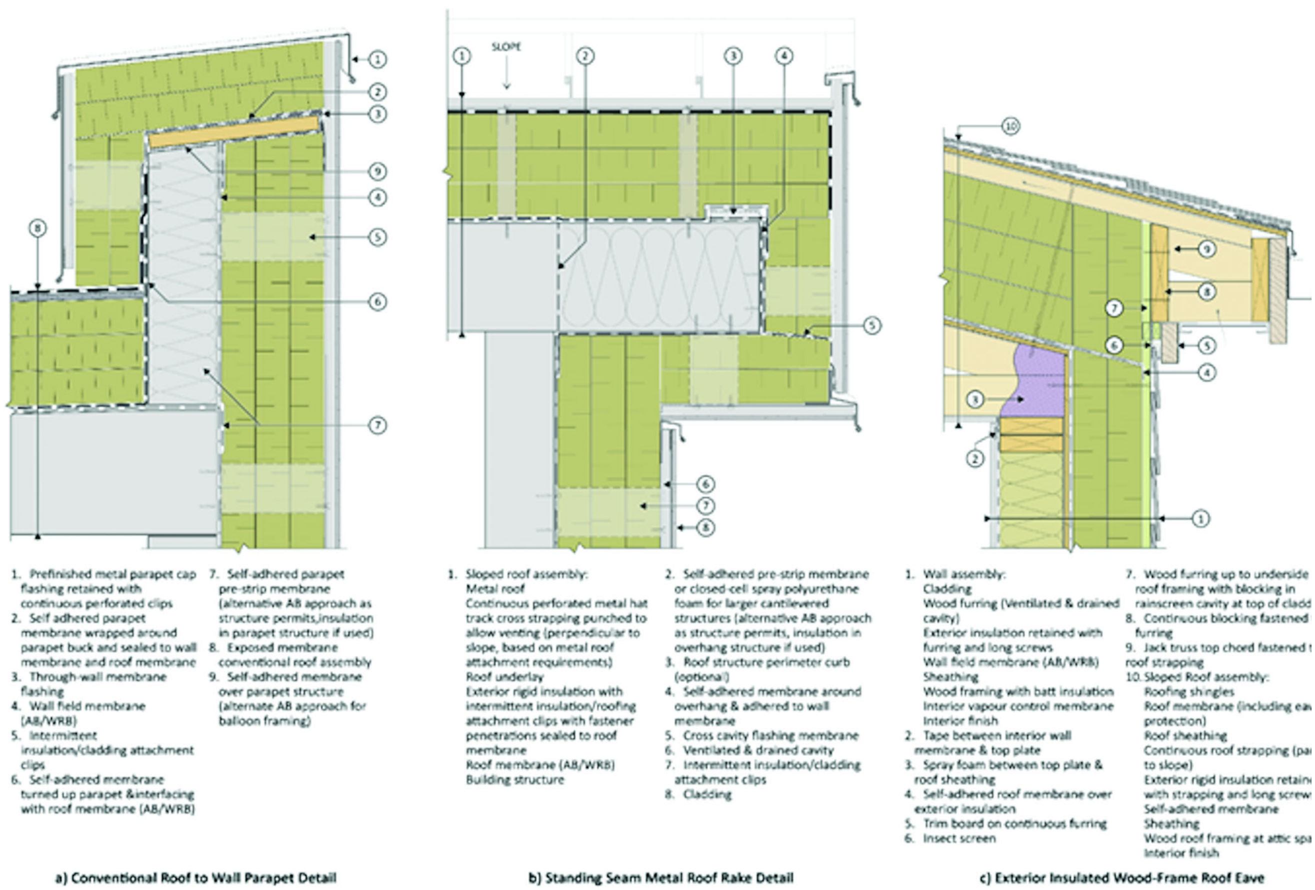


Figure 11 *Schematic roof-to-wall details showing key design elements for high-performance detailing, (a) conventional roof-to-wall parapet detail, (b) standing seam metal roof rake detail, and (c) exterior insulated wood-frame roof eave. In particular, note the continuity of control layers including the air barrier systems and the insulation in each of the details.*

improved building energy resilience. Special consideration shall be given to air barrier details at the roof/wall joints.

Specific building envelope designs and their characteristics do (and will continue to) vary country by country. This paper's intent is to provide an additional consideration for authorities having jurisdiction (AHJ) when they are setting their building envelope guidelines for buildings located in cold and Arctic climates regarding building thermal energy system resilience.

ACKNOWLEDGEMENTS

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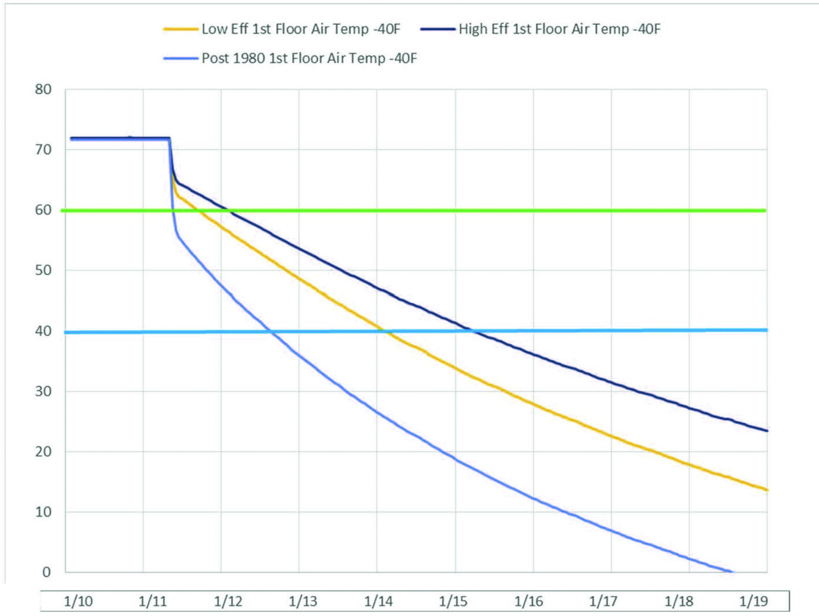
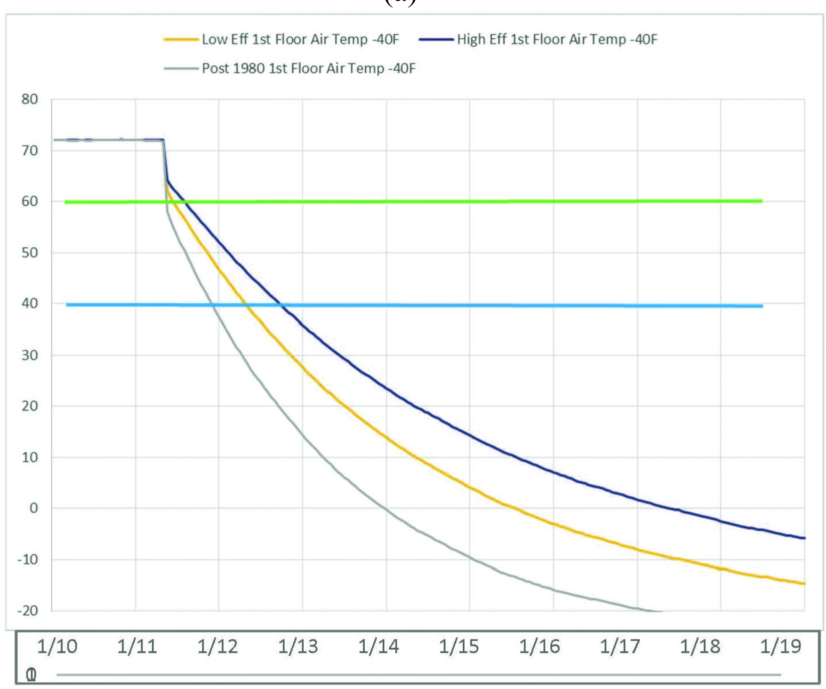


(a)



(b)

Figure 12 *Indoor air temperature decay in a high-efficiency building versus a lower-efficiency building when the heat supply is interrupted at an outdoor air temperature of –40°F (–40°C): (a) a thermally massive building and (b) a framed building.*

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Table 4. Building Envelope Characteristics for Mass and Frame Buildings Located in Cold and Arctic Climates used for Liesen et al. (2021) of Interior Temperature Decay when Heating is Interrupted

Building Parameters	Mass Building			Frame Building		
	Typical/Post 1980	Low Efficiency	High Efficiency	Typical/Post 1980	Low Efficiency	High Efficiency
Walls, (R-Value: F•ft^2•h/Btu)	20.5	40	50	20.5	40	50
Roof, (R-value: F•ft^2•h/Btu)	31.5	45	60	31.5	45	60
Air Leakage, cfm/ft^2 at 75Pa	0.4	0.25	0.15	0.4	0.25	0.15
Window, (R-value: F•ft^2•h/Btu, U-factor, Btu/(F•ft^2•h))	Double Pane; R = 1.78/U =.56	Double Pane; R = 3.34/U =.3	Triple Pane; R = 5.25/U =.19	Double Pane; R= 1.78/U =.56	Double Pane; R= 3.34/U =.3	Triple Pane; R = 5.25/U =.19
MaxTTR Hab. 60°F (16°C)	1 hours	3 hours	10 hours	< 1 hour	2 hours	4 hours
MaxTTR Sust. 40°F (4°C)	20 hours	36 hours	51 hours	10 hours	18 hours	24 hours

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