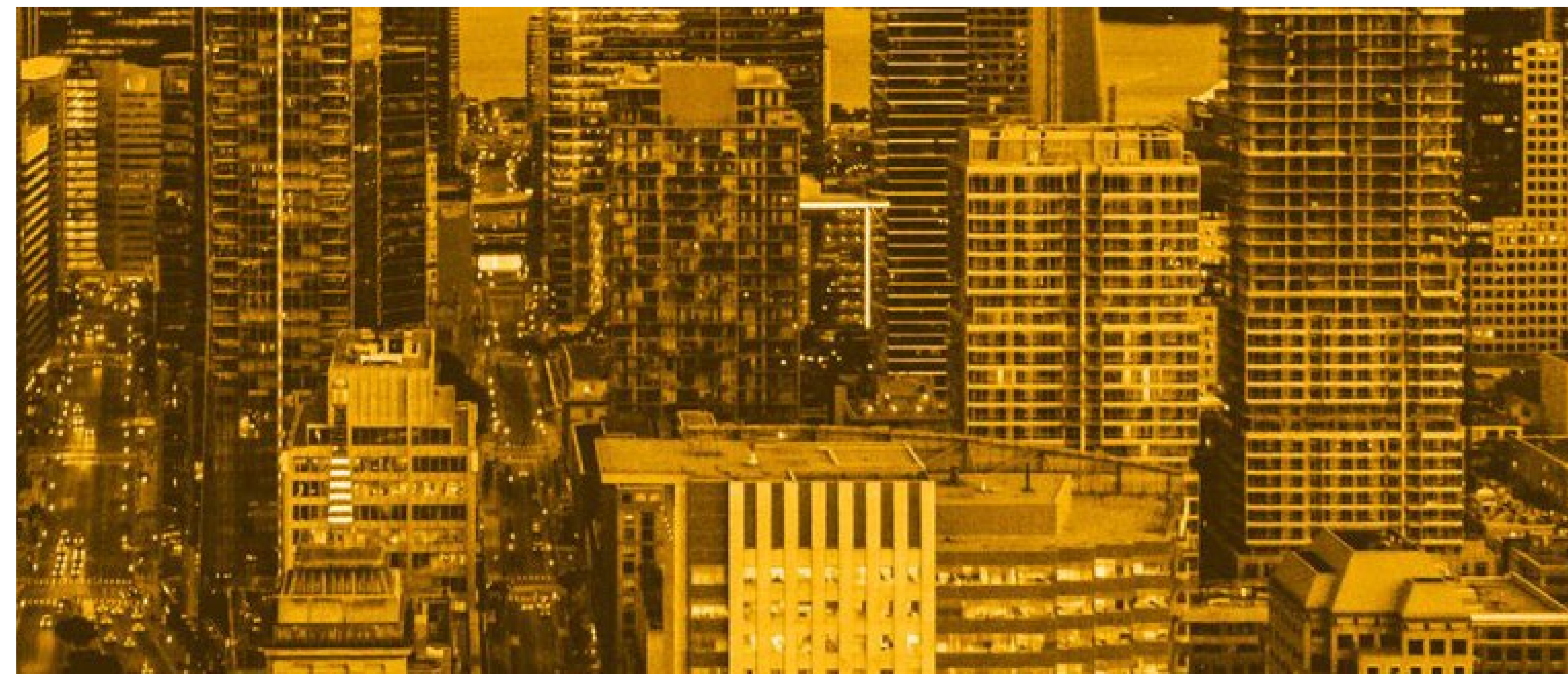
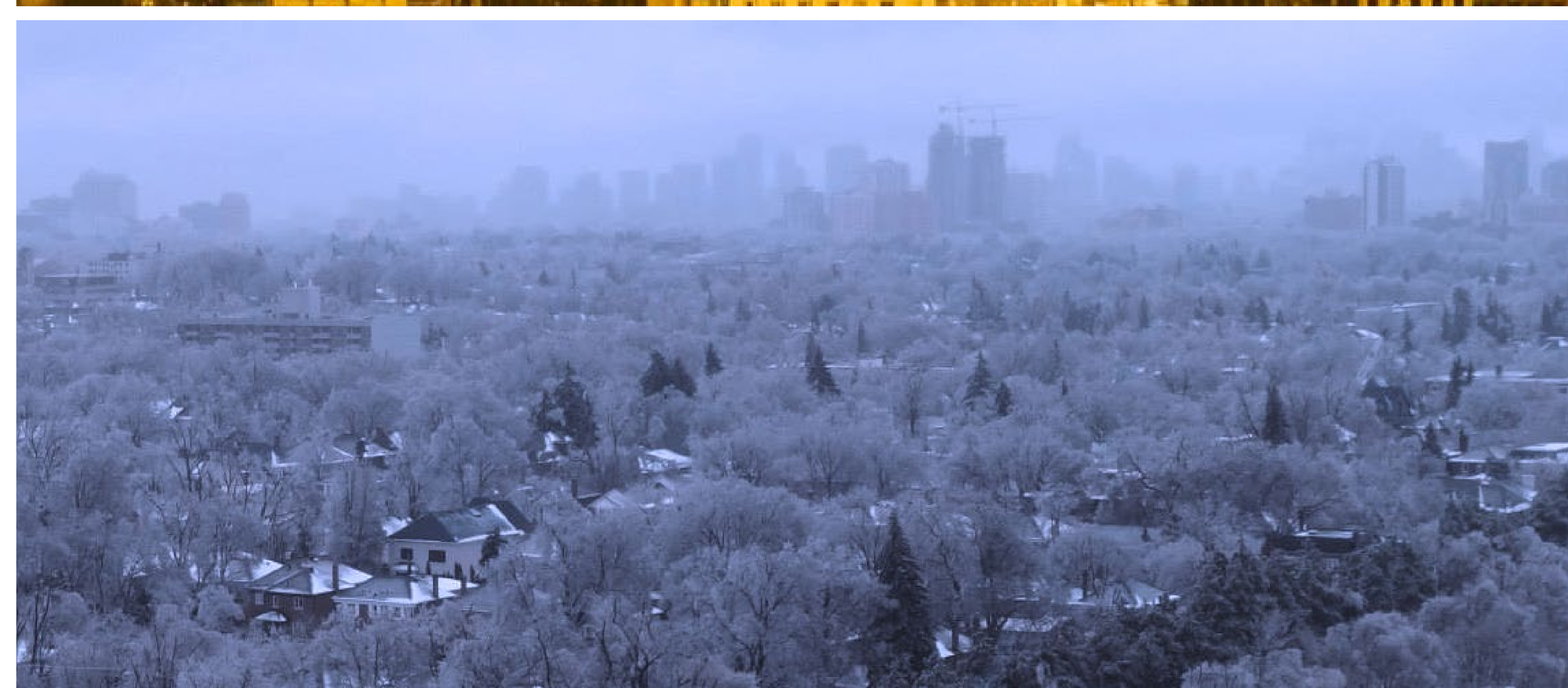
Thermal Resilience Design Guide

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UNIVERSITY OF TORONTO
JOHN H. DANIELS FACULTY OF ARCHITECTURE, LANDSCAPE, AND DESIGN

ROCKWOOL

Thermal Resilience Design Guide
Sponsored by ROCKWOOL North America 2019.

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The information presented in this publication is intended to provide guidance to knowledgeable industry professionals qualified in the design of new and retrofit buildings. It remains the sole responsibility of the designers, constructors and authorities having jurisdiction that all thermal resilience measures deployed in professional practice adhere to sound building science principles. These guidelines are not a substitute for prudent professional practice, due diligence and compliance with applicable codes and standards. While care has been taken to ensure the accuracy of information presented herein, this publication is intended solely as a document of building science guidance to enhance the thermal resilience of buildings. This publication should not be relied upon as a substitute for architectural, engineering, or retrofit advice by qualified practitioners. ROCKWOOL, the authors, contributors and referenced sources assume no responsibility for consequential loss, errors or omissions resulting from the information contained herein. The views expressed in this guide are those of the authors and do not necessarily represent the views or policies of ROCKWOOL North America.

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ROCKWOOL

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About This Guide

This design guide is aimed at building industry professionals who wish to enhance the thermal resilience of buildings.

Aging energy infrastructure and extreme weather events due to climate change can lead to extended power outages that cause buildings to be much too cold or hot to inhabit. Intelligent enclosure design can take advantage of passive measures to futureproof buildings. This guide contains information that is useful to architects, engineers, energy modellers, facility managers and building owners.

The scope of this guide focuses on North America and its associated climate zones where both space heating and cooling are required to provide inhabitants with thermal comfort. It is important to recognize that the information presented in this guide should be viewed as the preliminary basis for more comprehensive analysis and design. Additional references are provided so that users of this guide gain access to more extensive information about thermal resilience design in buildings.

How To Use This Guide

At its most basic level, thermal resilience design involves risk management and it is critical to appreciate that durability is a prerequisite for resilience in buildings.

Thermal resilience measures should reasonably persist over the service life of the building, and as the most effective measures are related to the design of the enclosure, it is essential that durability is not compromised.

After durability criteria have been addressed, determine if the risk exposure of your building, proposed or existing, is related to winter or summer thermal resilience challenges, or both.

The minimum recommended enclosure thermal resistance charts can be used to determine a reasonable baseline for each of the enclosure components (roofs, walls, windows, etc.) and these apply to both winter and summer conditions. Additional strategies are specific to hot and cold weather situations and the challenge is to integrate these within the enclosure design.

Active thermal resilience measures are viewed as a supplementary or back up means of maintaining thermal comfort and habitability that should not be relied upon to achieve the minimum acceptable level of thermal resilience. This minimum acceptable level of perfomance should be robust passive systems that remain serviceable over the life of the building.

By exploring the strategies and measures highlighted in this guide, it is intended that building professionals can efficiently develop effective design approaches at the early stages of design that may then be further analyzed and refined such that a comprehensive, integrated solution for thermal resilience may be achieved. It is important to recognize that the diversity of building types, climate zones and peculiar site conditions make it virtually impossible to advance prescriptive solutions, hence building performance simulation is essential to informing thermal resilience design. Since thermal resilience is a relatively new performance requirement for sustainable buildings, and extreme weather events that coincide with extended power outages are not frequent, it will take time to correlate predicted versus actual behaviour in real buildings, and then to gain confidence in the effectiveness of thermal resilience strategies and measures. Until such time as we gain the ability to reliably predict thermal resilience in practice, a prudent factor of safety (ignorance) is warranted going forward.

What Is Thermal Resilience?

Thermal resilience involves many aspects of building design and performance related to how the building-as-a-system, including its constituent materials, components and assemblies, manages various forms of thermal stress.

There are both passive and active system measures for managing thermal stresses that may be due to extremely hot or cold outdoor temperatures, or extreme heat exposure to fire.

Thermal resilience is an important attribute for buildings because climate change is causing an increase in the frequency and severity of extreme weather events. When these extreme weather events result in extended power outages that coincide with prolonged heat and cold spells, buildings are challenged to safely shelter their inhabitants and avoid serious damage or accelerated deterioration.

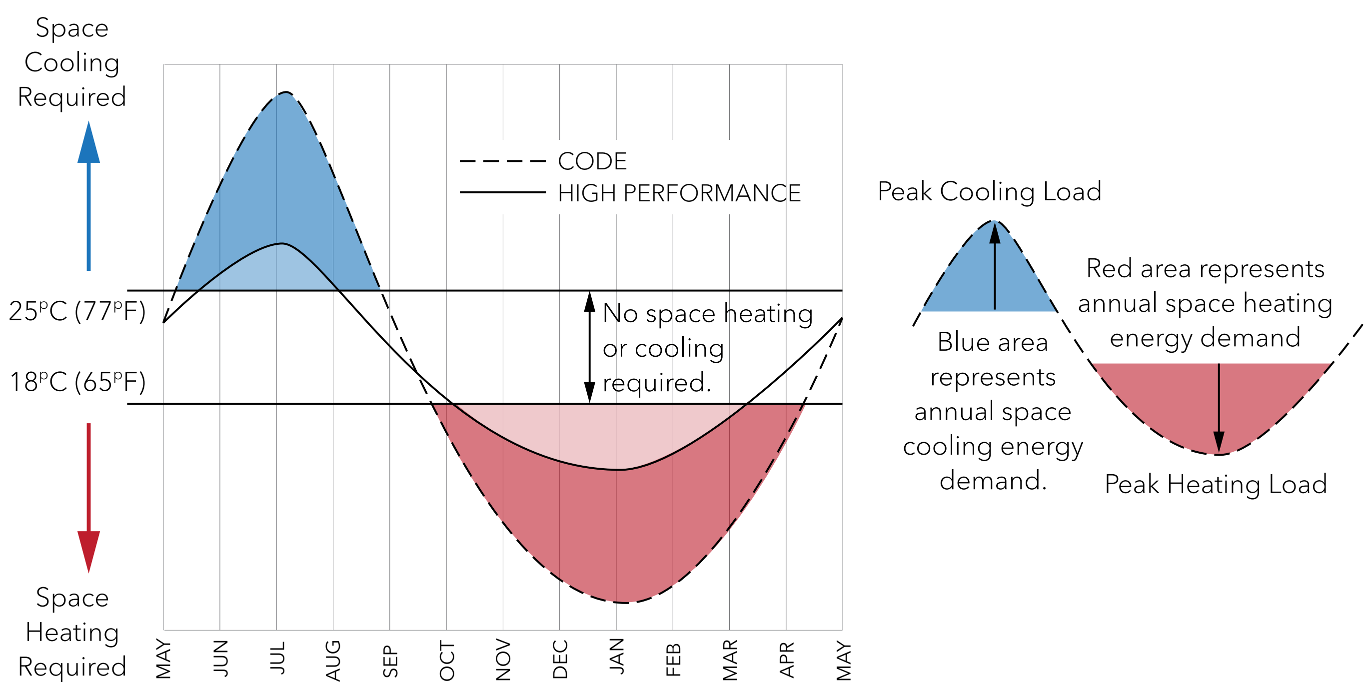
The key aspects of thermal resilience outlined in this design guide are:

1. **Thermal Autonomy**
2. **Passive Habitability**
3. **Fire Resistance**

These three key aspects of thermal resilience are explained in the sections that follow.

Thermal Autonomy

The fraction of time that a building maintains comfortable indoor conditions without inputs from active systems is termed thermal autonomy. The metric for thermal autonomy is based on comfort conditions defined as a range of operative indoor temperatures between 18°C and 25°C (64°F and 77°F).



Thermal autonomy measures the passive performance of the enclosure. *A comparison of thermal autonomy between a building with Code minimum enclosure efficiency and its high performance counterpart indicates both the peak and annual space heating and cooling energy demands are significantly reduced*

To assess thermal autonomy, a building is put into "free-running" mode where all of the active system and occupancy inputs are turned off in an energy model and the thermal performance of the building is simulated for a typical weather year. The number of hours where the indoor temperature is between 18°C and 25°C is compared to the entire year which comprises 365 days X 24 hours per day = 8,760 hours. For example, if a free-running simulation indicates that the building is between 18°C and 25°C for 4,500 hours, then the thermal autonomy is expressed as a passive fraction of 4,500/8,760 = 51.4%.

Thermal autonomy *is a measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs.*

The higher the thermal autonomy, the more the passive enclosure system contributes to managing acceptable indoor conditions, and the less reliance on active system inputs to achieve thermal comfort. Recent research indicates the greater the thermal autonomy, the smaller the peak and annual energy demands for active space heating and cooling.

The contributions that thermal autonomy makes to thermal resilience are manifold. First, the useful life of active system equipment (HVAC) is extended to provide service over a longer period of time, thus enhancing its reliability and durability. Second, energy sources supplying the active systems are conserved and for remote facilities that store energy on site (wood, propane, oil, etc.) this provides better energy security during periods of inclement weather when delivery of energy may be impaired. Third, the peak demands on the energy grid are reduced resulting in fewer brownouts while extending the useful capacity of the grid. Fourth, the carbon footprint of the building may be significantly reduced to positively contribute to climate change mitigation and reduce even more frequent and severe extreme weather events in the future.

Guidance on building energy modeling protocols for determining thermal autonomy are provided in the **Building Energy and Performance Simulation** section of this guide.

Passive Habitability

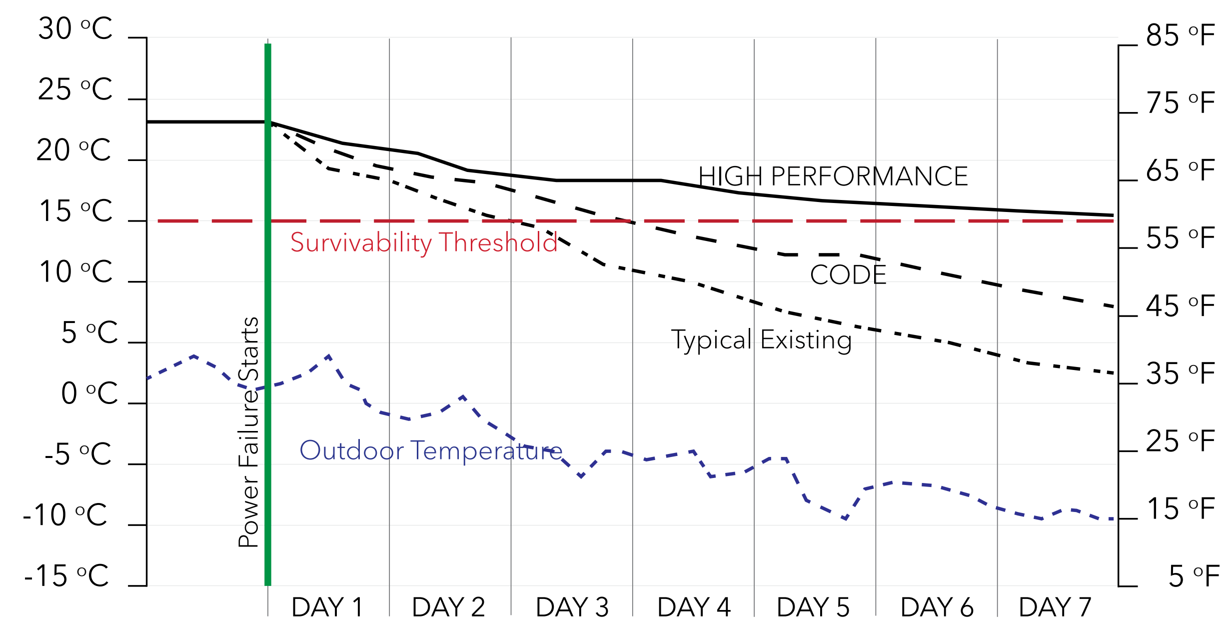
Passive habitability is a thermal resilience metric that is related to a number of passive survivability measures that consider energy, water, sanitation, daylighting and natural ventilation. Unlike thermal autonomy, where thermal comfort criteria are applied to obtain a performance metric, habitability criteria are related to marginally acceptable, or reasonably tolerable, temperatures.

Since the beginning of human history, passive habitability has driven the design of buildings. *It is only since the Industrial Revolution that widespread access to plentiful and affordable energy caused architecture to put passive habitability on the back burner. Climate change is influencing building designers to rethink building reliance on active systems that became dominant during the 20th century.*

There are two conditions that should be investigated when estimating the passive habitability of a building. A period of prolonged and extreme cold weather is normally used in building energy simulations to determine the heating season passive habitability. In some cases, analysis may be extended to examine how long it will take a building to reach the 0°C (32°F) in order to provide adequate protection against damage to freezing of water pipes and sensitive contents. To determine the cooling season passive habitability, the performance of the building enclosure during a prolonged period of extreme hot weather (heat wave) is assessed.

Guidelines for passive survivability indoor temperature and humidity conditions remain to be fully developed and standardized. To simplify energy modeling of passive habitability, the lower indoor operative temperature threshold of 15°C (59°F) is often used for the space heating period. For the space cooling period, an operative temperature of 30°C (86°F) is normally used for the upper threshold. At this time, defining suitable and practically enforceable indoor heat thresholds remains problematic for a number of reasons, including the age and health of inhabitants, the achievable rate of natural ventilation, and the provision of overheating management measures, such as shading devices, that are available for manual deployment by the inhabitants.

Passive habitability *is a measure of how long a building remains habitable during extended power outages that coincide with extreme weather events.*



Building envelope design is the most significant factor influencing passive habitability. *Heating season passive habitability is critical in cold climates where the difference between minimum efficiency and high performance enclosures can mean several or more days of habitability.*

Guidance on building energy modeling protocols for determining passive habitability are provided in the **Building Energy and Performance Simulation** section of this guide.

Fire Resistance

A dramatic increase in extended periods of drought brought about by climate change has caused a significant increase in the frequency and severity of wildfires. Recent estimates indicate that the economic toll of the 2017 wildfire season in California will rise to $180 billion. Most of these costs are associated with fire damage are related to buildings. For this reason, buildings situated in high risk areas should consider appropriate fire resistance measures.

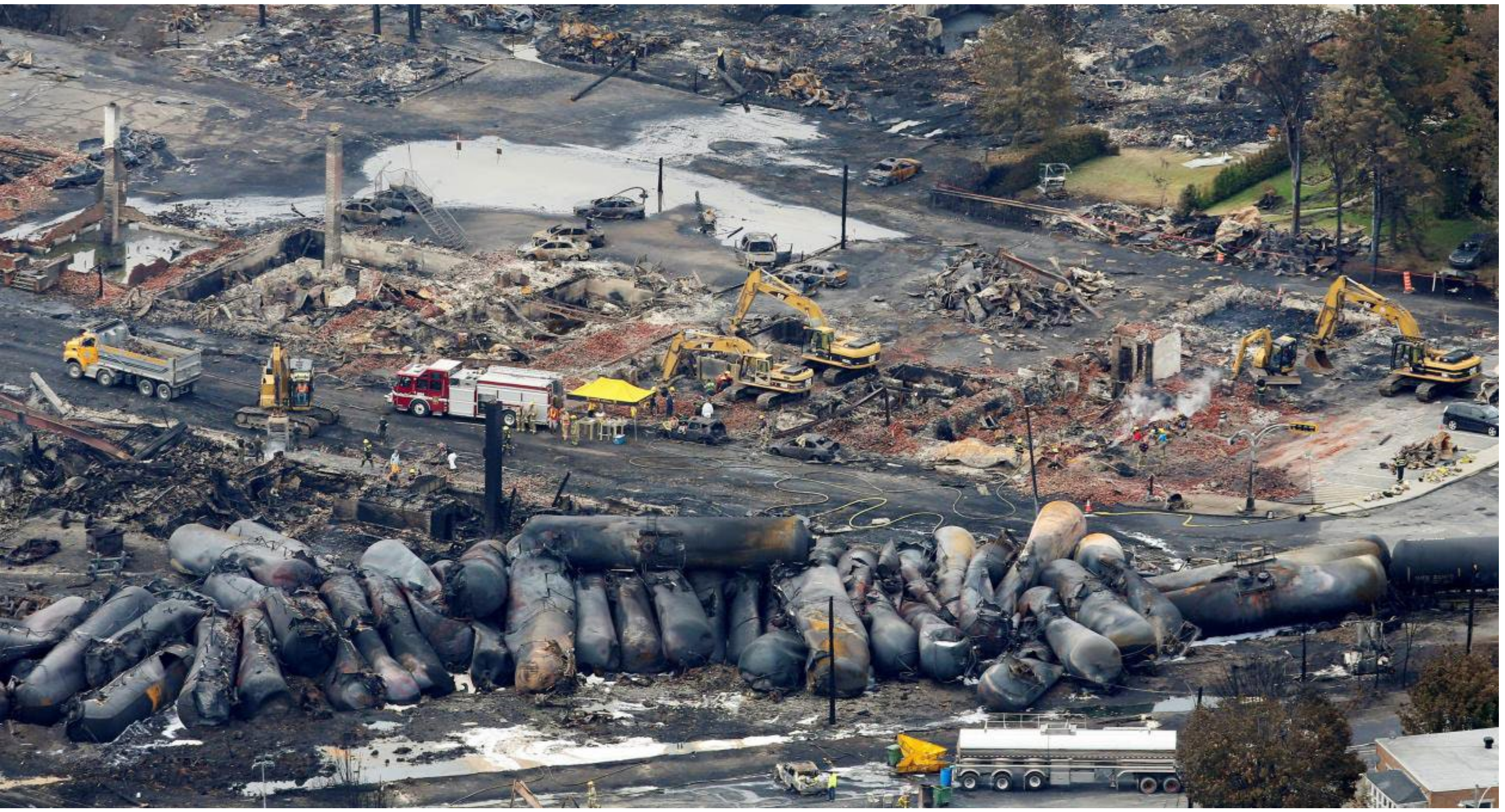
Wildfires are posing increasing risks to communities across North America. *The effects of global warming on temperature, precipitation levels, and soil moisture are turning many of our forests into kindling during wildfire season. Properties at the "wildland-urban-interface" are at the greatest risk.*

A passive measure to guard against fire damage involves incorporating fire-resistive assemblies in buildings. Building codes require the provision of fire-resistive assemblies, in some cases to prevent a fire from spreading beyond its zone of origin within a building or between adjacent buildings, and in other cases to prevent a building from ignition by external fire sources. Fire safety is a complex specialty engineering field that goes beyond the scope of this guide, but for the purposes of thermal resilience design, the major focus is fire-rated roof assemblies within the context of wildfires. Some important definitions are provided to explain the terminology of fire resistant assemblies.

Roof Covering - The exterior roof covering or skin of the roof assembly (e.g., shingles, tiles, slate, metal panels, roof membrane, etc.).

Roof Assembly - An assembly of interacting roof components, including the roof deck, and any additional provided materials (such as vapor retarders, insulation, and/or insulation cover boards, etc.), and the roof covering.

Fire-Rated Roof Assemblies - The resistance of roof assemblies to external fire is rated according to test methods set out by the American Society of Testing and Materials (ASTM), specifically ASTM E108-17 Standard Test Methods for Fire Tests of Roof Coverings. The method includes measurements of the surface spread of flame, the ability of the roof assembly to resist fire penetration from the exterior of the building to the underside of the roof deck, and the potential for the roof covering to develop flying brands of burning material. Roof assemblies are rated Class A (highest rating), B, or C. Assemblies that fail the test (do not meet the Class A, B, or C criteria) are unrated.



Thermal resilience is not a guarantee of fire safety. *As evidenced in the horrific fire caused by a rail disaster in the town centre of Lac-Mégantic, Quebec in 2013, buildings with many different types of fire-resistive building assemblies were all destroyed. Fire safety is complex and involves many considerations, many of which are not related to building design.*

Fire resistance *is a measure of the period of time a building assembly will serve as a barrier to the spread of fire and how long the assembly can function structurally after it is exposed to fire - this is also sometimes termed the assembly's fire endurance.*

Roof assemblies are the most vulnerable component of the building envelope in a wildfire because of their horizontal orientation and size. Embers and firebrands can ignite the roof covering, other roof components, and debris on the roof. Once the roof has ignited, the fire commonly propagates into the interior of the building, resulting in substantial damage to, or total loss of, the building. The probability that a building will survive a wildfire is greatly influenced by the components of the roof assembly. The type and arrangement of the components govern their potential for ignition and their propensity to transfer heat into the interior of the building. The complexity of the roof's shape also influences the potential for ignition. A roof with valleys and roof/wall intersections where combustible debris, such as leaves and needles, can collect has more potential for ignition than a roof without them.

The fire resistance of roofs poses the greatest risk for sustaining wildfire damage to a building. *Fire resistance testing of roof assemblies provides designers with ratings that can be considered when selecting roof coverings and assemblies.*

Fire testing of roof assemblies does not replicate actual wildfire conditions. *In many cases, actual wildfire exposures are much more severe than those induced during the testing. Wildfire risks should be assessed on an individual case basis that considers the specific context for the building and its immediate surroundings.*

The Role of Passive Versus Active Systems

Effective planning for thermal resilience must take into account the risks and consequences associated with protective measures in buildings. Modern buildings are a complex integration of passive and active systems and the boundaries between these two types of systems are often confused in the design process. It is important to appreciate the critical differences between passive and active systems in order to make prudent decisions.

Passive/Active Building Systems Defined

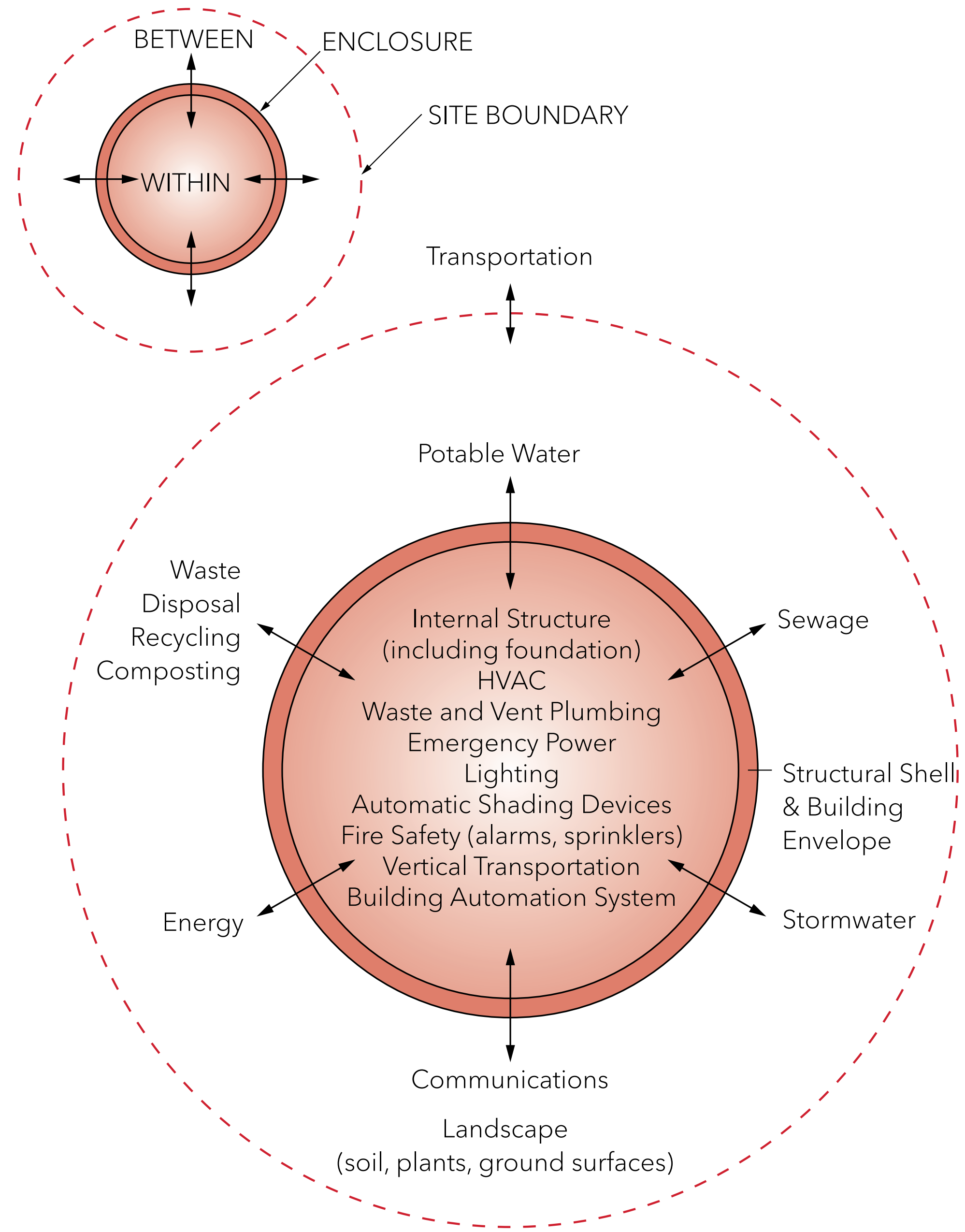
With the exception of the most simple buildings, practically all buildings consist of both passive and active systems which ideally complement each other to achieve functionality and a desired condition of environmental control. Given the context of climate change and the need to reduce our carbon footprint, passive and active roles may be defined as:

Passive Role

To moderate the environment for the safety, health and well-being of the occupants without the appreciable consumption of non-renewable energy over the useful life of the building.

Active Role

To supplement the passive systems to the extent that is required to achieve the desired level of environmental control and functionality, preferably with a minimal input of non-renewable energy.

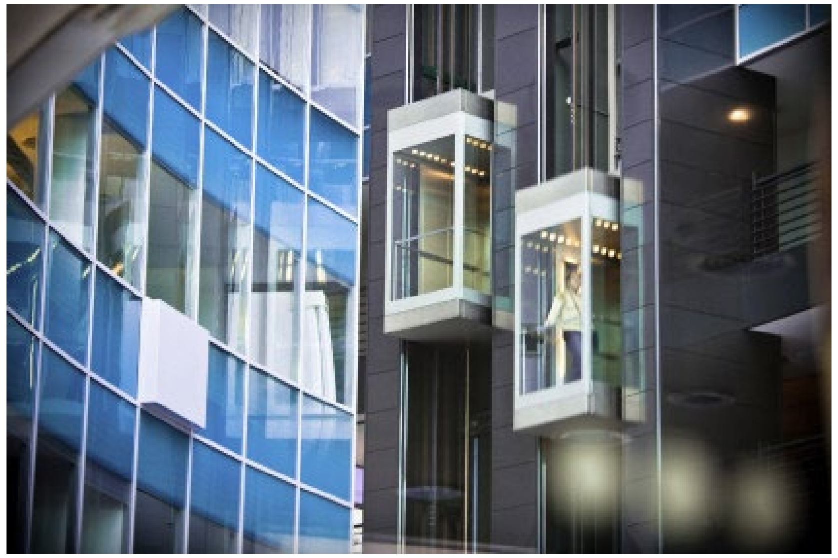


Active building systems may be classified as either being entirely contained within the building system, and/or connected between the building system and the surrounding site and services infrastructure.

Many active systems may be substituted with either passive measures, or active technologies which rely on site renewable energy systems.

It is important to recognize that active systems can never substitute for passive measures related to thermal resilience since they are disabled during extended power outrages.

Responsible systems integration is key to effective thermal resilience design.
A building's passive measures, not its active systems or occupancy, determine the upper boundary of its environmental performance potential.



Active systems often fail under emergency conditions. *Elevators do not operate during fires and power outages. Stairs are reliable because they are the passive means of vertical circulation in buildings that do not require any energy inputs.*

Hybrid measures can also be resilient. *Escalators can augment elevators and also serve as stairs in case of power outages, mechanical failures or fire emergencies. Active systems that failsafe in a passive mode are compatible with resilient design objectives.*

Passive systems establish the armature of the building within which all active systems are nested. The relative permanence of passive elements suggests their performance should approach best in class. Only then will the ability of active systems to extend or augment performance not be compromised by an inferior armature.

It is helpful and informative to consider the relationship between stairs and mechanical vertical transportation devices in buildings. Even if building codes permitted, no responsible designer would provide only elevators in a building to enable vertical circulation. It is suggested that a similar approach be taken to the design of passive measures in buildings that promote thermal resilience. Muscular HVAC system are not a responsible substitute for a robust building enclosure.

With these issues in mind, the next part of this thermal resilience design guide examines passive strategies for enhancing thermal resilience.

Passive Strategies for Enhancing Thermal Resilience

Thermal resilience and passive building design are not new concepts, but they are being recognized as increasingly important within our emerging context.

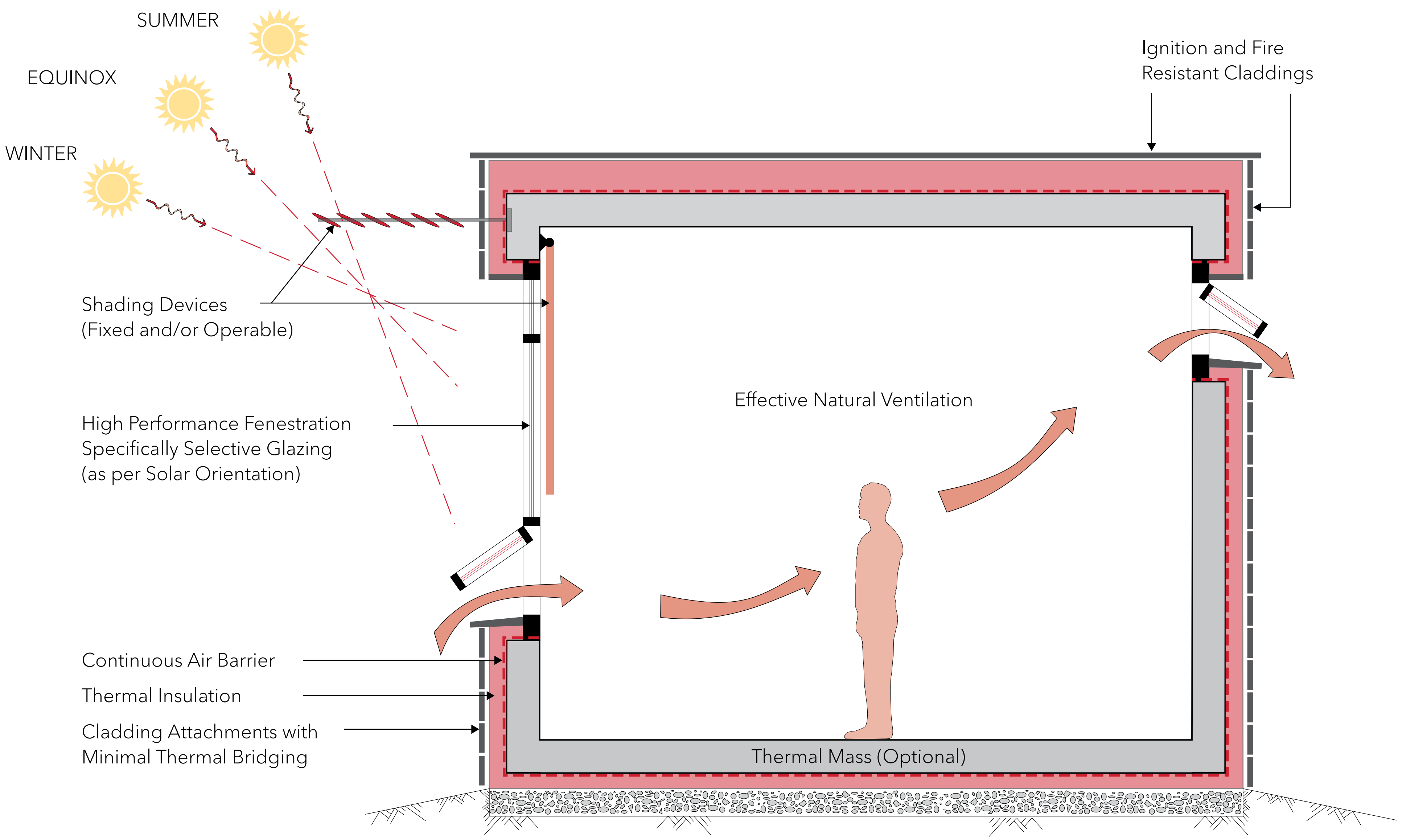
That context sees two related trends influencing how building design is being reconsidered. First, climate change is driving a sharp increase in the frequency and severity of extreme weather events. Flooding, hurricanes, wild fires, heat waves, freezing rain storms and cold snaps are frequently breaking weather records. These events often cause prolonged power outages that result in buildings with inoperative active systems for heating, cooling, ventilation, lighting and plug loads - disabled elevators and pressure boosting pumps in tall buildings often leave people with mobility challenges stranded without water in upper levels of the building. Second, developed and developing nations are becoming increasingly urbanized with more and more of the population living in urban settlements that depend on centralized infrastructure for vital services such as drinking water, sewage, energy and telecommunications. Unlike rural and remote communities where people and buildings are typically more resilient, people in urban environments are more vulnerable to power outages. It is unlikely they have access to secondary sources of energy, such as wood-burning appliances, photovoltaics or generators, and this is particularly the case for urban dwellers living in multi-unit residential buildings.

Given these two emerging trends, thermal resilience is most relevant to the design of housing, however, it may also make sense for non-residential buildings, such as government and institutional buildings, that may serve as places of refuge for disaster relief.

Thermal resilience is assessed through three basic indicators: thermal autonomy, passive habitability and fire resistance. All of the associated metrics for these three indicators are time-based and measure the duration of time over which buildings passively provide safe and/or comfortable shelter.

Time-based metrics are much more intuitive than many of the engineering data provided in reports generated from computerized energy simulations. This does not mean that these data are unimportant, but many are too fine grained to be of use during the early stages of design when energy performance and thermal resilience strategies are being formulated.

It is now widely recognized that passive measures in buildings, not active systems, are what deliver thermal resilience. Fortunately, the palette of passive measures is relatively limited and quite manageable at the early stages of design.



Thermal resilience involves the application of basic building science.
Passive measures for buildings have the advantage of requiring no external energy sources to deliver habitable shelter under a variety of extreme conditions.

A number of issues are raised about the adequacy of shelter design whenever disasters occur and people are forced out of dwellings that are too hot or too cold to inhabit, or they must evacuate communities that are threatened by wildfires and standby helplessly to see if their homes are destroyed by fire. This design guide does not address the absence of minimum thermal resilience requirements in building codes and regulations. Instead it proactively seeks to provide guidance on the critical passive measures that impact thermal resilience and how to incorporate these into the early stages of building design.

The sections which follow will deal with:

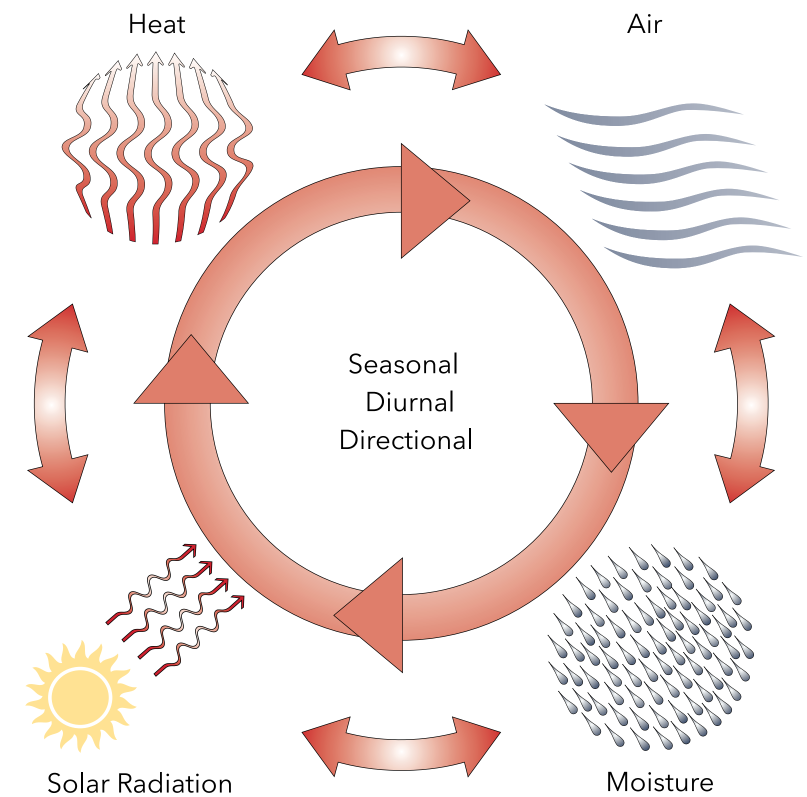
- Thermal Control (Thermal Insulation and Air Barriers);
- Fenestration and Window-to-Wall Ratio;
- Shading Devices;
- Natural Ventilation;
- Thermal Mass; and
- Fire Resistance Ratings.

Technical guidelines and energy modeling protocols will be provided in subsequent sections after the basic passive strategies are reviewed.

Thermal Control

The key to achieving thermal resilience in buildings, both thermal autonomy and passive habitability, is the provision of appropriate measures for thermal control. Thermal autonomy is achieved by providing thermal comfort without significant active space conditioning systems input. The idea is to deliver thermal comfort to the greatest practical extent through passive measures, hence thermal control is a critical consideration in virtually all buildings. Thermal control requires an understanding of heat transfer phenomena and temperature profiles across building materials, components and assemblies. This knowledge is important for assessing energy use, thermal comfort, thermal movements due to expansion and contraction, durability, and the potential for moisture problems.

It is important to appreciate that enclosure heat flows involve conduction, convection and radiation. Heat transfer across the enclosure through opaque enclosure components is primarily due to conduction and convection within wall and roof cavities. The dominant heat transfer mechanism for solar gains through transparent and translucent components, such as windows and skylights, is radiation, but conduction, convection and radiation continue to affect fenestration heat flows after the sun has set. Air leakage and ventilation represent a significant proportion of the total heat flows across a building enclosure unless an effective air barrier system and ventilation heat recovery are deployed. Heat flow can also be generated within the building by occupants and their activities, as well as by the operation of lighting and equipment, hence the management of interior heat generation can be as significant as the influence of the external weather and climate. Understanding the mechanisms driving heat flows enables designers to develop more efficient enclosures cost-effectively by allocating budgets to components that are most critical to high-performance buildings.



Thermal control plays a critical role in the management of heat, air, moisture and solar radiation flows. *Thermal resilience is almost entirely determined by the degree of thermal control afforded by the building enclosure.*

Thermal control is also an important consideration in fire safety when seeking to design assemblies and enclosures that provide a specified level of fire resistance, ignition and combustion potential. This topic is presented in greater detail in a later section of this guide, but at this point it is important to recognize the central role of thermal control when designing for the numerous aspects of building resilience.

Guidance on building energy modeling protocols for determining thermal autonomy are provided in the Building Energy Modeling and Performance Simulation section of this guide.

Thermal Insulation

While the control of moisture is practically a universal requirement for buildings, the importance of the control of heat transfer tends to become more critical as the severity of climate, either hot or cold, increases. Managing heat flows is critical to occupant thermal comfort, energy efficiency, durability, and increasingly, thermal resilience during periods of extended power outages.

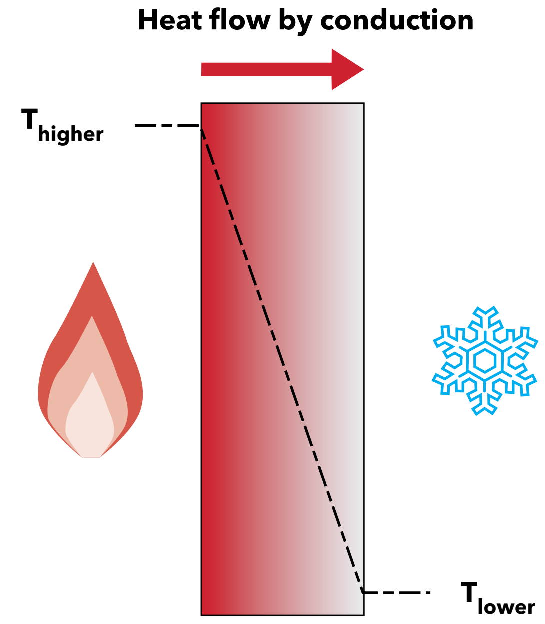
Principles, concepts and strategies for heat transfer and air leakage are outlined in the sections that follow, and links to a number of authoritative publications have been provided to access the many means by which heat transfer and air leakage can be managed as part of a whole building strategy for achieving high-performance buildings.

It is important to appreciate that enclosure heat flows involve conduction, convection and radiation and effective thermal control is achieved by matching thermal control strategies to the heat flow phenomena. Heat transfer across the enclosure through opaque enclosure components is primarily due to conduction and convection. The dominant heat transfer mechanism for solar gains through transparent and translucent components, such as windows and skylights, is radiation, but heat transfer across fenestration is also affected by conduction and convection. Air leakage affects opaque enclosure components and fenestration alike, and so these components and assemblies must be integrated to provide an effective air barrier system. Understanding the mechanisms driving heat flows enables designers to develop more efficient enclosures cost-effectively by allocating budgets to components that are most critical to high-performance buildings.

Conduction

Thermal conduction involves energy transfer between parts of a continuum in a physical substance. In solids, heat energy is transferred as kinetic energy at the atomic level. The heat is transferred from hotter regions with higher kinetic energy, to cooler regions with lower kinetic energy. As heat is applied to some part of a material, and as it is extracted from another part, a thermal gradient is formed. The thermal gradient is typically measured as a temperature difference across the material. Heat energy transferred in this way is referred to as conductive heat transfer, the primary mechanism in solid, opaque building materials.

The conductive heat flow through a material depends on the magnitude of the temperature difference across the material, its area, the thickness of the material, and the material's thermal conductivity. Thermal conductivity is a measure of the ability of a material to conduct heat. For a given thickness of material, its ability to conduct heat is termed the thermal conductance, also known as its U-value. Building materials and insulation are often specified and labeled by their resistance to heat transfer. This is simply the reciprocal of the thermal conductance, and is commonly referred to as its R-value. Energy codes are increasingly based on effective U-values, rather than R-values, of enclosure components and assemblies since these are more intuitive metrics - the lower the U-value, the lower the heat transfer. Some progressive codes and standards are understanding that the overall effective U-value of the entire enclosure may be more important than the U-values of individual components and assemblies, especially as these values relate to thermal resilience.



The rate of heat flow is proportional to the temperature difference and the thermal conductance or U-value of the material. The rate of heat flow is measured in British Thermal Units per hour, or BTU/hour.

U-value, or thermal conductance, is measured as the amount heat flow per hour across one square foot of material having a temperature difference across it of 1 degree Fahrenheit. U-1.0 = 1 BTU/hour. ft2.°F.

R-value, or thermal resistance, is the reciprocal or inverse of thermal conductance and a measure of the flow of heat is resisted by a material. R-1.0 = 1 hour. ft2.°F/BTU.

The higher the U-value, the greater the rate of heat flow. Since U=1/R, the higher the R-value, the lower the rate of heat flow. Good insulators have high R-values and inversely low U-values.

Heat flows by conduction from higher to lower temperatures. *Conduction occurs in all materials that are exposed to a temperature difference across them. Good insulators resist the flow of heat by conduction.*

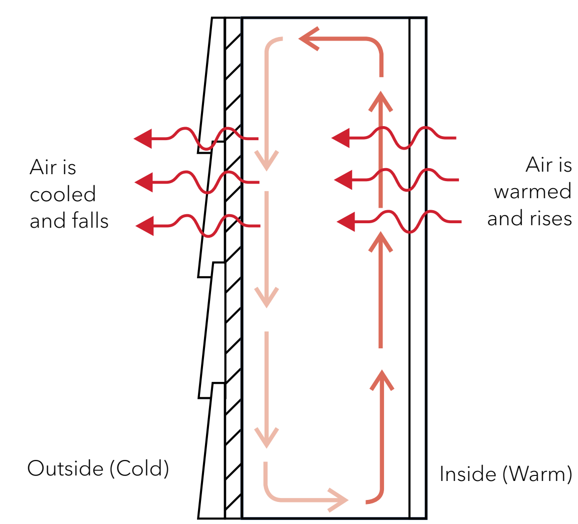
Thermal bridging is common to many forms of conventional construction. *Prior to detailed studies of thermal bridging in building enclosure assemblies, designers did not pay attention to heat flow by conduction through steel studs and reinforced concrete structures that did not benefit from continuous exterior insulation.*

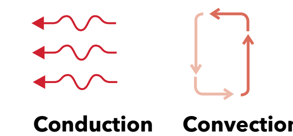
Convection

Convection is the transfer of heat between a solid or a fluid, and a moving fluid (a liquid or a gas). The force that moves the fluid can be gravitational (natural convection), as in the case of buoyancy forces (for example, rising hot air), or it can be mechanical (forced by a fan, for example).

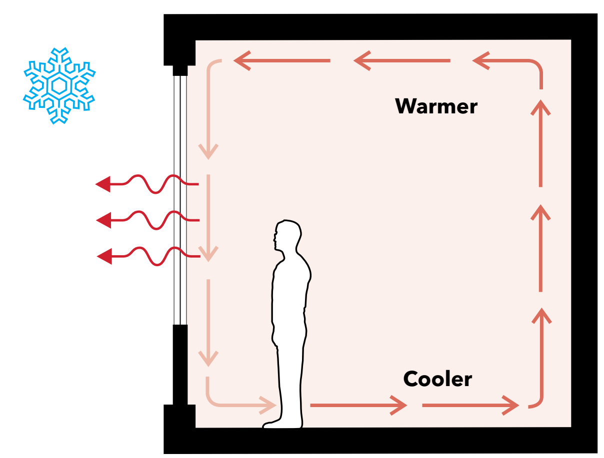
Convection is actually a form of conductive heat transfer. The exchange of energy between the fluid or gas, and another solid, fluid or gas occurs during the brief period of contact, when the energy is transferred by conduction. The liquid or gas, however, moves quickly away from the point of contact physically transferring energy.

Natural and forced convection (by fan or pump) describe a great number of phenomena: The weather and winds result from natural convection within the earth's atmosphere. The heat transferred across air spaces, as in the case of wall cavities and multi-pane windows, is another example of natural convection. The delivery of heat by a forced air furnace is a common example of forced convection. The convective exchanges in rooms, between walls, windows, ceiling and floor, are now recognized as important comfort considerations. Convective heat transfer across the building enclosure is largely controlled by the provision of air barriers and to a lesser extent by the maintenance of uniform interior surface temperatures through minimization of thermal bridging.





Convection is a form of conduction occurring in a fluid in either liquid or gas form. In this example, air molecules in the wall cavity make contact with warm inner surfaces where heat is transferred by conduction. This makes the air adjacent the warm side more buoyant causing it to rise. It then transfers the heat energy it gained to the cooler outside surface of the cavity causing it to fall, setting up a convective loop. In empty wall cavities, heat is transferred by convective loops from the warm side to the cold side of the cavity. This explains why it is important to properly install cavity insulation to avoid convective loops that bypass the insulation. Convection is always driven by conduction.

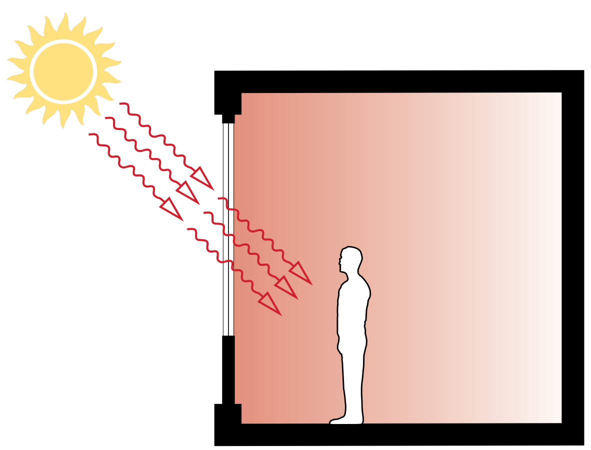


Convection may also occur in rooms or spaces and lead to thermal stratification - the difference between the temperatures taken near the floor and near the ceiling. Research conducted at the University of Illinois in 1929 revealed that the less thermally efficient the exterior enclosure, the greater the level of thermal stratification in the room. In thermally inefficient enclosures, the thermal stratification during cold weather can be as high as 11°C (20°F), resulting in cool drafts at foot and leg height. This explains why during cold weather, inhabitants experience drafts and comfort problems adjacent exterior walls that are poorly insulated and/or have large, thermally inefficient window areas.

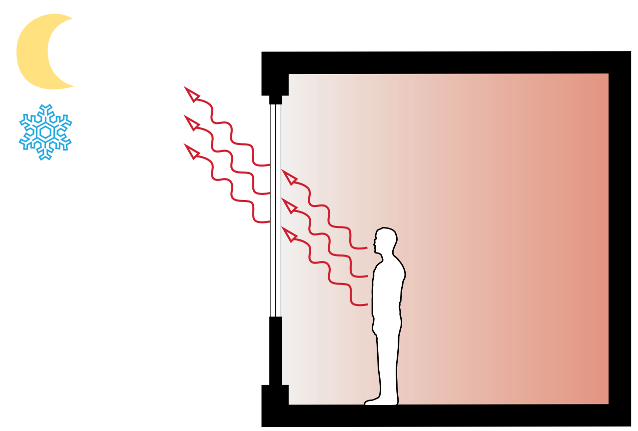
Convection occurs when moving fluids contact surfaces at different temperatures. *Convective heat transfer occurs in enclosure cavities unless they are properly insulated. The same phenomenon occurs in rooms with thermally inefficient exterior enclosures, setting up drafts as room air is cooled, especially by large glazed areas, falls and flows along the floor at the outside perimeter. High floor to ceiling temperature stratification is an indicator of a thermally inefficient wall enclosure.*

Radiation

Radiative heat transfer is an interaction between objects at different temperatures. All objects lose energy continuously by emitting electromagnetic radiation and gain energy by absorbing electromagnetic energy from around them. No medium is required between an object which emits radiation and one which receives it. The energy transferred is simply a function of the absolute temperature difference between the two objects.



All of the sun's energy flows to earth in the form of short-wave radiation.Solar radiation transfers its electromagnetic energy to the bodies and surfaces it strikes.



During the evening when the weather is cold outside, warm bodies and surfaces inside of a building transfer heat energy by long wave radiation to colder surfaces (windows).

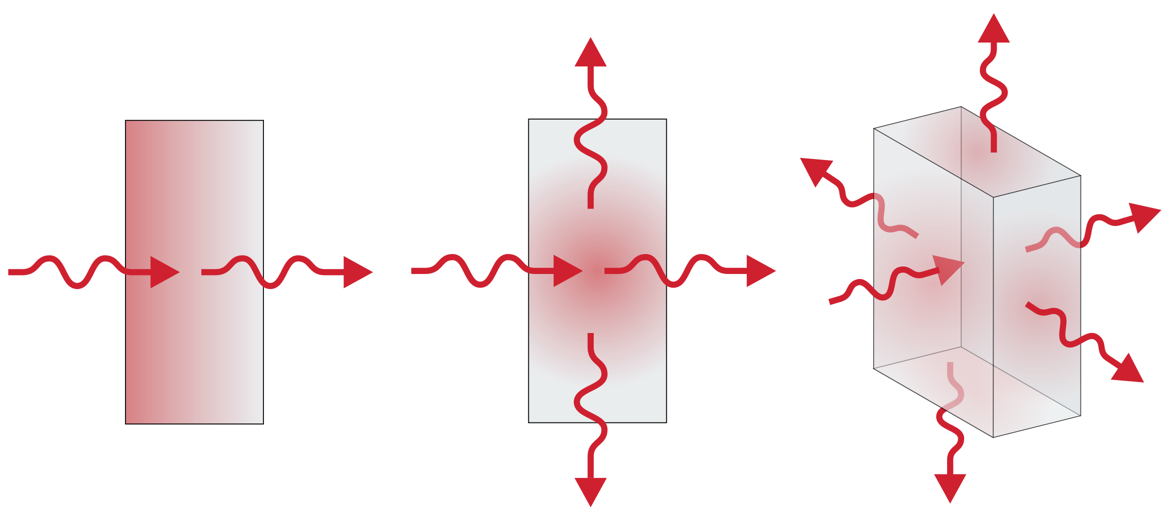
Radiation exchange is always occurring between buildings and their external environment. *Heat transfer by radiation is responsible for solar gains which cause discomfort when they are excessive. Radiative heat loss at night can cause inhabitants to feel a chill. Controlling radiative heat transfer is critical to maintaining thermal comfort in buildings.*

Objects at different temperatures will emit radiation of different wavelengths. The sun being very hot emits essentially short-wave radiation, whereas relatively cooler objects on earth tend to emit long wave infrared radiation. This distinction is important particularly as it relates to the use of low-emissivity coatings on glass to both retain heat energy in a building and reject it from warm outdoor surfaces radiating toward the building. Radiative heat loss is also associated with the discomfort sometimes experienced when sitting near cold surfaces, such as large single glazed windows in winter.

As noted earlier, all three mechanisms of heat transfer occur in real buildings. But these are not the only mechanisms of heat transfer. The latent heat of evaporation and condensation associated with phase changes in liquids and gases is not normally considered in the modeling of building assemblies for thermal performance, however latent heat transfer is considered in hygrothermal analysis to accurately assess the interactions between heat and moisture in constituent materials.

Heat Transfer Modeling

For the design of comfortable and energy efficient buildings, conduction, convection and radiation can now be accurately modeled. In the past, before the widespread availability of computing, simple methods of calculating heat transfer were employed by building designers, typically in the form of 1-dimensional heat flow models. Starting several decades ago, 2-dimensional analysis was applied to heat flow analysis through window frames and similar types of assemblies, but within the past decade or so, 3-dimensional finite element modeling of complete building assemblies such as walls, windows, and roofs is available to practitioners.



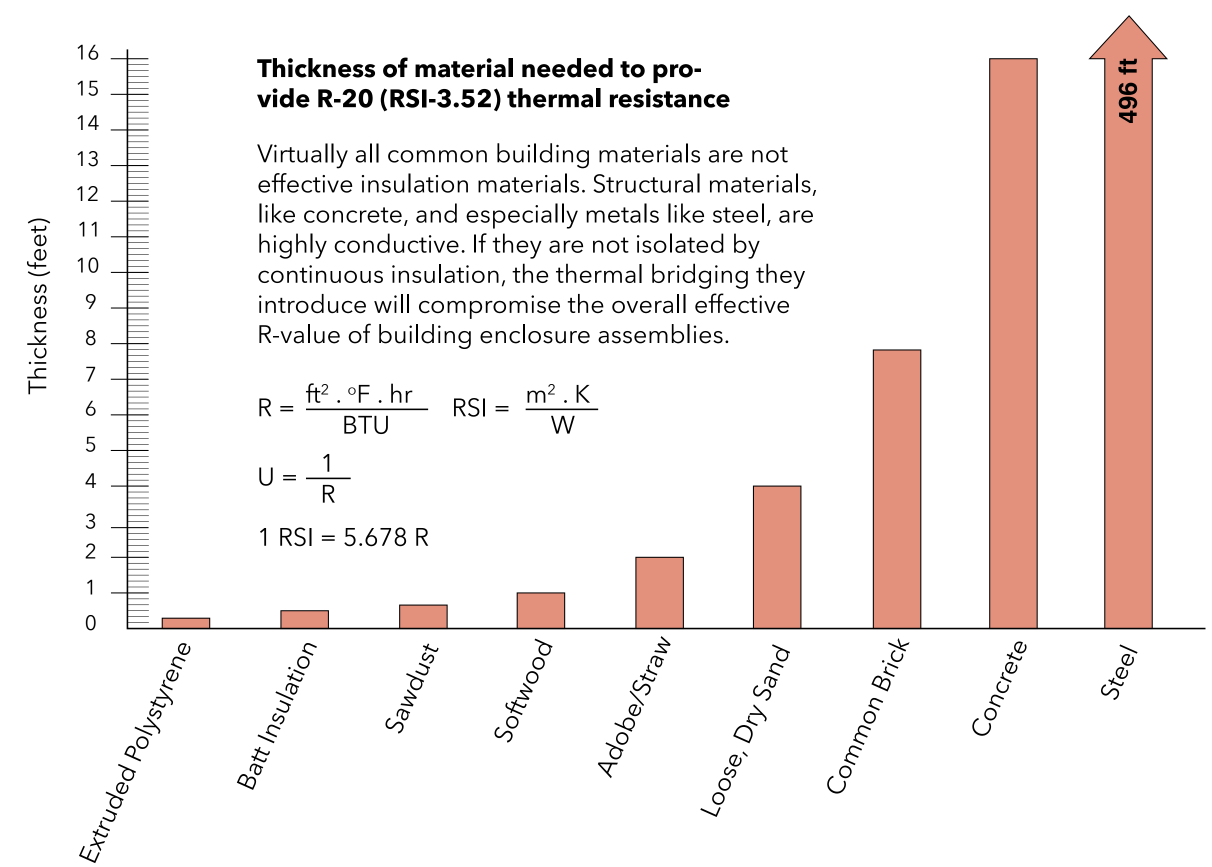
1-Dimensional Heat Flow
Heat is assumed to travel uni-directionally across the material or assembly.

2-Dimensional Heat Flow
Heat is assumed to flow in two orthogonal directions across the material or assembly.

3-Dimensional Heat Flow
Heat is assumed to flow in three orthogonal directions across the material or assembly.

Heat transfer models range from simple to complex. *The 3-dimensional modeling of heat flow is the only means of accurately determining the effective thermal resistance of building assemblies, by taking into account thermal bridging effects.*

As a result of more detailed 3-dimensional analyses of how heat moves through real buildings, the significance of thermal bridging across building assemblies is now widely recognized and techniques for minimizing the reduction in insulation effectiveness have been developed and continue to be refined. Traditional building assemblies may have been durable but they are not thermally efficient. The widespread use of steel studs and cladding attachments in exterior wall assemblies introduces a highly conductive material that causes thermal bridging. Avoiding assemblies that compromise the overall effective thermal resistance requires careful selection, arrangement and detailing of components.



Most building materials are poor insulators. *Insulation is orders of magnitude more thermally efficient than most common building materials, and should be intelligently employed in the design of high-performance building enclosures.*

Insulation Type	RSI-value m².K/W per 25 mm	R-value °F.ft².hour/BTU per inch
Cellulose	0.56 - 0.65	3.2 - 3.7
Fiberglass	0.44 - 0.65	2.5 - 3.7
Mineral Fiber Wool	0.63 - 0.70	3.3 - 4.0
Extruded Polystyrene	0.88 - 0.95	5.0 - 5.4
Expanded Polystyrene	0.63 - 0.77	3.6 - 4.4
Urethane Spray Foam, Low Density	0.63 - 0.70	3.6 - 4.0
Urethane Spray Foam, Medium Density	0.85 - 1.06	4.8 - 6.0
Phenolic	0.70 - 0.88	4.0 - 5.0
Polyisocyanurate	1.09 - 1.20	6.2 - 6.8

Typical range of thermal resistance values after aging for commonly available insulation materials

Insulation materials come in a wide variety of types and applications. *While the thermal efficiency of insulation is important, other characteristics such as combustibility, air permeability and whether the insulation material is hygroscopic or hydrophilic, should be taken into account to better inform design decisions.*

Cavity insulation is not as effective as continuous insulation. *Continuous insulation placed over a reinforced concrete structure is an effective means of achieving a highly durable and energy efficient building enclosure. To achieve the same effective thermal resistance in the wall areas with steel studs, more insulation and careful detailing will be required.*

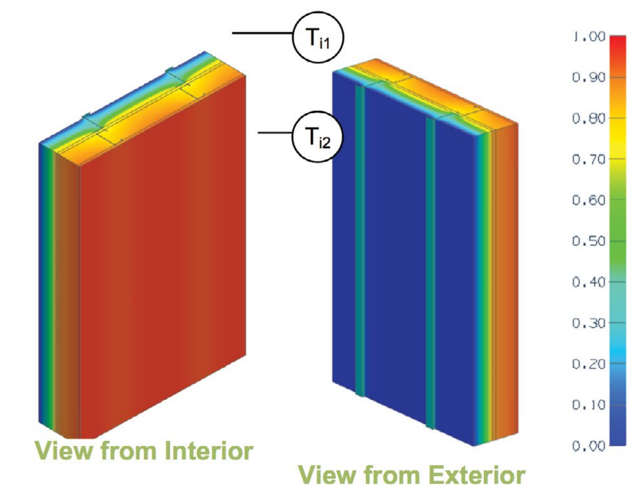
Insulation Effectiveness and Thermal Bridging

In the past, requirements for thermal insulation were often expressed as nominal R-values for various enclosure assemblies. For assemblies made with highly conductive materials, such as steel stud walls, field observations and infrared thermography indicated extensive thermal bridging. More recently, researchers have been able to model and quantify the impacts of thermal bridging on the overall thermal effectiveness of enclosure assemblies.

The results of this research have been published and disseminated and an example of 3-dimensional thermal analysis is shown in previous figure. As was widely suspected, the composition of enclosure assemblies and methods of cladding attachment result in thermal bridging that significantly compromises the insulation effectiveness.

Appendix B: Catalogue Thermal Data Sheets BUILDING ENVELOPE THERMAL BRIDGING GUIDE

Detail 5.1.3 **Exterior Insulated 3 5/8" x 1 5/8" Steel Stud (16" O.C.) Wall Assembly with Vertical Z-Girts (16" O.C.) Supporting Metal Cladding – Clear Wall**



Thermal Performance Indicators

Assembly 1D (Nominal) R-Value	R_{1D}	R-3.2 (0.56 RSI) + exterior insulation
Transmittance / Resistance	U_o, R_o	"clear wall" U- and R-value
Surface Temperature Index[1]	T_i	0 = exterior temperature 1 = interior temperature

[1]Surface temperatures are a result of steady-state conductive heat flow with constant heat transfer coefficients. Limitations are identified in final report.

Nominal (1D) vs. Assembly Performance Indicators

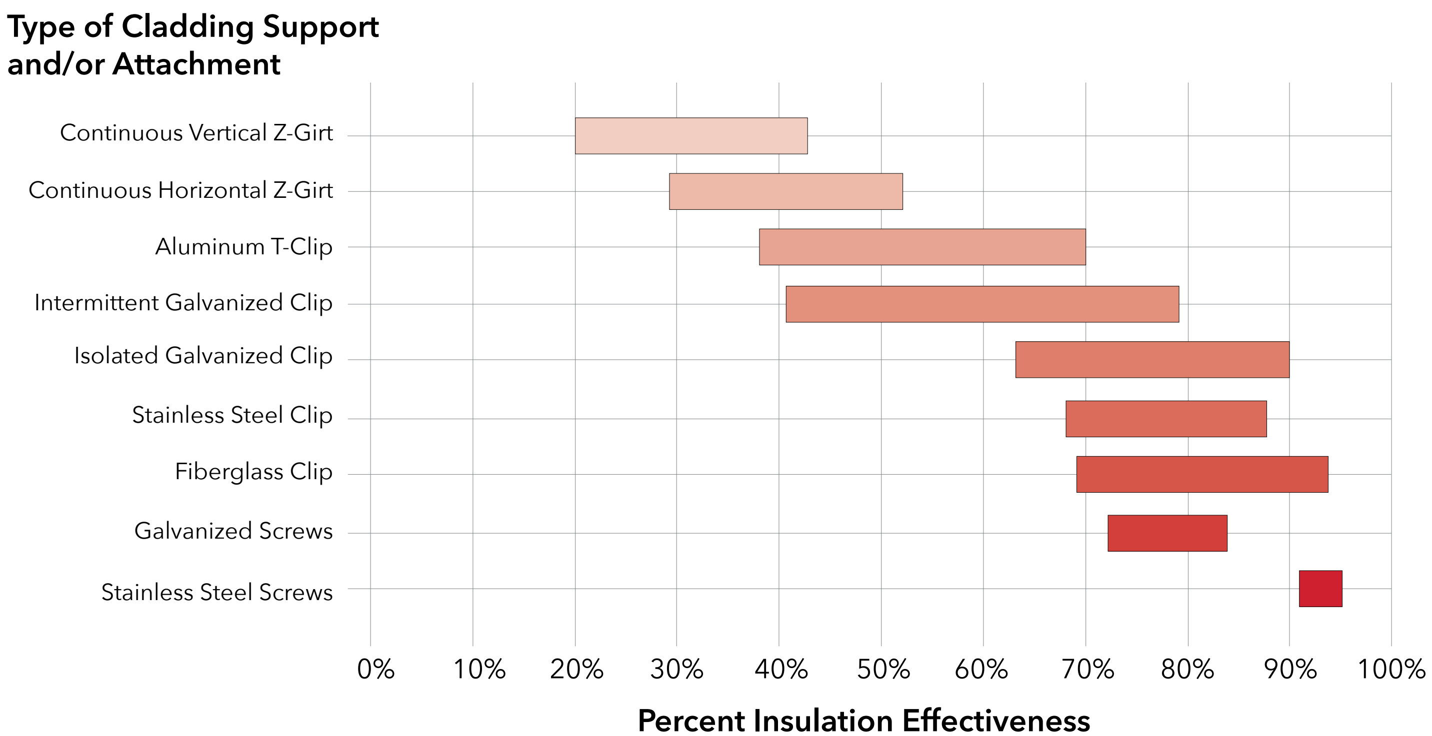
Exterior Insulation 1D R-Value (RSI)	R_{1D} ft²·hr·°F / Btu (m² K / W)	R_o ft²·hr·°F / Btu (m² K / W)	U_o Btu/ft² ·hr ·°F (W/m² K)
R-5 (0.88)	R-8.2 (1.44)	R-6.4 (1.12)	0.157 (0.89)
R-10 (1.76)	R-13.2 (2.32)	R-8.3 (1.47)	0.120 (0.68)
R-15 (2.64)	R-18.2 (3.20)	R-9.7 (1.71)	0.103 (0.59)
R-20 (3.52)	R-23.2 (4.08)	R-11.0 (1.93)	0.091 (0.52)
R-25 (4.40)	R-28.2 (4.96)	R-12.0 (2.11)	0.084 (0.48)

Thermal Efficiency
$= R_{effective}/R_{nominal}$
= 12.0/25
= 48% effectiveness of exterior insulation

Temperature Indices

	R5	R10	R15	R20	R25	
T_{i1}	0.63	0.70	0.72	0.75	0.76	Min T on sheathing, along girts at stud intersection
T_{i2}	0.72	0.80	0.84	0.86	0.87	Max T on sheathing, centre of stud cavity

Thermal bridging reduces insulation effectiveness. *Recent research has catalogued the performance of typical enclosure assemblies and indicates that many conventional assemblies are thermally inefficient and provide unacceptable levels of insulation effectiveness due to thermal bridging. [Source: Building Envelope Thermal Bridging Guide, Version 1.1, April 2016. Morrison Hershfield Ltd., Vancouver BC. https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/builders-developers/building-envelope-thermal-bridging-guide-1.1.pdf)*



Cladding attachment can compromise insulation effectiveness. *Percent effectiveness of exterior insulation with various cladding support systems and typical thicknesses of exterior insulation (2″ to 8″ ranging from R-8 to R-40). [Source: Cladding Attachment Solutions for Exterior Insulated Commercial Walls. Graham Finch and James Higgins, RDH Technical Bulletin No. 011, December 2015.]*

Based on the previous figure for cladding supports and/or attachments, the range of effectiveness values for the various methods of cladding support and/or attachment result from different substrates, spacings and sheet metals. It is apparent that traditional techniques, such as Z-girts, can at best achieve about 50% exterior insulation effectiveness, essentially requiring double the thickness of exterior insulation to achieve an effective thermal resistance that approaches the nominal value. It should be noted that the ranges of percent insulation effectiveness capture different spacing for attachment members. Heavier cladding or cladding on tall buildings with high wind loads will have girts, clips or screws closer together – this will result in performance at the lower end of the percent insulation effectiveness range.

High-performance buildings require high-performance enclosures that manage heat flows effectively. The proper selection, arrangement, detailing, and integration of enclosure components and assemblies to maintain the continuity of thermal insulation and the air barrier system are no longer best practices but standard practices needed to comply with codes and standards. A number of guides for incorporating these best practices are now available and a wide range of products exist to enable the design and construction of high-performance enclosures. Refer to sources of information provided at the end of this guide.

Air Barriers

Uncontrolled air leakage due to infiltration and exfiltration of air in buildings can have serious consequences because the infiltrating air is untreated and may entrain pollutants, allergens and bacteria - contaminants that compromise indoor air quality in buildings. The influence of air leakage on air pressures can interfere with the proper operation of HVAC systems leading to discomfort and high energy consumption for space heating and cooling. Further, infiltration and exfiltration through the building enclosure can lead to condensation of moisture from the exfiltrating air in cold climates, and from infiltrating warm, humid air in hot climates, causing mold growth, decay, and corrosion leading to health and durability problems. For these reasons, it is imperative to provide a continuous, durable and structurally supported air barrier system, especially in highly insulated buildings where the potential for moisture damage is increased due to large temperature differences across and within the building enclosure.

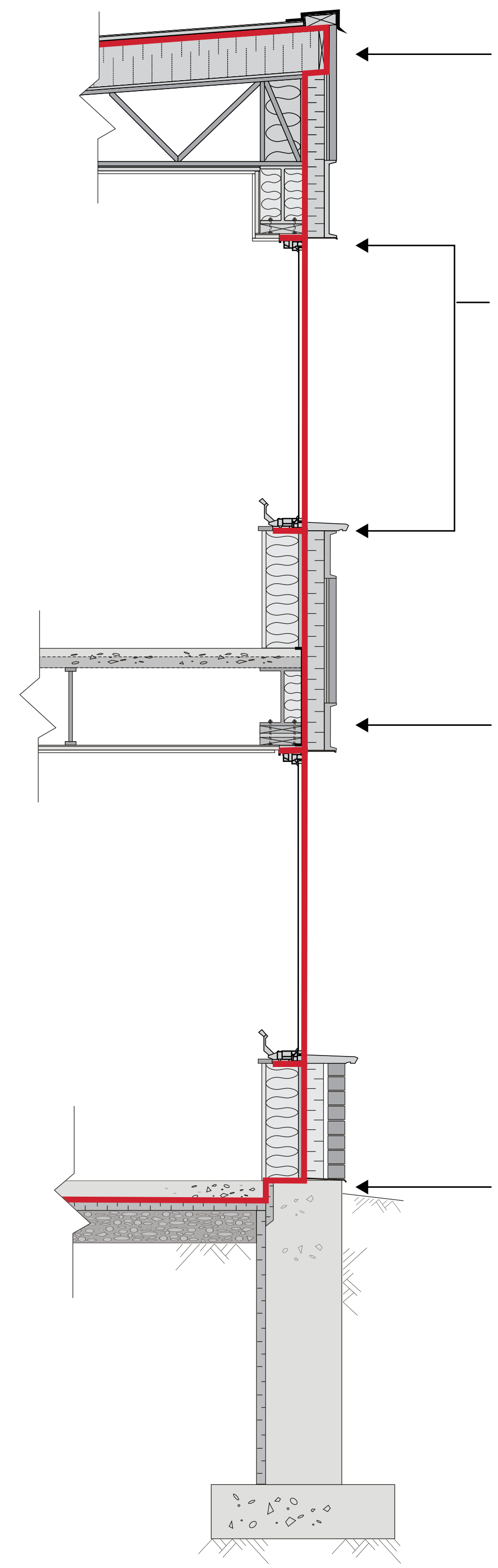
Air Barrier System Critical Requirements

Continuity
Every component of the air barrier system must be interconnected at all joints between materials, and all transitions between components, assemblies, and systems, including all penetrations.

Structural Integrity
Every component of the air barrier system must resist forces exerted by wind, stack effect, and HVAC fan pressures without rupture, displacement or excessive deflection. Ensure adequate resistance to these pressures by membranes, fasteners, tapes, adhesives, sealants, etc.

Air Impermeability
Materials, assemblies and then the entire building enclosure must comply with applicable performance criteria for airtightness. Field testing by fan depressurization is the only means of confirming and assemblies have been properly integrated to form an effective air barrier system.

Durability
Materials and assemblies selected for the air barrier system must perform their function for the expected life of the building-as-a-system. Alternatively, the air barrier must be accessible for periodic maintenance (e.g., recoating, caulking, etc.) or ease of replacement.



Roof to Wall Transition
- Ensure material compatibility of roofing and wall air barrier membranes
- Fastening / adhesion at transition to provide adequate resistance to wind forces
- Coordination among trades to designate party responsible for trying together the transition

Window to Wall Transition
- Selection of appropriate air barrier transition materials and their arrangement to withstand wind pressures and building movements
- Detailing of window placement to accommodate subsequent installation of air barrier transition by other trade(s)
- Material compatibility between window frames, membranes and sealants
- Account for maintenance of air barrier system integrity in the event of window replacements (e.g., extreme weather damage)
- Integration of air barrier with moisture management measures around all window assembly openings

Floor to Wall Transition
- Selection of appropriate air barrier transition strategy to minimize delays in construction sequence and complex coordination among trades
- Attention to thermal insulation strategy to ensure practicality of insulation placement without compromising air barrier performance and vice-versa
- Material compatibility between substrates, membranes and sealants
- Integration of air barrier with moisture management measures such as drainage planes, flashings and pressure-equalization compartments in facade assembly

Foundation and Slab to Wall Transition
- Formulation of air barrier strategy that is practical in terms of sequencing to allow for interconnection at transitions by durable materials that can withstand abuse during construction
- Selection of a forgiving system where the control of soil gas by sub-slab depressurization is required
- Selection of appropriate air barrier transition materials to withstand settlement and building movements
- Coordination among trades to designate party responsible for tying together the transition

Air barrier systems are key to resilient, high performance buildings. *Failure to address air barrier system critical requirements often leads to buildings that fail to achieve comfort, durability and energy efficiency expectations.*

Air barrier systems are comprised of materials such as air barrier membranes and building envelope assemblies that must all be completely sealed at transitions and penetrations to achieve an acceptable level of airtightness for the entire building. A material is considered to perform adequately as an air barrier if its air permeance is no greater than 0.02 L/s.m^2 @ 75 Pa (0.004 cfm/ft^2 @ 1.57 psf) as measured using ASTM E 2178-13 Standard Test Method for Air Permeance of Materials. The maximum air leakage for building assemblies is limited to 0.2 L/s.m^2 @ 75 Pa (0.04 cfm/ft^2 @ 1.57 psf) as measured using ASTM E 2357-17 Standard Test Method for Determining Air Leakage of Air barrier Assemblies. Finally, after combining all of these materials and assemblies into a complete building enclosure, the maximum air leakage allowed is 2 L/s.m^2 @ 75 Pa (0.4 cfm/ft^2 @ 1.57 psf) when tested according to ASTM E779-10 (2018) Standard Test Method for Determining Air Leakage Rate by Fan Depressurization.

Application	Metric	U.S.	Test Method
Material	0.02 L/s.m^2 @ 75 Pa	0.004 cfm/ft^2 @ 1.57 psf	ASTM E 2178-13 Standard Test Method for Air Permeance of Materials
Assembly	0.2 L/s.m^2 @ 75 Pa	0.04 cfm/ft^2 @ 1.57 psf	ASTM E 2357-17 Standard Test Method for Determining Air Leakage of Air Barrier Assemblies
Whole Building	2 L/s.m^2 @ 75 Pa	0.4 cfm/ft^2 @ 1.57 psf	ASTM E779-10 (2018) Standard Test Method for Determining Air Leakage Rate by Fan Depressurization

Air barrier performance criteria for materials, assemblies, and whole building enclosure. *It is important to appreciate these are minimum requirements and that airtightness will gradually diminish over the building life cycle.*

It is important to recognize that while materials and assemblies can be tested and certified in laboratories as providing acceptable levels of airtightness, the only means of confirming an adequate air barrier system is through field testing by the fan depressurization method. Increasingly, building envelope commissioning is being elected by owners and their architects to engage an integrated process that begins at the early stages of design and includes peer review of critical details, field reviews of installation and assembly of the air barrier system and air leakage testing to confirm acceptable air barrier system performance.

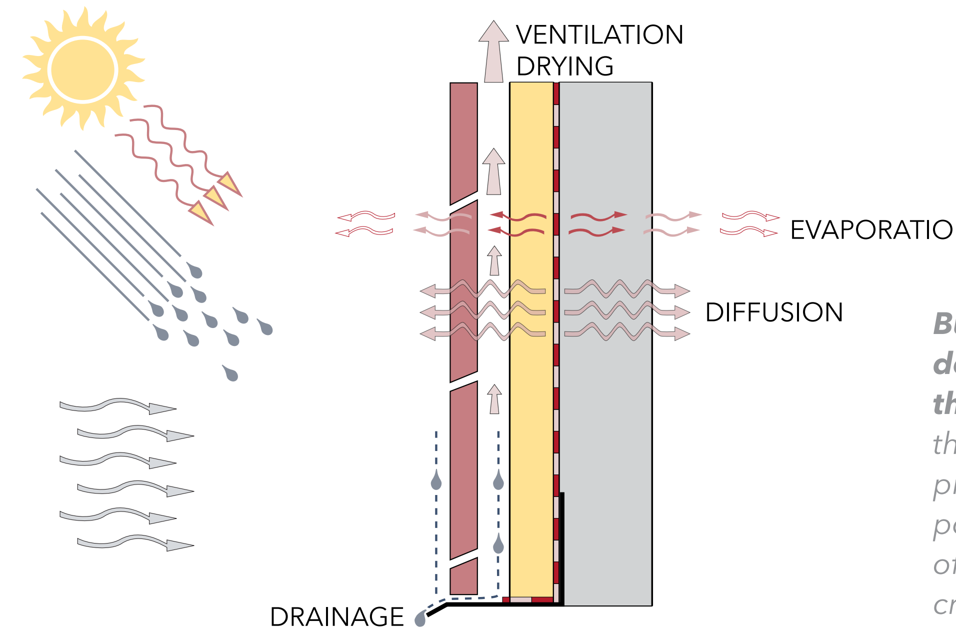
Fan depressurization testing of a commercial building air barrier system is an essential part of building envelope commissioning. *By observing best practices for building envelope commissioning, it is possible to avoid discovering unsatisfactory performance after it cannot be easily remediated.*

Two important points that should be considered when designing and specifying the air barrier system. First, a large number of materials are typically combined to achieve a continuous air barrier system and while an air barrier material, in the form of a sheet or liquid-applied membrane or mastic, may be the primary contributor to airtightness, attention to transitions and penetrations is a critical responsibility. Second, not all air barrier materials have the same properties, particularly in terms of their vapor permeability.

Class	Permanence (US Perms)	Metric Perms	Vapor Permeability
I	Less than 0.1	Less than 6	Impermeable
II	0.1 to 1.0	6 - 60	Semi-Impermeable
III	1.0 to 10	60 - 600	Semi-Permeable
none	Over 10	Over 600	Permeable

Vapour control layer classification based on dry cup (Method A) of ASTM E96 Standard Test Methods for Water Vapor Transmission of Materials

Air barriers can also be vapour barriers. *Hygrothermal modeling may be engaged to determine if a vapour permeable air barrier is needed to manage wetting and drying potentials, especially in building envelope assemblies with a combination of cavity and exterior thermal insulation placement. A wide range of products exist that are multifunctional with respect to critical control functions for air, vapour and bulk water management.*



Building enclosures should be designed to dry out easier than they get wet. *This is often easier said than done in climate zones with high precipitation exposure and low drying potentials. The vapor permeability of air barriers is among the many critical factors affecting hygrothermal performance.*

Air barriers can also have the properties of a vapour barrier or retarder and it is important to have a qualified building science professional assess the hygrothermal performance of the various building enclosure assembles for walls and roofs to determine the class of vapour control layer that is needed to ensure adequate drying potential of the assemblies to avoid moisture problems.

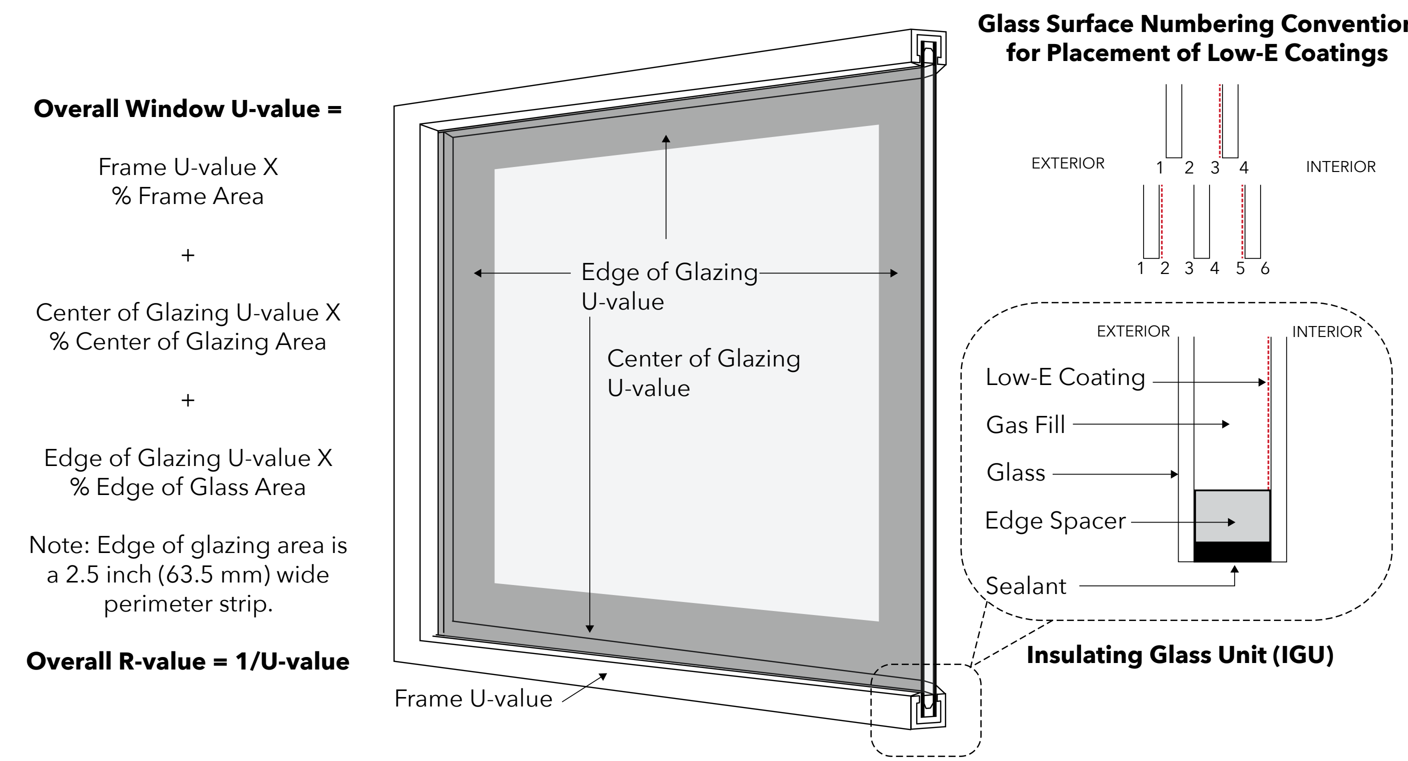
Thermal resilience requires much higher effective thermal resistance levels beyond code minimum values for building enclosure components, and this often significantly reduces their drying potential. Air barrier materials that also serve as water resistive barriers should be carefully assessed to ensure that the drying potential they afford building envelope components exceed the wetting potential associated with the climate zone, precipitation exposure and indoor climate class of the proposed building design.

In summary, thermal control for opaque enclosure components and assemblies intended to deliver satisfactory thermal resilience requires high levels of thermal insulation that are not compromised by thermal bridging, combined with a continuous air barrier system to manage air uncontrolled air leakage and pressure differences across the building envelope. And these must be properly integrated with the fenestration components to achieve an overall effective building enclosure thermal resistance rating.

Fenestration and Window-to-Wall Ratio

Fenestration plays a key passive role in thermal resilience because it is a practical means by which to provide effective natural ventilation while affording passive solar gains and daylight during extended power outages. In order to achieve acceptable levels of thermal resilience it is important to recognize the different fenestration strategies for cold weather and hot weather thermal resilience. These are presented within this section of the guide, but first it is necessary to understand window performance characteristics.

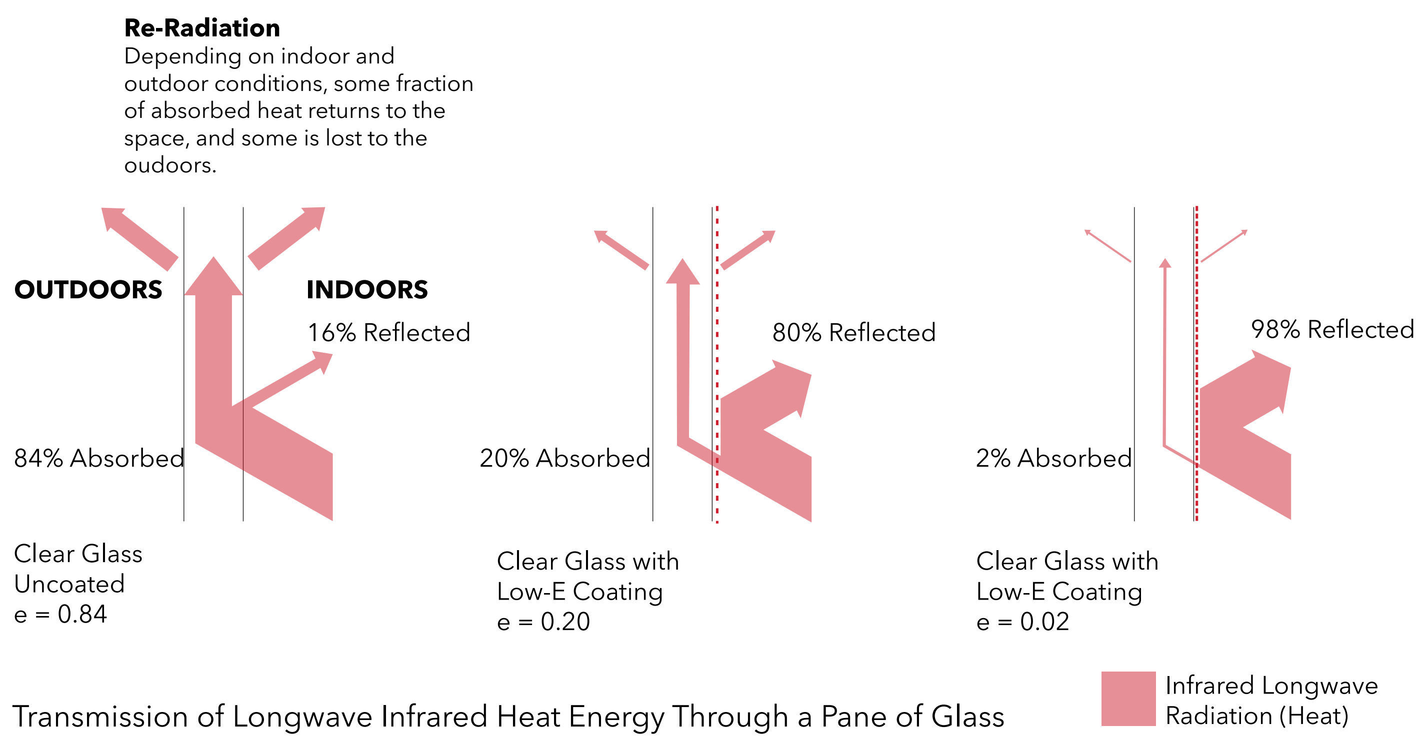
Windows transfer heat energy by conduction, convection and radiation. Convection, in the form of air leakage across the window assembly, is managed by selecting windows with high levels of airtightness. Contemporary windows are relatively airtight assemblies based on current standards, however it is critical to address the continuity of the air barrier around window openings, as discussed in the previous section on air barriers. Conduction through windows is a function of their overall effective U-value which accounts for heat transfer through the window frame, the edge of glazing region of the window, and the center of glazing area. Features including inert gas fills, such as argon and krypton, low conductivity edge seals and low emissivity (low-E) coatings, as well as thermally broken and/or insulated frames all contribute to making for a high-performance window assembly.



Innovations in window technology are capable of delivering high performance. *Today's windows are capable of delivering energy efficiency, comfort and condensation control, but specifying appropriate features is more challenging due to the wide array of choices - designers need to work with their energy modelers to optimize fenestration performance within the building-as-a-system.*

A significant innovation in glazing technology is low-e coatings that are designed to reflect longwave infrared radiation (radiant heat energy) that is emitted from interior surfaces and objects. This heat reflecting feature acts in both directions, whether the longwave radiation comes from outdoor or indoor sources.

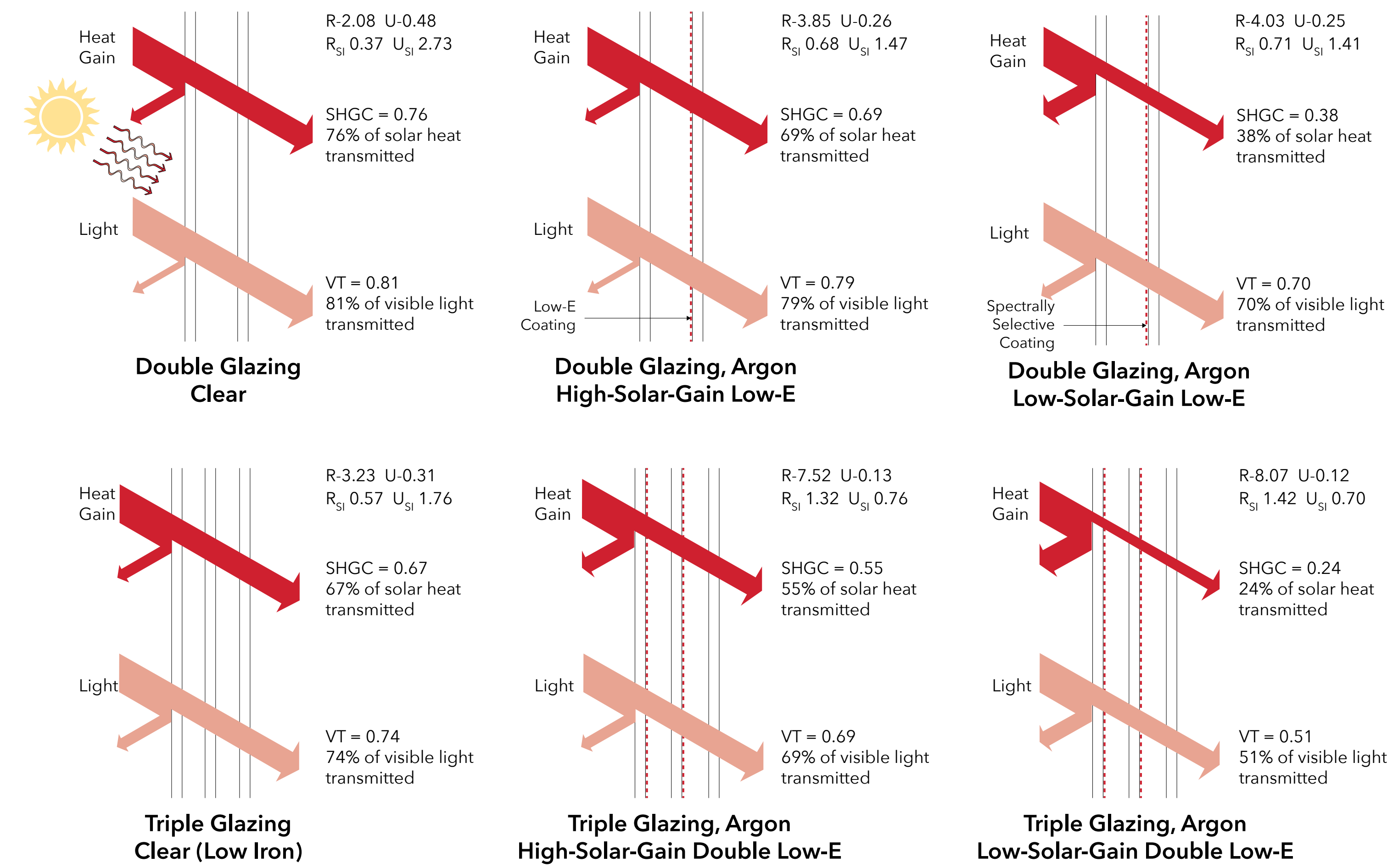
The effectiveness of the heat reflecting property of the coating is expressed with a term called emissivity, which represents the proportion of incident longwave radiation (heat) that is not reflected, but instead transmitted through the coating. The greater the heat reflectivity of the coating, the less longwave is transmitted through it, and the lower its emissivity.



Transmission of Longwave Infrared Heat Energy Through a Pane of Glass

Low emissivity coating enhances glazing energy efficiency. *They are also engineered to potentially control both shortwave radiation (solar heat gains) and longwave radiation (infrared heat energy from warm objects and surfaces.*

Low-E coatings are deployed in insulated glass units to improve their energy efficiency while selectively controlling solar gains. This is a significant innovation because thermal resilience is greatly enhanced with glazing that contains heat loss from inside the building during cold weather, and also rejecting solar heat gains during hot weather.



Low-E coatings can be strategically selected to provide enhanced thermal resilience. *The visible transmittance of daylight is variably affected by low-E coatings depending on the type of coating selected and energy modeling is recommended to optimize the thermal and daylighting performance of fenestration systems.*

Looking at the table of typical window technologies available today, it is evident that a large number of high-performance alternatives to clear double glazing provide significant thermal control benefits. It is now possible to reduce winter heat loss, reject summer heat gains while not compromising daylighting potential.

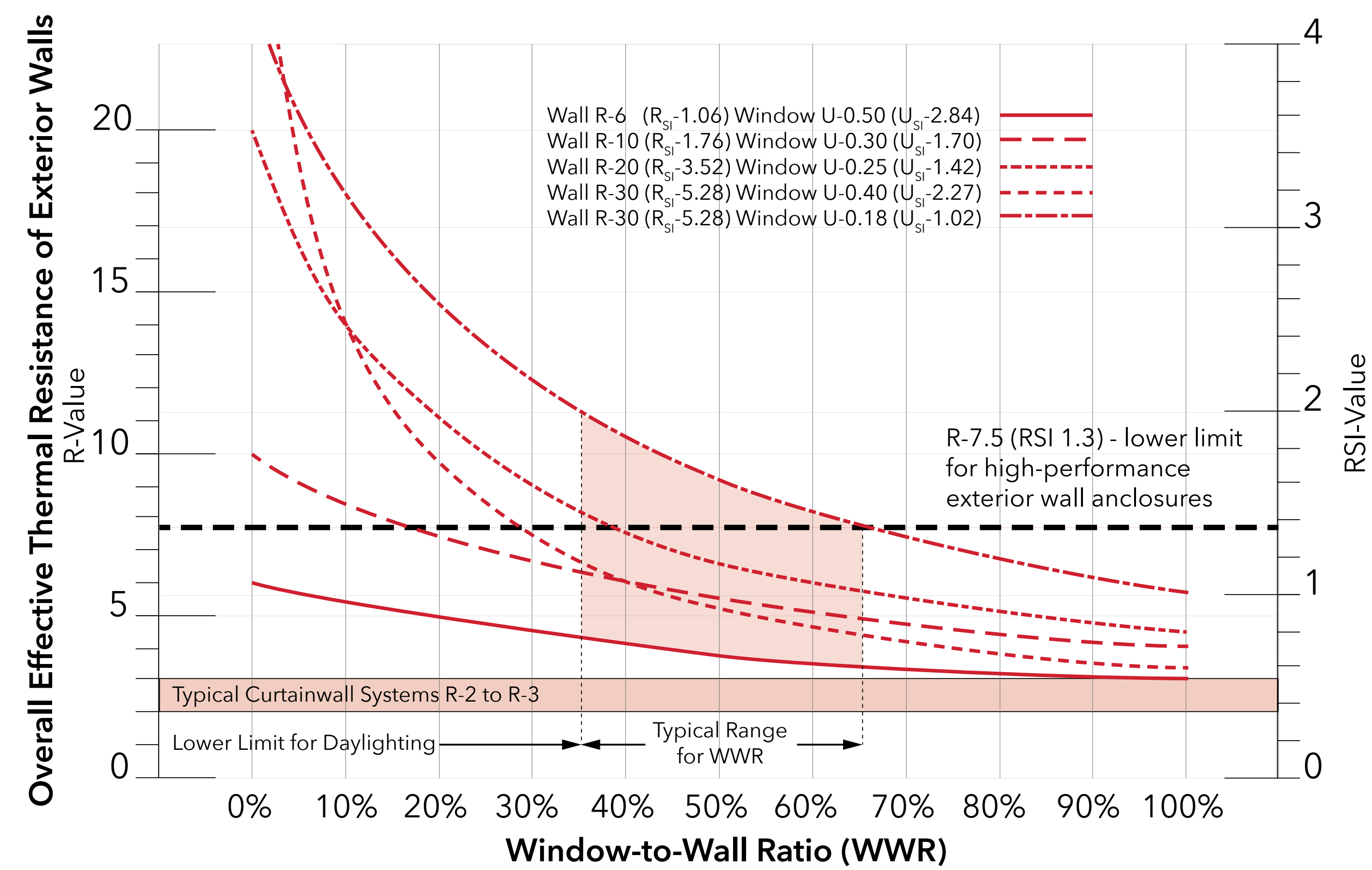
Window Type	U-Value (BTU/hr.ft².°F)	R-Value (hr.ft².°F/BTU)	U_{SI} (W/m².K)	R_{SI} (m².K/W)	SHGC	VT
Double Glazed, Aluminum Frame (Thermally Broken) Argon, Warm Edge Spacer, Clear	0.58	1.73	3.29	0.30	0.76	0.81
Double Glazed, Aluminum Frame (Thermally Broken) Argon, Warm Edge Spacer, High Solar Gain Low-E	0.47	2.13	2.67	0.37	0.69	0.29
Double Glazed, Insulated Fiberglass Frame Argon, Warm Edge Spacer, Low Solar Gain Low-E	0.31	3.23	1.76	0.57	0.38	0.70
Triple Glazed, Aluminum Frame (Thermally Broken) Argon, Warm Edge Spacer, Clear (Low Iron)	0.32	3.12	1.82	0.55	0.67	0.74
Triple Glazed, Insulated Fiberglass Frame Argon, Warm Edge Spacer, 1 High Solar Gain Low-E Coating	0.22	4.54	1.25	0.80	0.55	0.69
Triple Glazed, Insulated Fiberglass Frame Argon, Warm Edge Spacer, 2 Low Solar Gain Low-E Coating	0.18	5.57	1.02	0.98	0.24	0.51

Advances in window technology have produced products that provide net energy gains on an annual basis for certain solar orientations and climate zones. *Unlike only several decades ago, designers can tune building energy performance with the intelligent selection of window technologies.*

Beyond the window technologies themselves, another critical consideration in the design of building facades is the window-to-wall ratio (WWR) because it influences the overall effective thermal resistance of the exterior wall enclosure. Too little glazing will reduce opportunities for daylighting and views, and too much glazing makes it difficult to achieve high-performance in terms of comfort, energy efficiency and resilience. The figure to the right indicates the resulting overall effective thermal resistance of wall enclosures for various combinations of opaque wall R-values and window/glazing U-values. Note that in all cases, the R-values and U-values are effective values that account for thermal bridging, transitions and edge effects, as discussed in the previous section.

Important Terminology Note: The term "exterior wall enclosure" refers to the total exterior wall area including all opaque assemblies, windows and glazing.

Exterior Wall Enclosure Area = Opaque Walls Area + Windows/Glazing Area
Window-to-Wall Ratio (WWR) = Windows/Glazing Area / Exterior Wall Enclosure Area

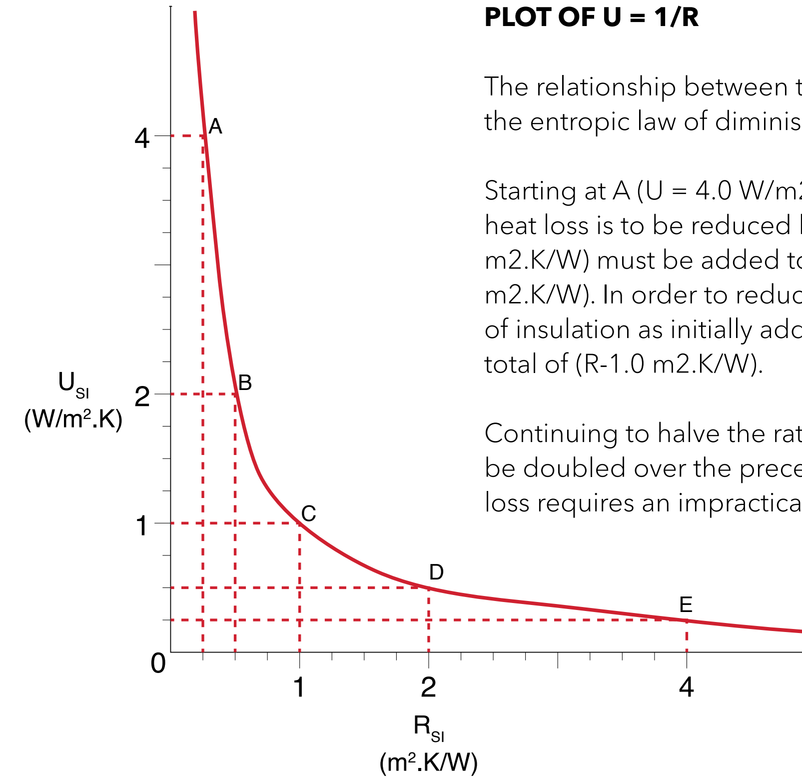


The window-to-wall ratio is a critical building enclosure design parameter.
The influence of window-to-wall ratio on wall enclosure overall effective R-value for various combinations of opaque walls and windows reveals that highly glazed buildings can never be thermally resilient.

There are several observations worth noting about the relationship between window-to-wall ratio and the overall effective thermal resistance of exterior walls:

- Fully glazed building facades using conventional curtainwalls and window walls are too inefficient to achieve acceptable thermal resilience.
- For anything higher than a 10% WWR, an R-20 opaque wall with U-0.25 windows outperforms an R-30 opaque wall with U-0.40 windows. The practical upper limit of thermal efficiency for wall enclosures is mostly determined by the thermal efficiency of the windows.
- For anything higher than a 40% WWR, an R-10 opaque wall with U-0.30 windows outperforms an R-30 opaque wall with U-0.40 windows. For typical ranges of WWR ratios in buildings, investments in more efficient windows deliver higher performance than investments in more efficient opaque walls.
- To achieve high-performance exterior walls over typical ranges of WWR, opaque walls should have a minimum effective thermal resistance value of R-25 and windows should have an effective U-value no greater than U-0.25.
- The lower limit of R-7.5 for exterior wall enclosures applies to hot and cold climate zones and takes into account comfort, energy efficiency, thermal resilience and the ability of low temperature / low intensity heating and cooling technologies to be effectively deployed.

The physics behind the lower limit of approximately R-7.5 for the overall effective thermal resistance of high-performance exterior wall enclosures is best appreciated by examining the relationship between U-values and R-values by plotting U = 1/R-value.



PLOT OF U = 1/R

The relationship between thermal resistance and thermal conductance reveals the entropic law of diminishing returns.

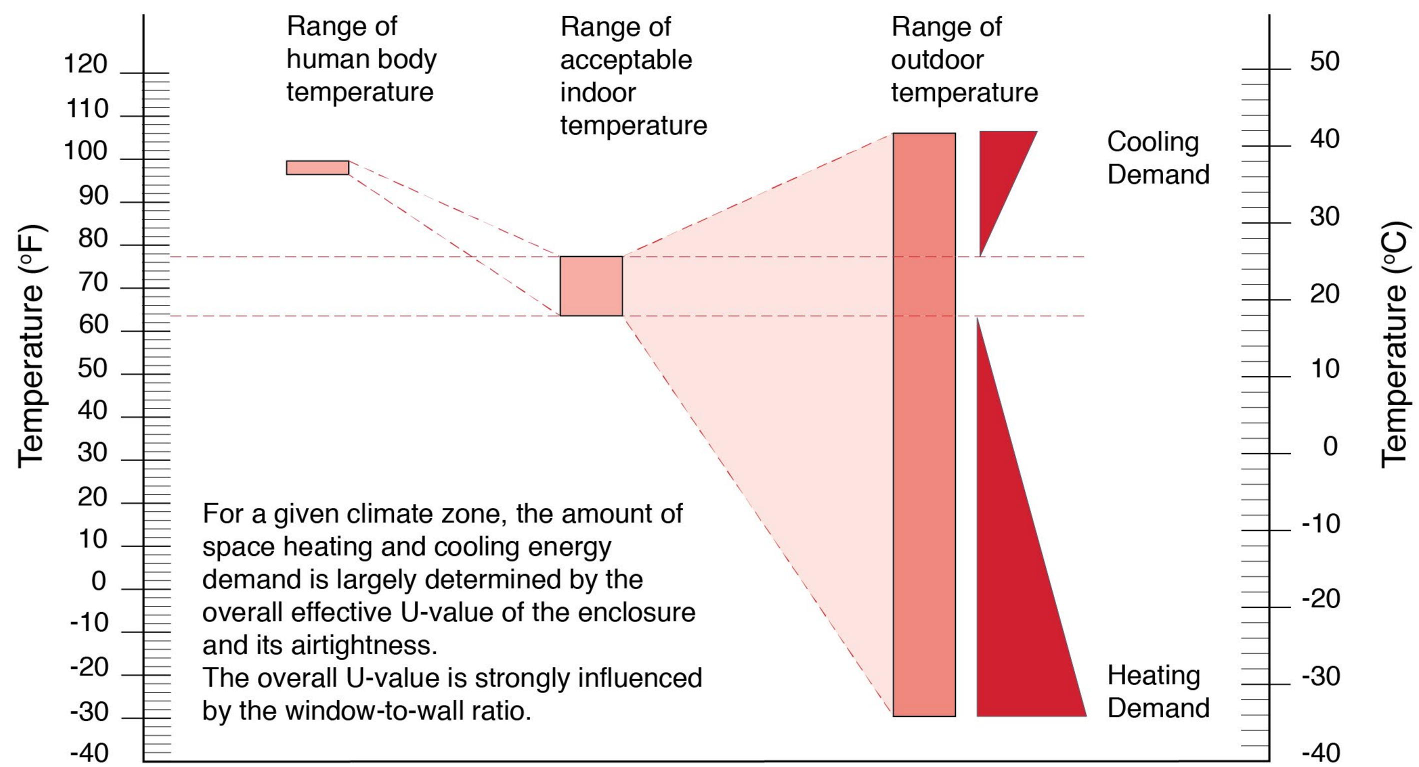
Starting at A (U = 4.0 W/m2.K, hence R = 1/U = 0.25 m2.K/W), if the rate of heat loss is to be reduced by half, a quantity of insulation equal to AB (R-0.25 m2.K/W) must be added to the existing (R-0.25 m2.K/W) for a total of (R-0.5 m2.K/W). In order to reduce the rate of heat loss by half again, twice the amount of insulation as initially added, BC (R-0.5 m2.K/W), must again be added for a total of (R-1.0 m2.K/W).

Continuing to halve the rate of heat loss requires that the amount of insulation be doubled over the preceding quantity. At some point, further reducing heat loss requires an impractical and/or uneconomical quantity of thermal insulation.

The optimal overall effective R-value of the entire building enclosure is more important than the amount of insulation provided in specific components, such as walls or roofs.
In most colder climate zones, the high-performance threshold for the overall effective R-value of exterior wall enclosures is the same as for the entire building enclosure, at around R-7.5 (RSI-1.32). This means that walls, roofs and exposed floors will have to be insulated to levels much higher than this overall threshold to compensate for the lower R-values associated with windows. Beyond this level, the benefits are marginal (diminishing returns) and it is usually more cost-effective to improve the energy efficiency of other aspects of the building-as-a-system.

In general, high-performance buildings are more easily achieved when the WWR is maintained between 40% to 50% and it is generally acknowledged that going beyond 65% results in what is termed a high-cholesterol building that is overly dependent on active systems rather than relying on the highly dependable passive performance provided by the enclosure.

Building enclosures moderate between the exterior environment and the narrow range of human body and thermal comfort temperatures. Active systems can only supplement the amount of heating, cooling, and ventilation that is needed – they cannot fulfill the role of passive systems because they cannot actually moderate the heating and cooling demands.



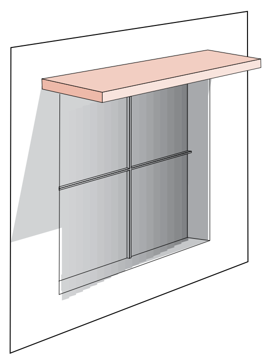
Efficient building enclosures are key to thermal resilience. *It is now recognized that the passive performance of the enclosure is what most cost-effectively delivers energy savings and thermal comfort in buildings because it moderates heating and cooling energy demands.*

Thermal control, fenestration and window-to-wall ratio are critical passive design strategies for cold weather thermal resilience. Managing heat flows through conduction, convection and radiation is key to maintaining passive habitability during extended periods of cold weather coinciding with prolonged power outages. While cold weather thermal resilience helps protect buildings against frost damage and freezing water pipes, the evidence indicates human health, in particular morbidity and fatality, are much more significantly impacted by exposure to extended heat waves.

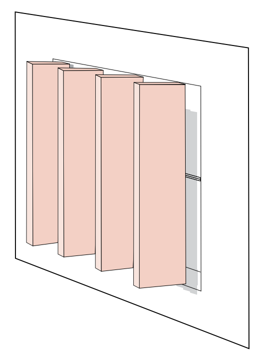
This guide now turns to consideration of passive measures that are primarily intended to address hot weather thermal resilience - shading devices and natural ventilation. It is not being suggested that these measures provide no benefits during cold weather periods, but in terms of hot weather thermal resilience, shading devices are critical in controlling excessive solar gains, while natural ventilation can remove heat build up and provide night cooling benefits.

Shading Devices

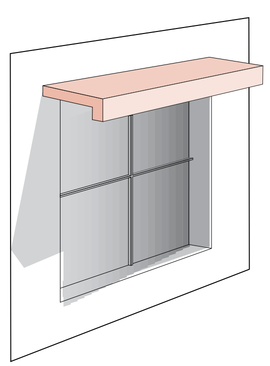
Managing solar gains is advantageous for both enhanced thermal autonomy and passive habitability. While it is not normally part of a thermal resilience design strategy, daylighting through properly sized and arranged fenestration should also be a significant design consideration since it improves overall resilience during extended power outages by rendering a better illuminated indoor space, while contributing to occupant health and well-being under normal operating conditions.



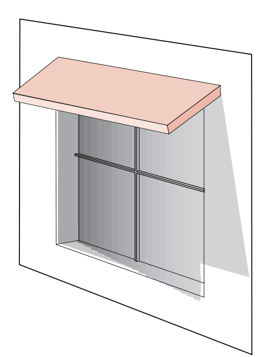
Standard horizontal overhang.



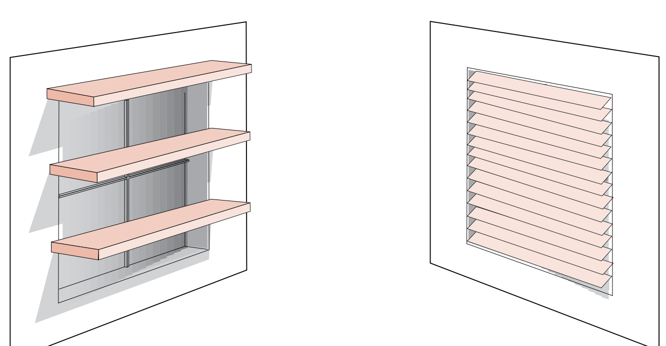
Vertical louvers or fins for east and especially west facades.



Drop the edge for less projection.



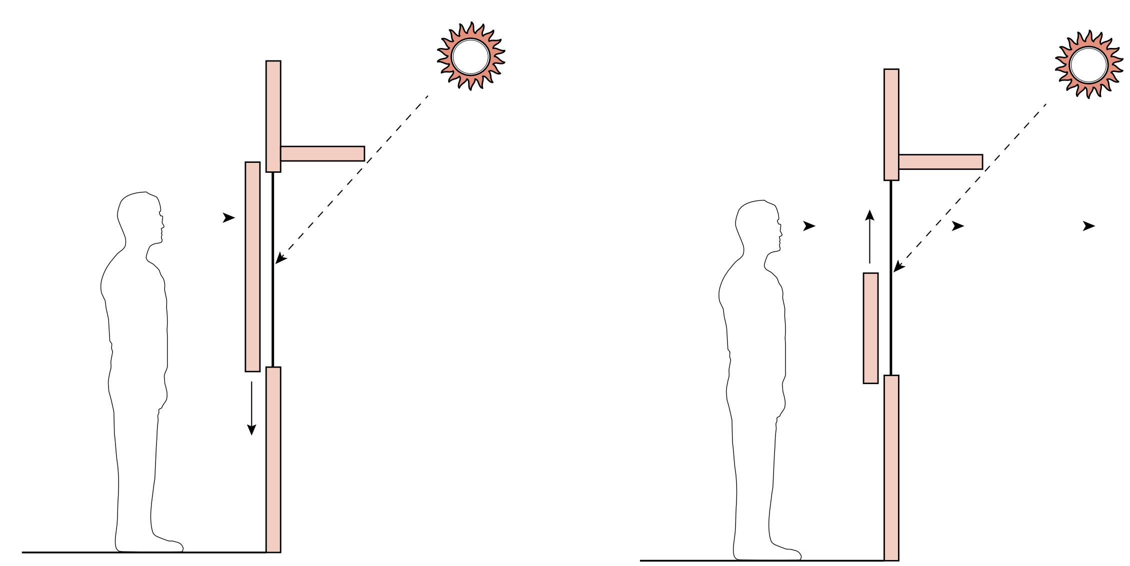
Slope it down for less projection.



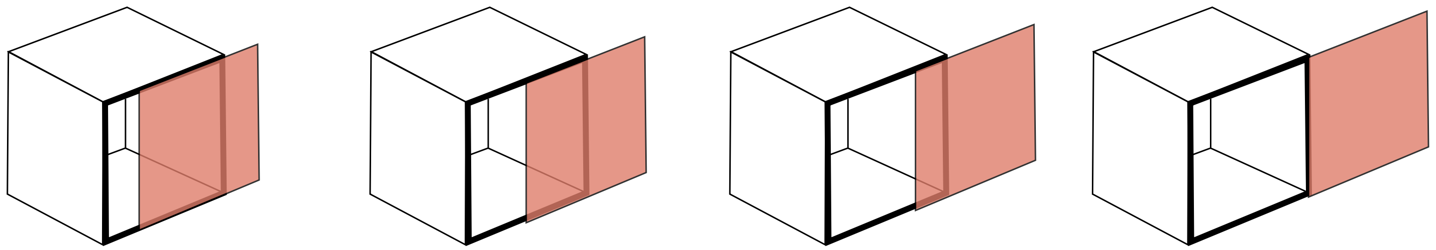
Break up an overhang for less projection.

External shading devices are more effective than internal shading devices. *External shading devices are largely absent from most contemporary buildings except for those having cantilevered balcony projections. Typically, the arrangement and projection of balconies are not optimized for shading and at times they can significantly reduce passive solar gains in winter, thereby reducing thermal autonomy and passive habitability. Properly selected and configured, external shading devices have the advantage of being able to intercept the direct solar gains before they enter the building, unlike internal shading devices that admit a fraction of the incident solar energy.*

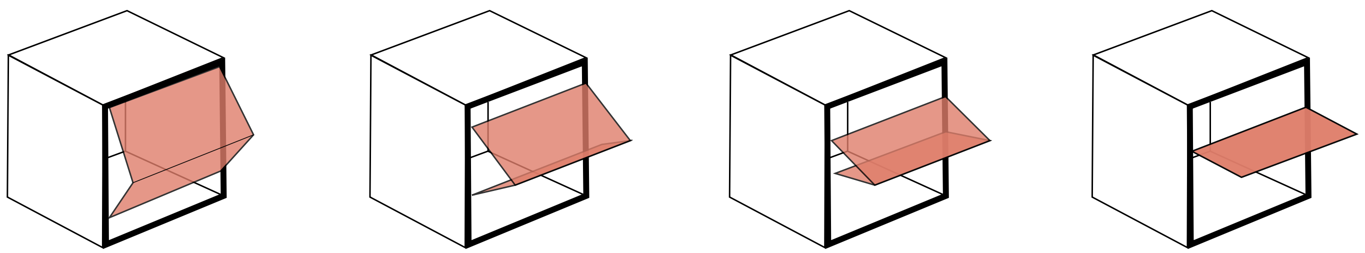
External and internal shading devices may be fixed or operable, and operable devices may be manual and/or motorized and automatic. All manner of products for managing solar radiation are now available to designers and issues related to durability and cold/freezing weather reliability have been largely resolved. Other issues which have emerged are related to effective control algorithms for automatic shading devices, and protocols for manual operation and override of automatic systems. In the case of hotel suites or multi-unit residential apartments, as long as each suite or apartment has control over the operation and adjustment of shading devices, there is no need for a protocol. But in offices, commercial and institutional buildings, protocols are needed to determine who is permitted to operate the shading devices, and how many occupants and their occupied floor area that are resultingly affected. It is not always possible, practical or desirable to assign each occupant with one window and its own shading device(s). The factors related to the control of shading devices noted above are important considerations when performing energy simulations that will accurately forecast passive thermal performance.



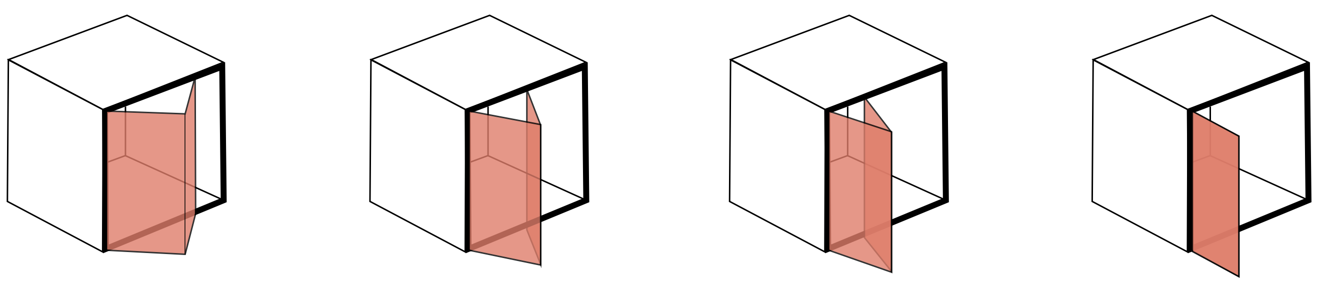
Internal shading devices are versatile and intuitive. *There are a number of internal shading alternatives available today that allow for control of daylight, while shading against excessive solar gains, maintaining views and providing visual privacy.*



Sliding panels are simple to fabricate and use, but offer the least flexibility.



Horizontal folding panels perform better than sliding panels, but are prone to developing snow and ice accumulations.



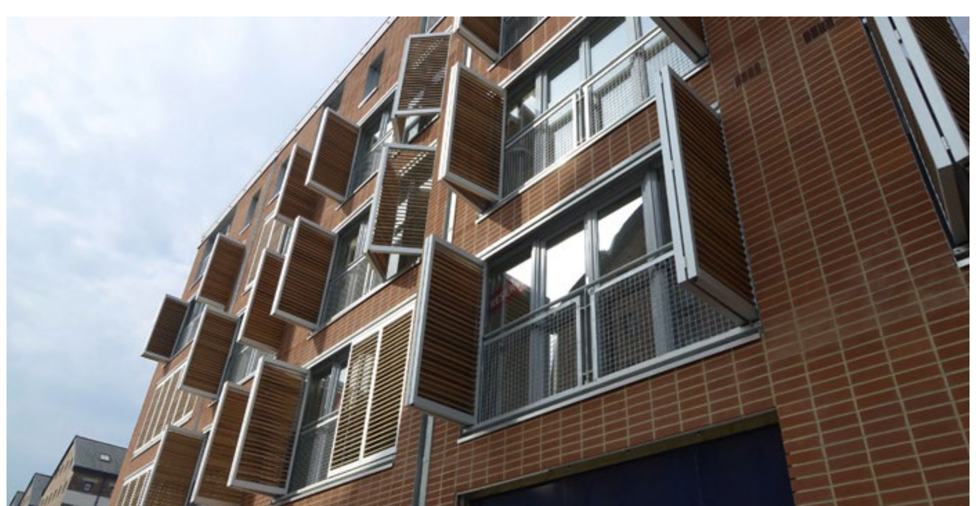
Vertical folding panels provide the best overall performance and flexibility, especially when panels are mounted on each side of the fenestration opening.

Moveable insulation panels (MIPs) are highly adaptive. *Research into the potential energy and daylighting benefits associated with moveable insulation panels in Nordic climate zones reveals that vertical folding panels are the most effective and adaptive overall. Insulated panels enhance cold weather passive habitability and also serve as a protective layer against airborne projectiles during extreme wind events. [Source: C. Du Montier, A.Potvin and Claude Demers, 2013. Adaptive facades for Architecture: Energy and Lighting Potential of Movable Insulation Panels. PLEA 2013 - 29th Conference, Munich, Germany.]*

Advances in facade technology are yielding innovative solutions to the control of solar radiation while enhancing other aspects of performance such as daylighting. Interestingly, traditional technologies like roller shades and shutters are being rediscovered and implemented in contemporary architecture. There is still no ideal strategy or approach that optimizes solar shading, daylighting, natural ventilation and passive habitability. One important realization emerging from field studies and post-occupancy evaluations is that inhabitants of buildings want to be able to engage passive measures on their own terms, to manipulate, adjust and fine tune them to suit their needs and desires.

Combined shading devices are multifunctional. *This facade employs internal adjustable shading devices and fixed external shading devices. The lower tiers of external shading also serve as light shelves to improve daylight penetration while reducing glare. Properly designed and deployed, shading devices can extend hot weather passive habitability while improving thermal autonomy and daylighting performance.*

Motorized exterior roller shades provide adjustable control of glare and solar gains. *But unless they are mounted far from the face of window openings, they will restrict natural ventilation air flows.*



Louvered bi-fold shutters are an effective compromise between shading and natural ventilation performance. *By making the angle of the slats adjustable and the gap between slats generous, it is possible to provide adequate shading while maintaining effective natural ventilation.*

It is important to recognize that while energy simulations may assume the ideal operation of shading devices, either automatically and/or manually by the occupants, it is seldom that such ideal operations are achieved in reality. There is not a great deal of evidence-based literature to help guide energy modelers towards more realistic predictions of actual thermal resilience performance. But it is apparent that shading devices are insufficient to control overheating by themselves, and therefore must be coupled to natural ventilation in order to achieve reasonable levels of hot weather passive habitability.

From a practical perspective, it is likely more important to avoid shading devices that impair natural ventilation than it is to capture exactly how the shading devices will be deployed in real occupied buildings. By providing inhabitants with access to light and air by intuitive ease of use and flexibility of adjustments, it may be assumed they will discover their own personalized optimal solutions.

Natural Ventilation

Passive buildings rely on natural ventilation to offset active mechanical ventilation systems to the highest extent possible, preferably under favorable conditions that do not adversely impact ventilation energy loads and occupant thermal comfort. But it is important to distinguish between thermal autonomy and passive habitability when it comes to natural ventilation system design.

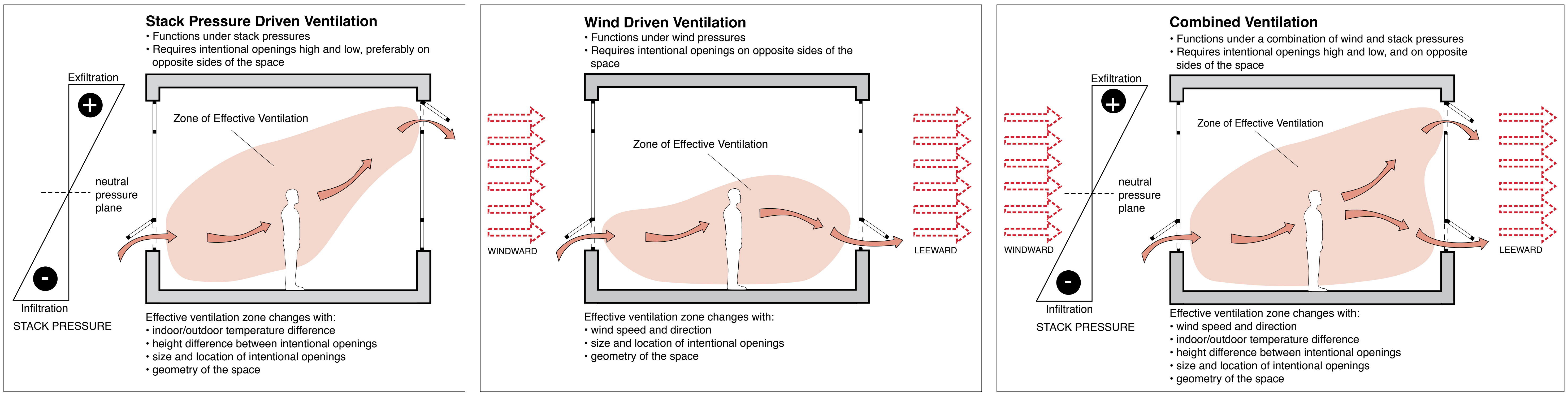
Ventilation autonomy is a term that is defined as the percentage of occupied hours per year where the required ventilation rate is provide by natural ventilation. The required ventilation rate depends on the number of occupants, the occupied floor area and the use of the space in relation to expected contaminant loads (e.g., residential, commercial, healthcare, etc.). Ventilation autonomy is not always directly related to thermal autonomy depending on the conventions that are adopted in energy modeling. [Note: Guidelines on modelling thermal autonomy and passive habitability are provided later on in this publication.]

Typically, thermal autonomy simulations assume that a base natural ventilation rate is provided during occupied hours regardless of whether or not such a ventilation rate can actually be reliably delivered throughout the year by passive ventilation openings serving the space under consideration. Thermal autonomy calculations assume a standardized set of assumptions for the sake of consistent comparisons between proposed designs and their associated passive measures - thermal autonomy is a comparative indicator rather than a precise metric intended to predict actual building performance.

Ventilation autonomy is more critically related to passive habitability, especially during prolonged periods of extreme hot weather coinciding with prolonged power outages. If the required air change rates in a space or building to control overheating are not provided, then passive habitability will be compromised. This does not suggest that ventilation autonomy is not an important consideration for cold weather passive habitability, but usually natural ventilation strategies designed to be effective during hot weather spells are much more effective during cold weather when normally higher stack and wind pressures will deliver higher than adequate natural ventilation rates.

From a thermal resilience perspective, natural ventilation is primarily a passive measure that needs to be integrated with shading devices to manage overheating due to solar gains and extremely high outdoor temperatures. The discussion that follows is intended to help inform the design of effective natural ventilation systems.

The physical forces affecting natural ventilation inform effective design strategies. Stack pressures are induced across a building enclosure by buoyancy forces resulting from indoor and outdoor temperature differences. The higher the temperature difference and the greater the distance from the neutral pressure plane, the higher the stack pressure driving air flows. Wind also generates pressure differences across building enclosures with positive pressures occurring on the windward side and negative (suction) pressures developing on the leeward side.



Natural ventilation is driven by buoyancy (stack effect) and wind pressures. *When there is little wind and a marginal temperature difference between indoors and outdoors, there are correspondingly low natural ventilation rates.*

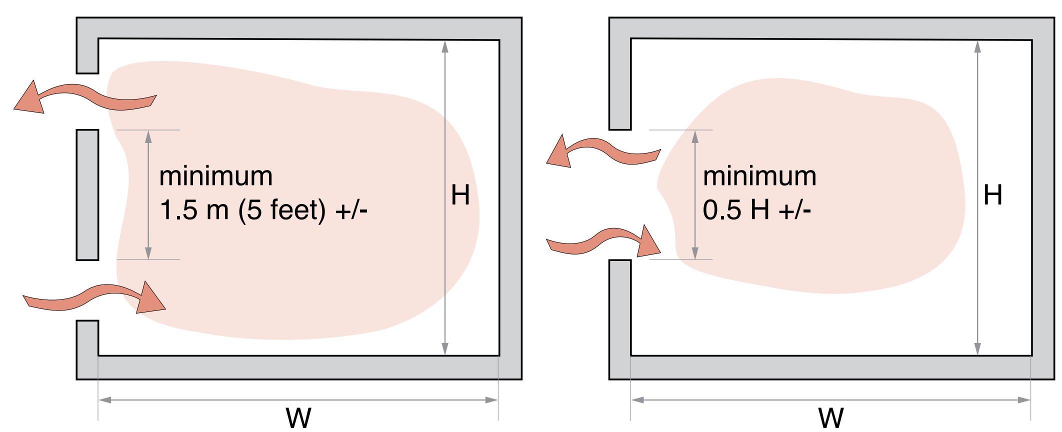
Stack pressure driven ventilation relies on openings, typically created by operable windows, that are located low and high in the space, preferably located on opposite or adjacent exterior walls of a space. The difference in height between the openings and their free area will determine the potential for natural ventilation at a given indoor-outdoor temperature difference. The geometry of the space and obstructions from furnishings, partitions, etc., will impact air flows.

Wind driven ventilation relies on openings, preferably located on opposite and/or adjacent exterior walls of a space. The wind speed and the size and location of the openings will determine the wind driven natural ventilation rate.

Combined ventilation occurs when both stack and wind pressures are acting across a building enclosure. This generally results in the highest driving forces being available to induce natural ventilation. But it is important to appreciate that the configuration of ventilation openings is a critical consideration in design. Single aspect facades, where all of the openings are located along a single face of the building or an enclosed space, are not as aerodynamically effective as configurations that place openings on opposite or adjacent sides. The amount of outdoor and indoor air mixing and the extent of mixing across the space determine the ventilation effectiveness.

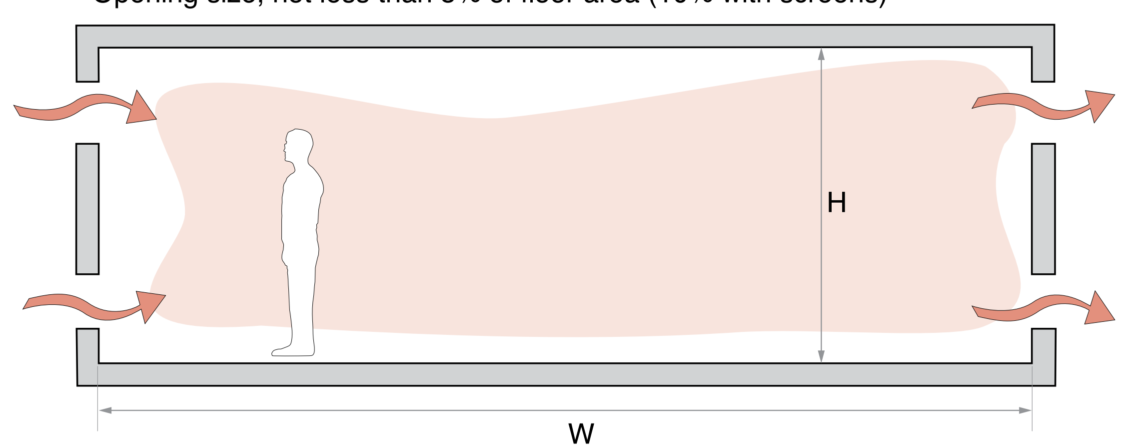
Rules of Thumb - Natural Ventilation Design Parameters

Single-Sided Ventilation
- W (depth) < 2.5 H
- Separate high/low windows more effective than a single opening
- Opening size not less than 5% of floor area (10% with screens)



indicates zone of effective ventilation

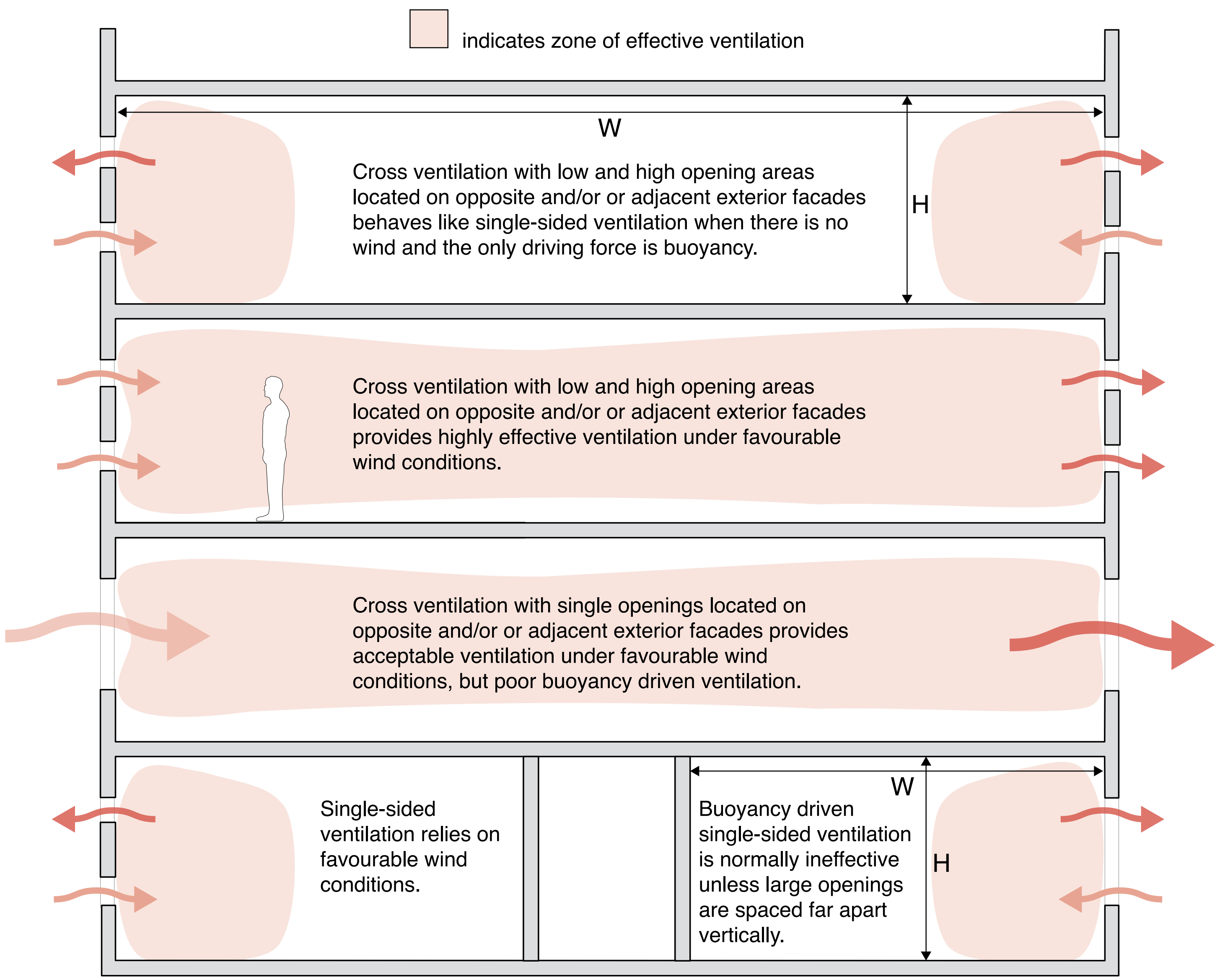
Cross Ventilation
- W (depth) < 5 H
- Separate high/low windows more effective than a single opening
- Opening size, not less than 5% of floor area (10% with screens)



Single-sided ventilation is less effective than cross ventilation. *These simple rules of thumb apply to wind driven natural ventilation system design. For stack pressure driven natural ventilation, effectiveness will normally be much less than for the wind driven case. The aspect ratio of the space (width/depth to height) and the free area of openings as shown should be observed as a minimum design guideline.*

Natural ventilation strategies are important to resolve during the early stages of design, similar to most other passive measures that need to be integrated to produce a resilient design. Hot weather passive habitability is a critical case to examine in the design of natural ventilation. One key issue is whether each compartmentalized space, such as a suite or apartment in a multi-unit residential building, needs to be adequately ventilated, or if only one or several selected spaces are needed to serve as a place of overheating refuge in a building or facility.

Buildings with shallow floor plates, generous floor to ceiling heights and ventilation openings on opposite and/or adjacent exterior walls are promising candidates for effective natural ventilation strategies. Single aspect facades with ventilation openings located on one side only are much more challenging unless the openings are large and spaced far apart, low and high on the exterior wall. It should be recognized that air change rates which are much higher than needed to satisfy ventilation requirements are often required to counter overheating in a space.

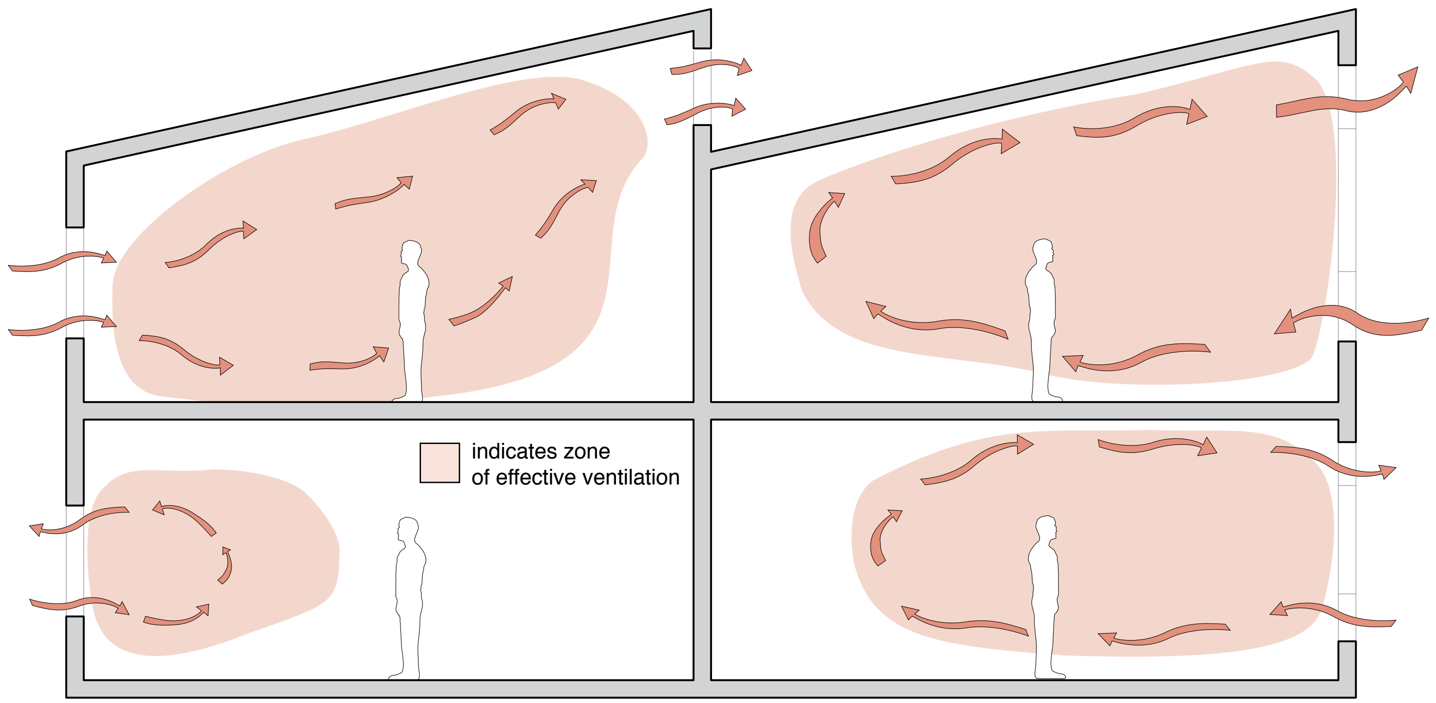


The effective natural ventilation of all compartmentalized spaces is challenging.
In buildings where, single-sided facades are unavoidable, it may be difficult to achieve effective natural ventilation at a rate that can offset overheating. One option is to create a place of overheating refuge that serves a large number of occupants, rather than crafting a natural ventilation solution for each and every individual space.

One means of maintaining passive habitability during extreme heat waves is through nighttime cooling. By cooling off the space overnight, and subsequently shading against solar gains while providing sufficient ventilation to remove heat accumulations, it is possible to maintain habitable temperatures over most of the day. The large ventilation openings needed for effective nighttime cooling may pose security risks unless they consist of a series of smaller openings that prevent ingress.

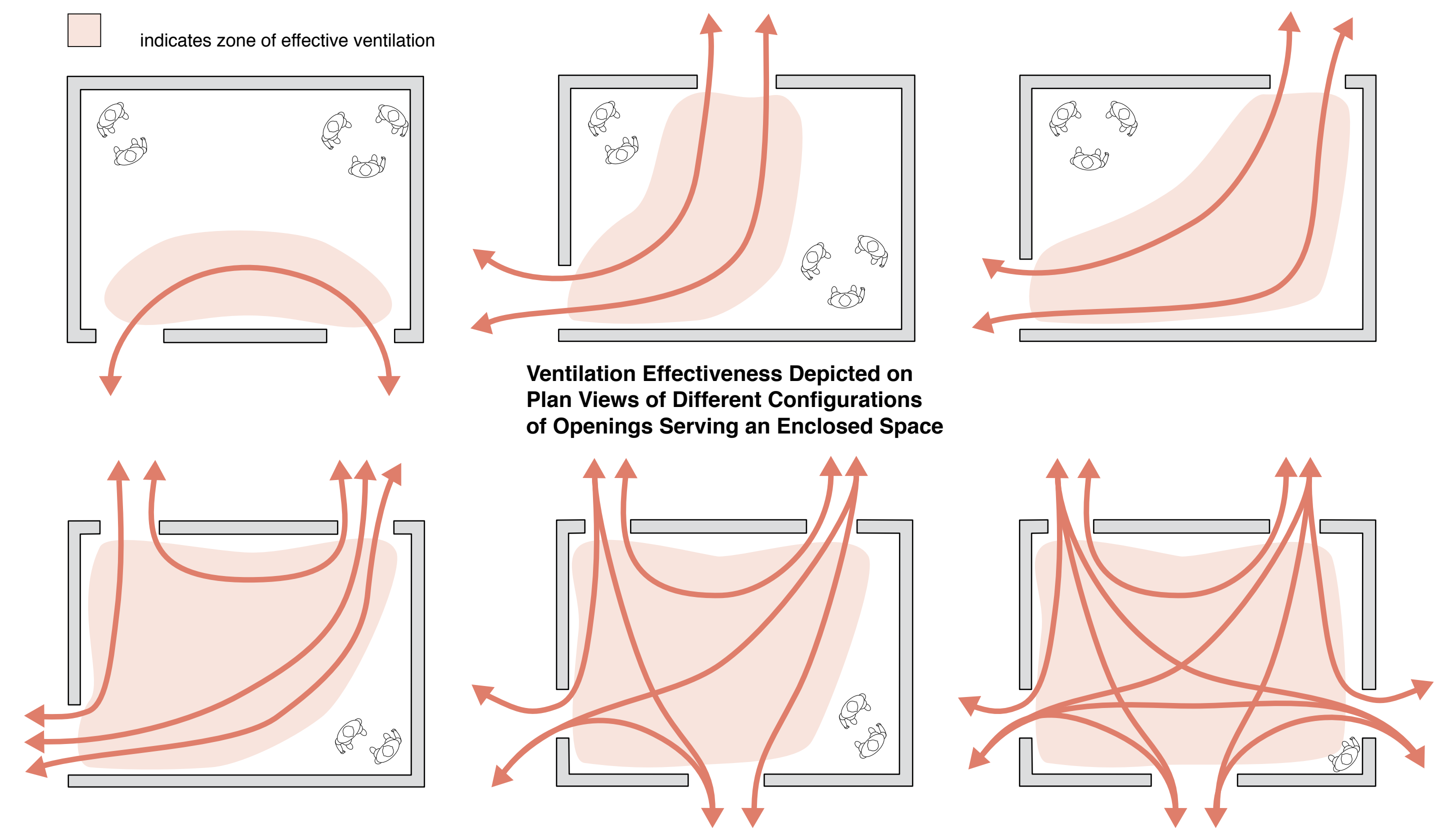
Cross ventilation with low and high opening areas located on opposite and/or or adjacent exterior facades provides highly effective natural ventilation.

Single sided ventilation with large, well spaced low and high opening areas combined with dynamic room geometry delivers acceptable ventilation effectiveness.



Single sided ventilation with small opening areas provides marginal ventilation effectiveness.

Single sided ventilation with large low and high opening areas improves ventilation effectiveness.

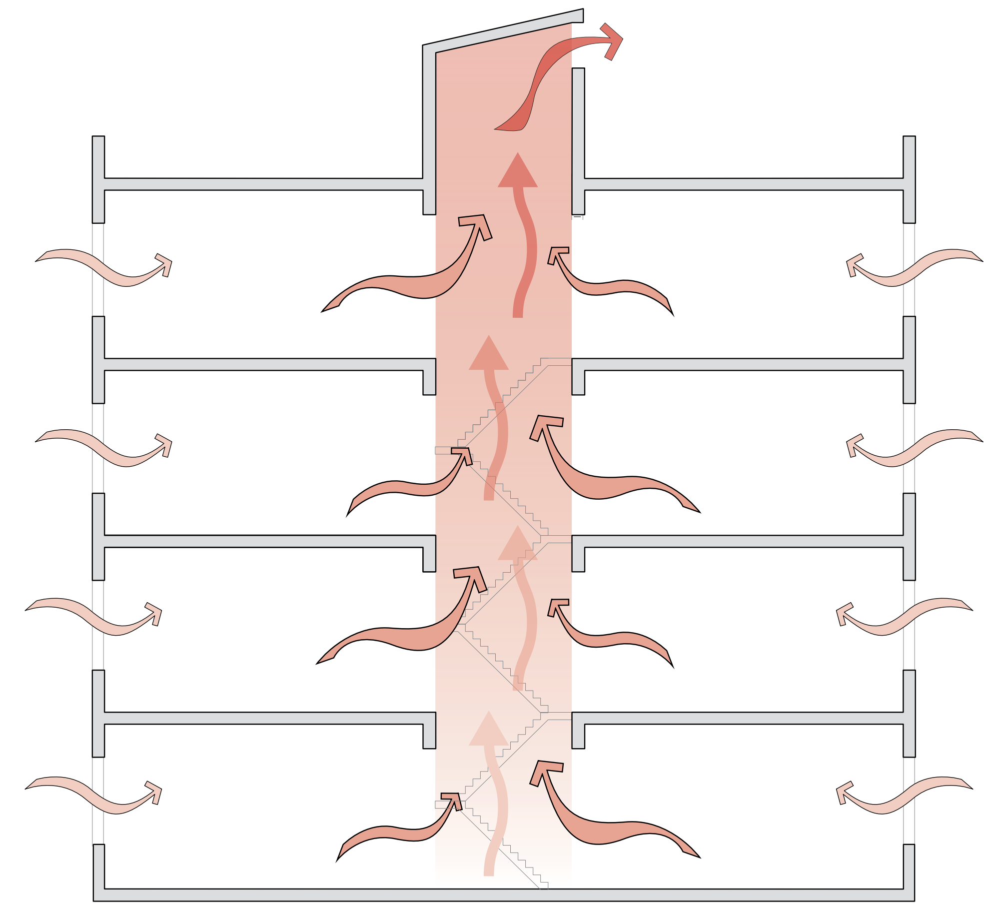


Natural ventilation techniques range in degrees of effectiveness. *Building shape, room geometry, and fenestration are among the numerous variables afforded to natural ventilation system design. Spaces that have ventilation openings on more than one exterior wall have a higher potential for achieving acceptable natural ventilation.*

The configuration of ventilation openings is among the most critical factors affecting natural ventilation effectiveness. *Wind speed and direction are unpredictable and providing numerous paths for air movement throughout a space can provide acceptable ventilation effectiveness under a broad range of conditions. This approach also has the benefit of allowing occupants to adjust the ventilation to suit their comfort.*

Large and tall buildings pose special challenges for effective natural ventilation. The conventional approach to these types of buildings is to mostly or entirely avoid operable windows and provide all the ventilation by mechanical means. These buildings often exhibit very poor passive habitability during extreme hot weather events, becoming uninhabitable in a matter of a few hours after baking in the sun without active cooling and ventilation systems.

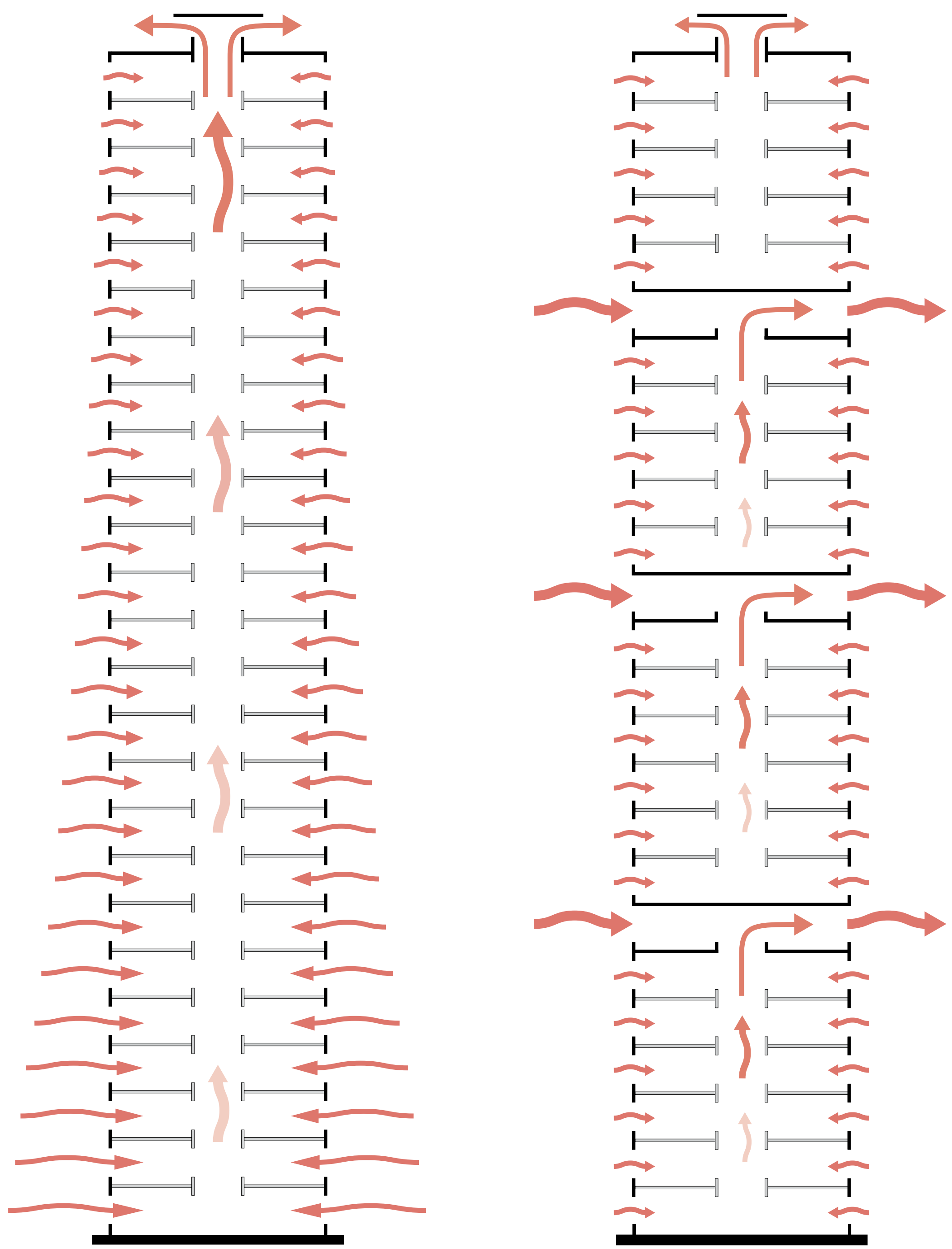
In the case of large buildings, it may prove difficult to afford every space or zone access to natural ventilation because the floor plates are very deep and the facade is of a single aspect. The use of an atrium or some form of a ventilation chimney is a possible solution, but it will require special design. More than one such atrium or ventilation chimney may be required if the building is very large and spread out. Segmentation of the floor plan into manageable zones is one approach. The other is to designate a cold weather place of thermal refuge deep in the core of the building, and then to also designate a hot weather place of thermal refuge where nighttime cooling and adequate natural ventilation can manage overheating passively. The expected number of occupants for these places of refuge must be considered in terms of ventilation requirements and the generation of body heat.



Vernacular architecture provides successful precedents for enhanced natural ventilation. *The central atrium with an adjustable opening at the top is a proven means of enhancing natural ventilation effectiveness. Such approaches require modelling and simulation to refine design variables such as the number and size of openings, as well as the atrium geometry. Internal partitioning and obstructions must also be taken onto consideration.*

Tall buildings are widely acknowledged as being the most challenging because the stack and wind pressures that are developed make it difficult to control natural ventilation rates and building pressures. Special adjustable openings must be fabricated that are not vulnerable to operational failures caused by excessive wind gusts and prolonged pressure differences. Compartmentalization of zones on a single floor plate must be carefully planned so that occupant operation of ventilation openings in one zone do not adversely affect natural ventilation rates in other zones.

Due to the potential for extremely high stack and wind pressures developing across tall building enclosures, the vertical segmentation of the building into manageable stacks is a commonly deployed strategy. Where an atrium or ventilation chimney are provided, it should be recognized that special attention must be paid to the fire safety implications associated with smoke movement.



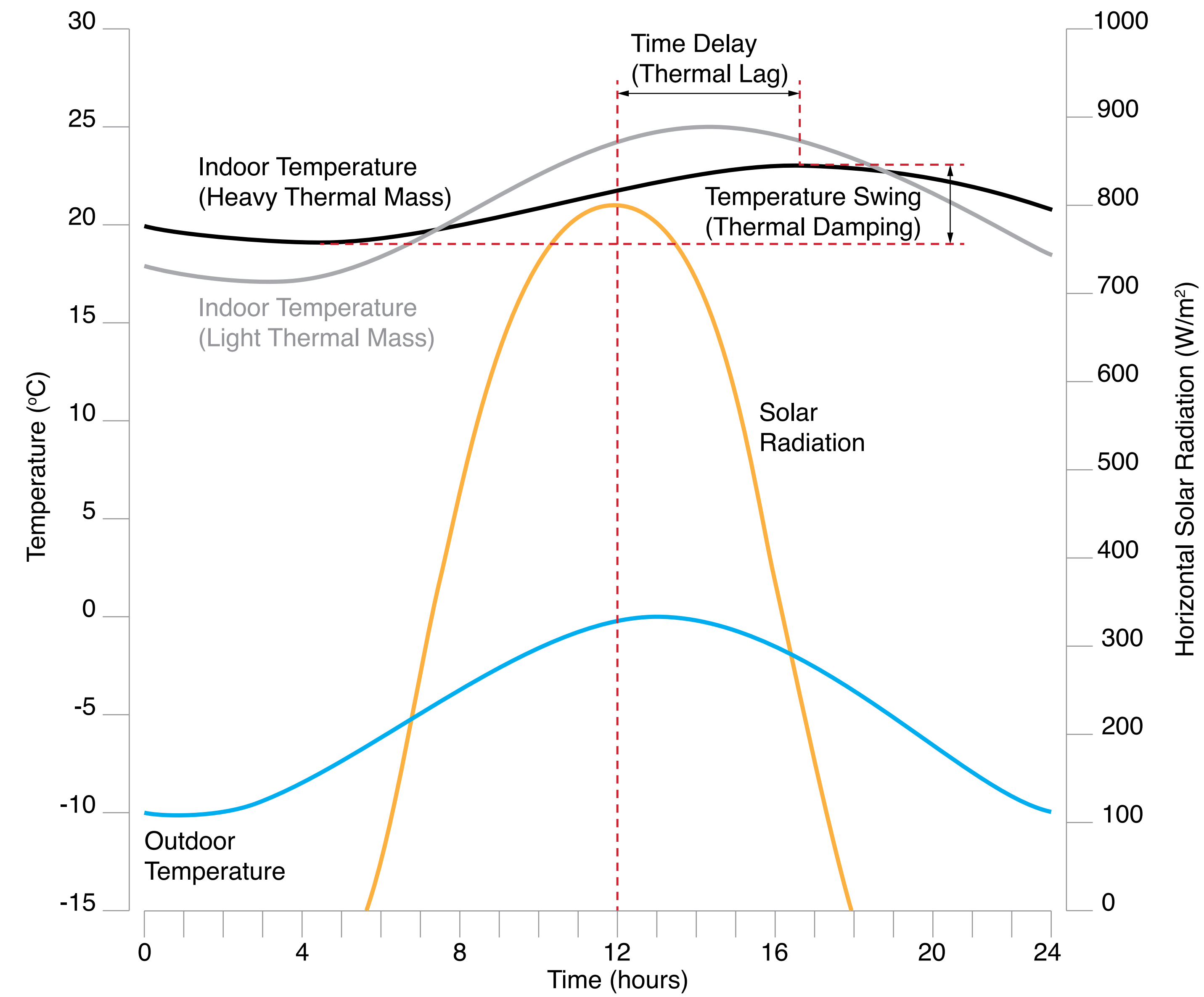
Natural ventilation in tall buildings must be specially engineered. *There are few precedents for tall buildings that are naturally ventilated compared to the numerous vernacular examples. Segmentation of a tall building into shorter sections reduces the magnitude of stack effects that make it difficult to manage building air pressures. Most tall buildings exhibit inferior passive habitability, not only because they often fail to properly address natural ventilation and shading, but because they are so dependent on active systems for vertical transportation and water supply. [Source: D.W. Etheridge and B. Ford. (2008). Natural Ventilation of Tall Buildings - Options and Limitations. CTBUH 8th World Congress, March 3 - 5, 2008, Dubai, UAE.]*

Despite the many challenges for all types of buildings, natural ventilation is a passive measure that provides numerous benefits, especially in terms of passive habitability during extreme hot weather. Naturally ventilated buildings are inherently more resilient because they are less dependent on active systems which in turn rely on energy sources that are vulnerable to prolonged outages or become quickly depleted on site.

Thermal Mass

Thermal mass that is exposed to building interiors has the ability to regulate the indoor thermal environment and moderate peak temperatures. This role has always been particularly important in passive solar buildings and other buildings that encounter high, periodic heat gains. But it is now also recognized as an important passive measure for enhancing thermal autonomy and passive habitability.

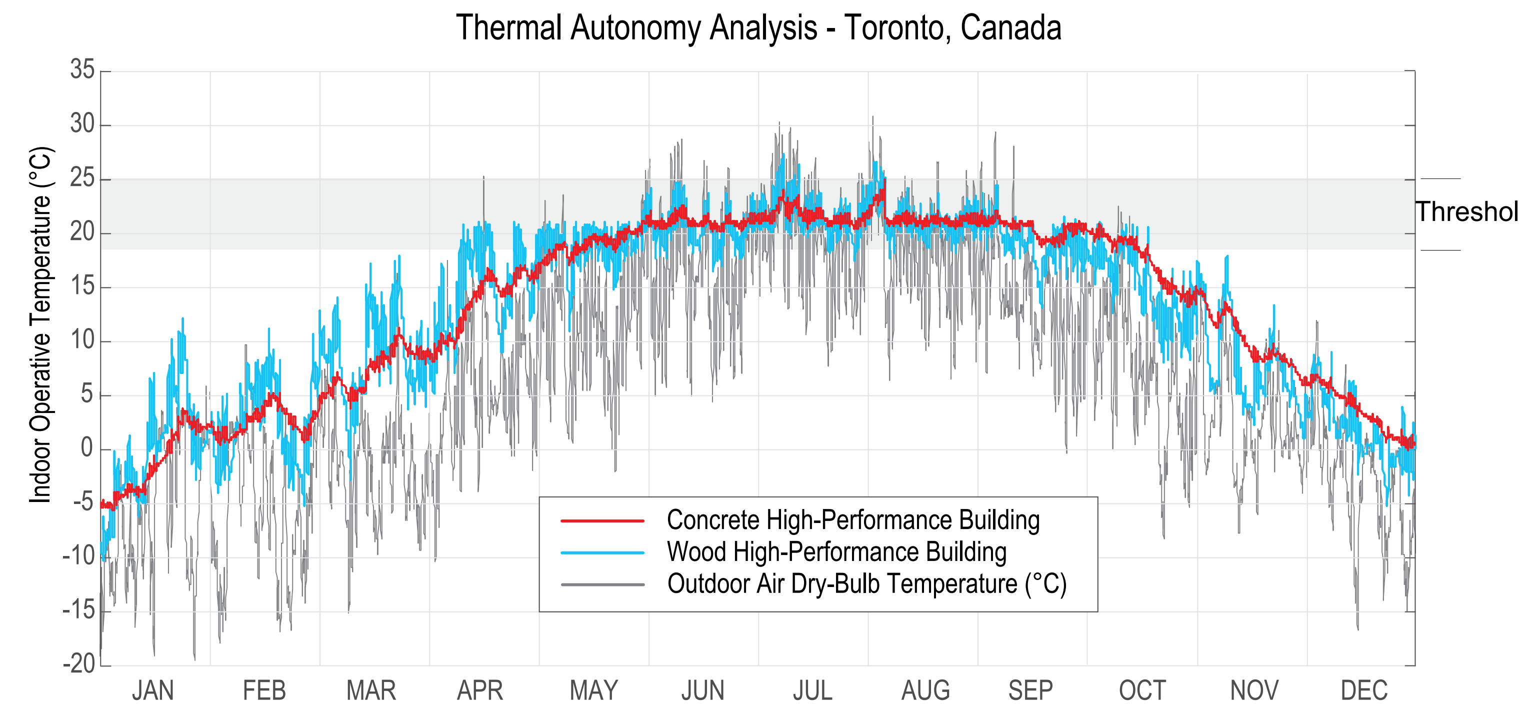
Traditionally, thermal mass was an attribute of building structures composed of concrete, masonry or stone materials that constitute high levels of embodied energy, require additional structure to support their mass, can reflect rather than dampen audible noise, and may cause localized discomfort such as cold feet. Thermal mass must therefore be deployed strategically and research indicates that location and quantity of thermal mass play a significant role in both comfort and energy use in passive buildings.



Thermal mass enhances thermal resilience.
Advantageous for both thermal autonomy and passive habitability, thermal mass stores heat energy and reduces temperature swings, thereby improving comfort and energy efficiency. Shifting peak heating and cooling loads is also beneficial to diversifying demands on the energy grid and reducing the capacity of HVAC equipment. [Source: O'Brien, W. and T. Kesik. (2016). On the Effectiveness of Different Thermal Mass Configurations for Comfort and Energy Performance in Passive Solar Houses. Research report funded by the Jeffrey Cook Trust, May 28, 2016.]

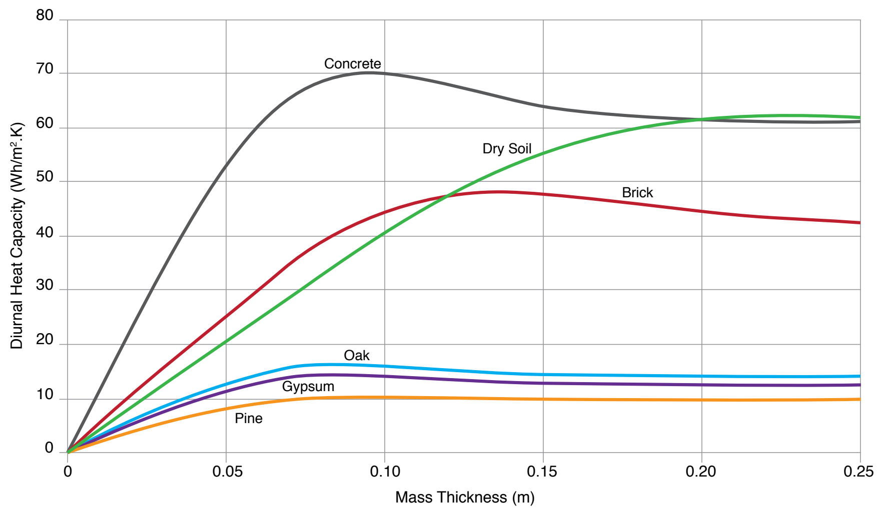
https://pbs.daniels.utoronto.ca/faculty/kesik_t/CookTrust/Thermal Mass Appendix - Passive Solar House Design Primer.zip

Light thermal mass buildings are much more thermally responsive than heavy thermal mass buildings, especially if they are highly insulated. Research into the energy, daylighting and comfort performance of low energy housing indicates that the variables of window-to-wall ratio, glazing characteristics and the provision of dynamic rather than fixed shading devices, must be carefully integrated to avoid glare, overheating and high space conditioning energy demands. Highly insulated and thermally lightweight buildings can rapidly overheat in the absence of effective solar shading, and if they are relatively airtight tend to cool down slowly unless they are adequately ventilated. This suggests that while thermal mass is largely advantageous for enhanced thermal autonomy and passive habitability, a well-integrated suite of passive measures in thermally lightweight buildings can achieve comparable thermal autonomy and passive habitability performance.



Thermal mass provides significant damping of diurnal temperature swings.
Data from a computer simulation modeling thermal autonomy indicate the significant difference in the range of daily temperature swings between reinforced concrete and light wood-frame buildings. In general, as the weather warms, the daily maximum temperatures are much higher in light thermal mass buildings than in heavy thermal mass buildings. As the weather cools, the minimum daily temperatures are much lower in light thermal mass buildings than in heavy thermal mass buildings. The thermal damping effect of thermal mass is beneficial for both hot and cold weather passive habitability.

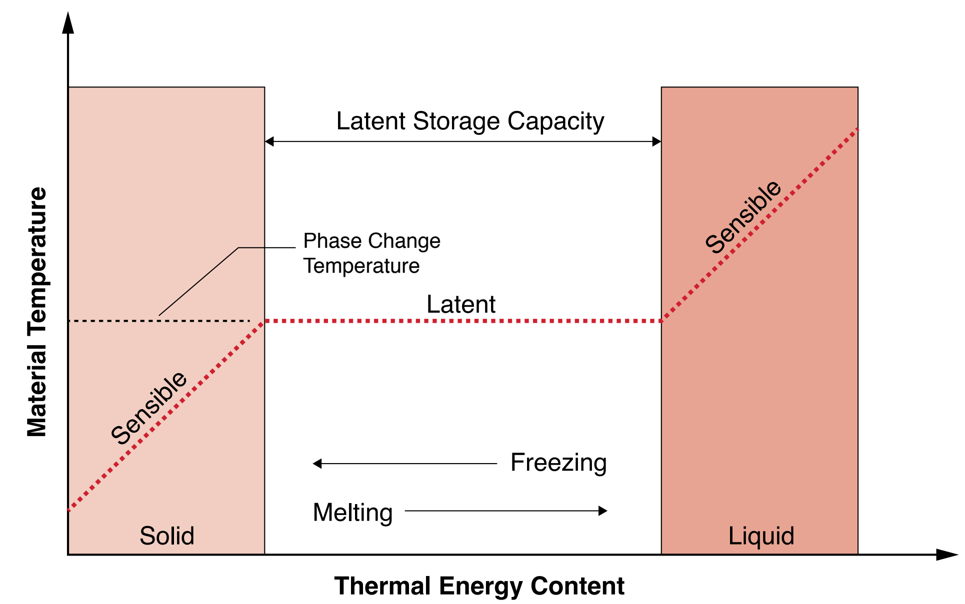
A hybrid approach to configuring the thermal mass of a building can be very effective where low embodied energy materials, such as mass timber, are selectively combined with thermal mass elements such as concrete floor toppings. In the case of normal density concrete, there is no appreciable diurnal heat capacity beyond a thickness of 100 mm (4 inches). Concrete toppings having a thickness between 50 mm (2 inches) and 75 mm (3 inches) provide near-optimal diurnal heat capacity without adding excessive weight. It is also important to recognize that furnishings and floor coverings, such as carpets, can significantly reduce the potential benefits of thermal mass by shielding it from direct solar gains.



More is not always better when it comes to thermal mass in buildings. *In many types of buildings, diurnal heat storage capacity is a critical factor affecting thermal comfort, thermal autonomy and passive habitability. Beyond a certain level of thermal mass, additional material thickness does not provide additional benefit for improving thermal performance.*

An alternative or complementary approach to thermal mass is latent thermal storage through the use of materials that undergo a phase change under normal operating conditions of a building. These so-called phase change materials (PCMs) are substances with a high heat of fusion. The heat of fusion is analogous to the specific heat or volumetric heat capacity for sensible storage and typical values for existing PCM materials range from 140 to 230 kJ/kg. Numerical and experimental results over the past three decades have demonstrated that thin layers (< 50 mm or 2 inches) of PCM can provide as much benefit to building performance as 10 to 20 cm (4 to 8 inches) of concrete. Ideal PCMs change state (e.g., liquid-solid, solid-solid) at a temperature near room temperature and would effectively resist temperature from increasing beyond comfortable air temperatures, unless considerable energy is added. Recommended phase change temperatures range from 1 to 3 °C above the average room temperature to between 1.1 to 3.3 °C above the minimum comfort temperature.

PCMs can be integrated with structural components such as concrete or with gypsum to form a compound to be used in walls, floors, or ceilings. An important factor when deploying PCMs is that they offer relatively little thermal storage if the space does not reach the temperature at which it changes state.



Phase change materials are an alternative to thermal mass. *Properly selected and integrated within the building-as-a-system, PCMs can store excessive solar and/or internal gains in order to shift peak loads, extend thermal autonomy and enhance passive habitability.*

Phase charge materials (PCMs) have a high heat of fusion and absorb thermal energy when they transform from solid to liquid phase, and conversely release thermal energy when they transform back to solid phase.

Typical phase change storage media consist of salts or organic compounds embedded in building materials, usually located inboard of the thermal control layer(s) of a building enclosure, preferably located in contact with the interior conditioned space.

Unlike thermal mass which involves radiant, sensible heat transfers, the heat storage capacity of a phase change material is largely determined by its latent heat storage capacity and the temperatures to which it is exposed.

It is possible to achieve thermal lag and damping in buildings by taking a hybrid approach of phase change materials in walls and ceilings combined with thermal mass located strategically in areas like floors. This approach enables low thermal mass and low embodied energy building systems, such as mass timber, to attain acceptable levels of thermal autonomy and passive habitability.

The next section deals with fire resistance, a special case of thermal resilience that involves making buildings that are less susceptible to damage by fire in regions where wildfires occur. Climate change is exposing many regions to unprecedented wildfires that consume entire communities in their path.

Fire Resistance

Fire resistance is a thermal resilience measure that is becoming increasingly important in certain regions, sometimes referred to as the wildland-urban interface (WUI), where wildfires pose a threat. While fire safety is critical to all buildings, modern fire and building codes focus predominantly on the management of fires that start inside of buildings, and how to control their spread to adjacent structures. Originally building codes were designed to protect buildings from a fire that started indoors, grew and spread slowly, eventually burning the building's structure. Fire resistance is a passive thermal resilience measure, typically rated in terms of hours, corresponding to how long a fire is contained and/or the building structure will stay up so that occupants can exit safely and firefighters can extinguish the fire without danger of structural collapse. However, climate change and an increase in the frequency and severity of wildfires has caused a shift in focus regarding fire resistance.

Wildfires are part of a natural process of wilderness rejuvenation. *The problem today is that an increasing level of development is occurring at the wildland-urban interface, and buildings along with their surrounding sites are not being designed to manage the risks of wildfire exposure.*

This section of the guide does not deal with conventional aspects of fire resistance within and between buildings since they are reasonably well addressed in current codes and standards. Instead, this section examines thermal resilience from the perspective of resistance to damage from wildfires. In regions where forests and undergrowth provide ample fuel for combustion, wildfires pose a risk to the exterior of buildings, often driven by strong winds, and reach peak temperatures in seconds, then pass over a site within minutes as soon as all the standing fuel is consumed. The risk posed to buildings is from secondary spot fires started on and within the home by wind-borne flames and embers. Fire resistance to wildfires involves designing the building and surrounding site to withstand a relatively brief but intense exterior fire exposure.

Fire Resistance Terms Related to Buildings

Building codes and more recently a number of special regulations for buildings located at the wildland-urban interface in regions prone to wildfires contain technical requirements for materials and assemblies that refer to fire performance terminology. The following terms are commonly found in codes and standards.

Combustible

Combusitble means that the material will ignite and burn. Examples of combustible materials are wood, paper, plastics, fabrics, etc. Combustible materials are very common in building construction, furnishings, and furniture. It is impossible to make a combustible material non-combustible by applying after-market chemicals or treatments.

Non-combustible

Non-combustible means that the material will not ignite, burn or release flammable vapors when exposed to fire or heat. Examples of non-combustible materials include steel, masonry, ceramics and certain insulating materials (such as fiberglass or mineral wool insulation). Gypsum wallboard is considered by the codes to be non-combustible although it does have a thick paper backing that is combustible. Most non-combustible materials have a Class A flame spread rating allowing them to be used for walls and ceilings in a building.

Fire resistant or fire resistance-rated

Fire resistant or fire resistance-rated refers to the fire ratings of the building's floors, wall, and ceilings. Fire resistant or fire resistance-rated walls are intended to contain a fire inside that compartment and prevent it from spreading for a period of time (expressed in minutes or hours). Examples would include a two-hour fire resistance-rated wall or a 20-minute fire-rated door.

Fire retardant or fire retardant-treated

Fire retardant or fire retardant-treated refers to chemicals, coatings, and treatments used to make combustible building materials resistant to charring and decomposition when exposed to fire. Examples include "fire retardant plywood" or "fire retardant-treated lumber." Fire retardant-treated lumber can only be accomplished in a factory setting; there are no after-market products that can give lumber a "fire retardant-treated" listing. The addition of fire-retardant materials does not make an item non-combustible, but it may become ignition-resistant.

Flame spread rating or flame spread index

Flame spread rating or flame spread indexrefers to how fire spreads across the surface of a material. It is used to provide a Class A, B, or C flame spread rating on materials used on walls or ceilings. There are chemicals that can be applied that will reduce the flame spread rating of a material.

Ignition-resistant

Ignition-resistant is a term used to describe materials based on meeting a minimum flame spread rating after the material has been subjected to a specified weathering procedure. A material labeled ignition-resistant has passed this test.

It is important to note that fire resilience at the wildland-urban interface is largely concerned with reducing structure ignition hazards through the use of non-combustible and ignition resistant materials and building assemblies.

Relevant Fire Resistance Standards

Many jurisdictions have enacted special code requirements for buildings located in regions where wildfires pose a risk. These thermal resilience requirements often reference technical standards, some of which are listed and described below.

External Fire Exposure Standards

ASTM E84-18b Standard Test Method for Surface Burning Characteristics of Building Materials
This fire-test–response standard assesses the comparative surface burning behavior of building materials. The purpose of this test method is to determine the relative burning behavior of the material by observing the flame spread along the specimen. Flame spread and smoke developed index are reported, but there is not necessarily a relationship between the two.

ASTM E108-17 Standard Test Methods for Fire Tests of Roof Coverings
The test methods described herein are intended to provide a basis for relative comparison of roof coverings. The test methods include simulated fire exposure to the outside of the roof coverings, and measure measure the surface spread of flame and the ability of the roof covering material or system to resist fire penetration from the exterior to the underside of a roof deck under the conditions of exposure. These test methods also provide criteria to determine if the roof covering material will develop flying burning material, identified as flying brands, when subjected to a 12-mph (5.3-m/s) wind during the simulated fire exposure tests.

ASTM E2632-13e1 Standard Test Method for Evaluating the Under-Deck Fire Response of Deck Materials
This test method addresses the suitability of deck materials by assessing their response to fire hazards associated with sources of flame located beneath the deck material.

ASTM E2707-15 Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure
The test method described herein measures the ability of the exterior wall covering material or system to resist fire penetration from the exterior to the unexposed side of the wall assembly under the specified conditions of exposure.

ASTM E2886-14 Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement
This test method evaluates the ability of exterior vents that mount vertically or horizontally to resist the entry of embers and flame penetration through the vent.

ASTM E2957-17 Standard Test Method for Resistance to Wildfire Penetration of Eaves, Soffits and Other Penetrations
This fire-test-response standard prescribes a method for qualitatively assessing the resistance to fire penetration of eave overhangs and other projections, such as the soffits of roof eaves and cantilevered floor projections, when exposed to direct flame impingement from a simulated external wildfire exposure, such as encountered in a "Wildland Urban Interface" scenario. This test method provides data suitable for comparing the relative performance of materials, which are used as the exposed underside surfaces of eave overhangs and other projections.

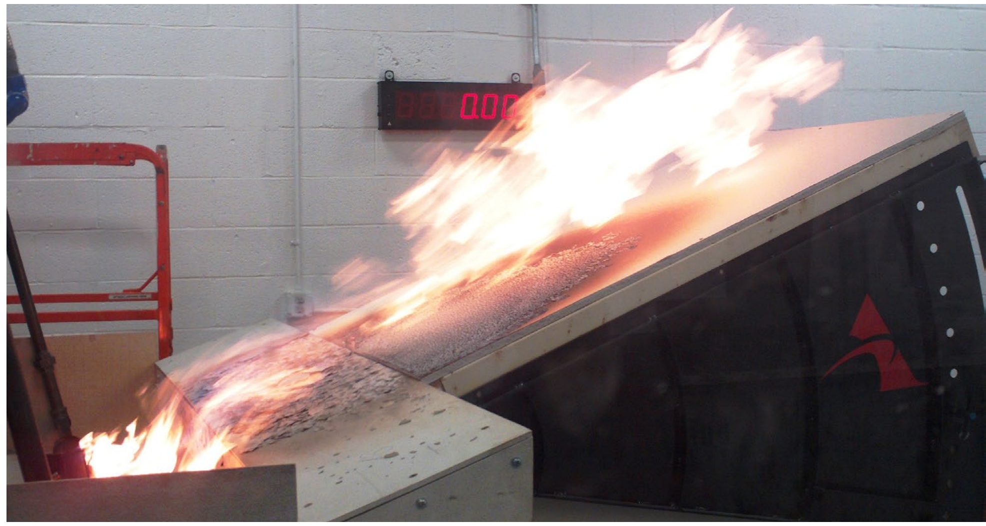
NFPA 1144 - 2018 Standard for Reducing Structure Ignition Hazards from Wildland Fire
Provides a methodology for assessing wildland fire ignition hazards around existing structures and provides requirements for new construction to reduce the potential of structure ignition from wildland fires. Revised to incorporate the latest industry data from the USDA Forest Service, NIST, and other authorities, the Standard's updated provisions cover design, construction and landscaping elements for structures in the wildland/urban interface.

Sources:
ASTM Fire Standards and Flammability Standards. https://www.astm.org/Standards/fire-and-flammability-standards.html
NFPA Firewise and Wildfire Preparedness. https://catalog.nfpa.org/Firewise-and-Wildfire-Preparedness-C30.aspx

External fire exposure criteria in standards can help design an appropriate level of fire resistance.
However, ongoing research indicates that full-scale outdoor testing beyond the standard test procedures can reveal significant differences between fire-resistant wraps and coatings. Always check with local authorities for guidance on successful measures to enhance fire resilience beyond minimum requirements.

Many communities enforce regulations regarding where and how buildings may be sited, designed, and constructed. The regulations, however, refer to minimum standards such as those established by external fire exposure standards - they are not a substitute for careful and cautious design. Individual property owners have the option to exceed these standards, and doing so very often increases the probability that the building will survive a wildfire.

Test methods are indicators of relative performance.
It is difficult to reproduce real fire conditions in laboratory testing due to a wide range of highly variable factors. Fire rating criteria are helpful in selecting appropriate materials and building enclosure assemblies, but they are not a guarantee of fire safety. Fire prevention and management measures are often more effective approaches to fire safety.



An emerging consensus among experts is that wildfire management needs to be driven by focusing on and regulating the vulnerability of communities. This proactive approach includes, but is not necessarily limited to, selective wildland fuel treatment at the community interface, the ongoing reduction of stray vegetation in the building ignition zone, and reinforcing building fire proofing measures in combination with sustainable urban planning in order to reduce wildfire risk.

While intrinsic factors such as wind speed, wind direction, community layout and wildland vegetation in the vicinity of a community cannot be altered to regulate vulnerability, it is possible to organize communities and invoke proactive strategies for buildings and their surrounding sites to minimize risk. Building designers may not be able to address fire suppression and emergency firefighting resource allocations, but they can make buildings more ignition-resistant and able to withstand responsibly managed wildfires.

Fire Resilience

Wildfire frequency and intensity have risen dramatically since the year 2000. The consequences of these wildfires include a significant number of deaths and enormous losses of property, infrastructure, crops and livestock. In North America, the 2016 Fort McMurray fire burned through 1,500,000 acres (607,000 hectares), causing destruction of approximately 2,400 homes and forcing an excess of 88,000 people to flee. Classified as the costliest disaster in Canadian history, the corresponding economic losses reached approximately C$9 billion. In the U.S. the 2018 wildfire season was the most destructive and deadliest on record in California. Some 8,400 fires burned an area of nearly 1,900,000 acres (765,000 hectares) causing numerous deaths and incurring billions of dollars in damages and expenditures. To make matters worse, climate change is causing more severe droughts while extending the duration of the wildfire season across affected regions. Ever increasing new residential development at the wildland-urban interface is compounding the risk and consequences of wildfires. Regulatory authorities have responded by advocating fire resistance measures above and beyond code minimum requirements.

Recommended Fire Resistance Measures

Roofs
Ensure roofing achieves Class A rating when tested according to ASTM E108-17, Standard Test Methods for Fire Tests of Roof Coverings. Clay tiles, concrete slate, and metal roofing typically comply, as do most fiberglass asphalt shingles.

Louvers, Hoods and Vents
Louvers, hoods and vents must be screened with wire mesh or hardware cloth, with openings no larger than 1/8 inch (3mm). Vents should be tested in accordance with ASTM E2886-14 Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement.

Eaves and Soffits
Soffits and fascia should be constructed using ignition-resistant material such as fiber cement or metal.

Gutters
Gutters should be kept clear of combustible materials and gutter guards are recommended. Metal gutters with metal flashing to extend over the roof edge and down into the gutter provides critical protection. Avoid vinyl or plastic gutters.

Cladding and Siding
In wildfire-prone areas, exterior cladding must be ignition-resistant. Approved materials include fiber cement, stucco, masonry, and manufactured stone. Natural wood, hardboard, and vinyl are prohibited.

Overhand and Projections
The exposed undersides of building projections such as bay windows are vulnerable to ignition from burning vegetation or accumulating embers. These surfaces must be protected with the ignition resistant materials such as those permitted for wall cladding.

Exterior Doors
Exterior doors must be either noncombustible or, if made from wood, to have solid cores at least 1 3/4 inches (45 mm) thick. Glazing in the door must be either tempered safety glass or multilayered glazing. Only front entry doors are allowed to incorporate decorative single-pane glass.

Windows and Glazing
Windows must be dual-pane with tempered glass. Solid wood, aluminum and pultruded fiberglass window frames perform better than vinyl which tends to distort under heat and release the glazing units. Non-combustible shutters or roll-down metal fire doors released automatically by fusible links offer additional protection. Avoid plastic bubble skylights.

Decks
Brush and trees near a deck can readily set it on fire, as can combustible material such as firewood stored under a deck. Windblown embers can also ignite a deck. Use ignition-resistant or non-combustible material for decking.

Base of Walls
Embers piling up against the base of a building can set the exposed bottom edge of wall sheathing on fire, even when the cladding is noncombustible. Protect wall bases with fire caulking (or 1/8-inch wire hardware cloth, if weep holes are needed). Provide a minimum 6-inch (150 mm) separation between cladding and the ground to reduce the risk of fire.

Site Layout
Maintain a defensible space surrounding buildings that inhibits the spread of fire. Provide generous access for firefighters and emergency vehicles. Thin out underbrush and prune tress regularly to minimize fuel sources.

Source:
FEMA Homebuilder's Guide to Construction in Wildfire Zones - Technical Fact Sheet Series, 2008.
https://www.fema.gov/media-library-data/20130726-1728-25045-1351/home_builders_guide_to_construction_in_wildfire_zones.pdf

***Minimizing the risk of fire damages is not expensive.** Many of the recommended measures described above are mandatory in a lot of jurisdictions where wildfires pose a significant risk. Prevention is one of the most effective ways of engagi.ng climate change adaptation.*

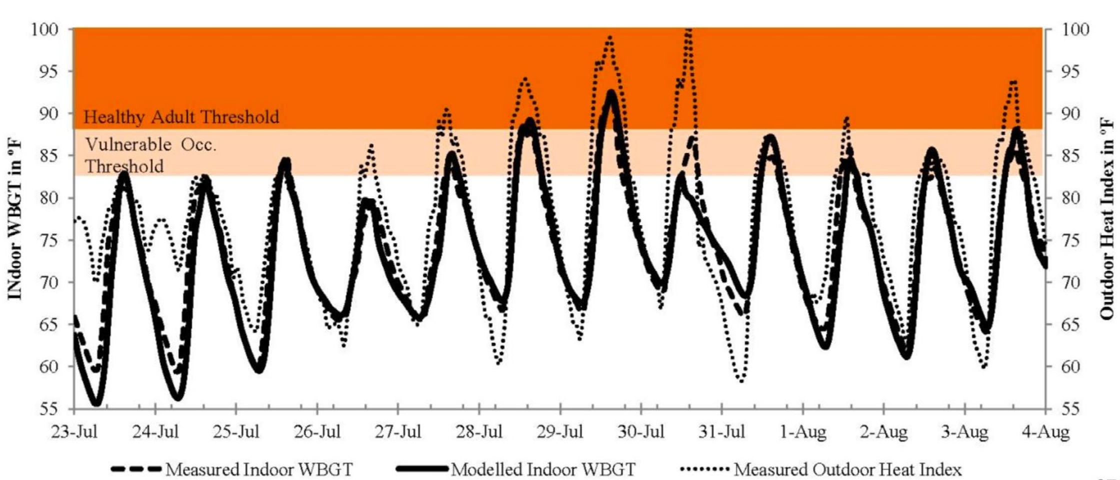
This section of the guide has served to provide an overview of the issues and fundamental approaches to enhancing the fire resistance of buildings against external exposure to wildfires. Refer to the sources of information at the end of this guide for additional resources and publications advocating effective measures to enhance the fire resilience of buildings at the wildland-urban interface.

The following part of this guide will present in-depth and detailed design methodologies for enhancing the thermal resilience of buildings. It is intended to help users of this guide apply passive measures at the schematic design stage that contribute most significantly to thermal resilience.

Fire resistance measures have limitations
Under extreme wildfire conditions, such as those occurring in northern California during 2018, all types of buildings and materials failed to resist being destroyed and consumed by fire. When thermal resilience measures fail, emergency measures and community resilience are the only means of bouncing back from disaster.

Thermal Resilience Modeling

This thermal resilience design guide is intended to provide a framework that can be employed until such time as practice guidelines become standardized. The primary aspects of thermal resilience that are being investigated are thermal autonomy (TA) and passive habitability (PH). Unlike more conventional energy performance metrics, it is important to appreciate that TA and PH are indicators - they are relatively, but not absolutely, meaningful.



Climate change is causing deadly heat waves.
Hot weather thermal resilience is becoming critical. [Source: Energy Model Validation for Indoor Occupant Stress Analysis. Seth Holmes, SimBuild 2016, pp. 275 - 282.]

Thermal resilience indicators are significantly impacted by occupant behaviour. The impacts may be either beneficial or problematic. For example, active inhabitants that adjust their clothing levels, deploy shading devices and open windows to promote natural ventilation can greatly enhance hot weather passive habitability. But passive inhabitants that do not engage the passive features of their buildings can render their indoor environments uninhabitable during extended extreme weather events. This uncertainty associated with occupant behaviour challenges energy performance modelers.

Weather data used to model thermal resilience are a source of uncertainty. Normal weather patterns are no longer as stable as historical averages indicate. The selection of weather files seldom captures record-setting extreme weather events (worst case scenario based on precedents) and energy modelers can only guess at how typical weather data may be impacted by climate change in future.

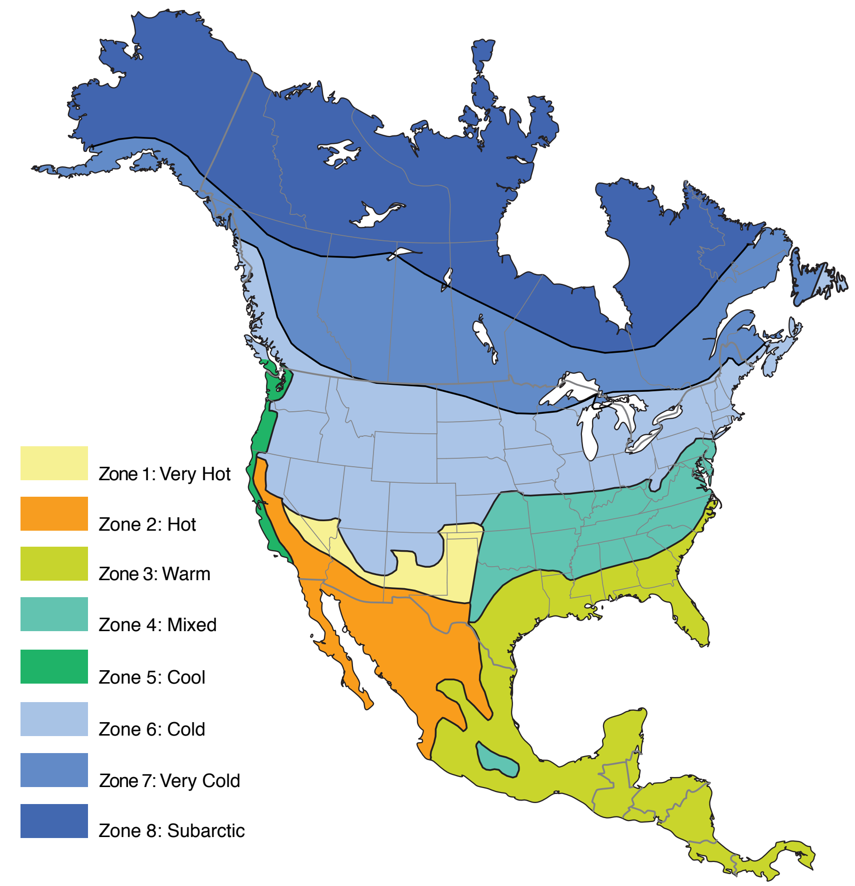
In buildings, the construed may be very different than the constructed. Seldom are buildings constructed to meet every specification and performance target set out at the design stage. Even when they are, they are not always operated and maintained as needed to achieve their proposed performance targets. Over time, buildings deteriorate and their performance lessens, and so it is difficult to decide at which point in a building's life cycle it is appropriate to assess its thermal resilience.

Thermal autonomy and passive habitability are correlated to other important performance metrics. Further research is needed to establish the relationships between thermal resilience indicators and other building energy performance metrics. Until such time, thermal resilience design is not an alternative to more conventional forms of building performance simulation, rather it is a complementary approach that is highly effective in establishing passive measures and strategies at the early stages of design.

Thermal Resilience Design Methodology

This part of the design guidelines focuses on thermal autonomy (TA) and passive habitability (PA). The general information that was presented about fire resistance earlier is not expanded upon in this publication as it is a specialized topic that only applies to regions of North America where wildfires pose a serious risk. Helpful references for fire resistance have been provided in the thermal resilience resources section at the end of this guide. Readers are urged to seek expert guidance and incorporate evidence-based local best practices to achieve enhanced fire resistance in buildings.

Only **ASHRAE Climate Zones 4, 5, 6, 7, 8** are considered in this guidance document. Hot weather passive habitability is difficult to achieve in Zones 1, 2 and 3 and more sophisticated design of special passive measures is required - these special considerations go beyond the scope of this publication.



ASHRAE Climate Zones

For the purposes of thermal resilience design, ASHRAE climate zones are used in this guidelines publication. These differ from the Köppen climate classification system, but have been widely adopted in energy codes and have sufficient resolution to establish baseline passive measures for more subsequent and detailed energy performance assessment purposes.

Zone Number	Zone Name	Thermal Criteria (I-P Units)	Thermal Criteria (SI Units)
1A and 1B	Very Hot –Humid (1A) Dry (1B)	9000 < CDD50°F	5000 < CDD10ºC
2A and 2B	Hot-Humid (2A) Dry (2B)	6300 < CDD50°F ≤ 9000	3500 < CDD10ºC ≤ 5000
3A and 3B	Warm – Humid (3A) Dry (3B)	4500 < CDD50°F ≤ 6300	2500 < CDD10ºC < 3500
3C	Warm – Marine (3C)	CDD50°F ≤ 4500 AND HDD65°F ≤ 3600	CDD10ºC ≤ 2500 AND HDD18ºC ≤ 2000
4A and 4B	Mixed-Humid (4A) Dry (4B)	CDD50°F ≤ 4500 AND 3600 < HDD65°F ≤ 5400	CDD10ºC ≤ 2500 AND HDD18ºC ≤ 3000
4C	Mixed – Marine (4C)	3600 < HDD65°F ≤ 5400	2000 < HDD18ºC ≤ 3000
5A, 5B, and 5C	Cool-Humid (5A) Dry (5B) Marine (5C)	5400 < HDD65°F ≤ 7200	3000 < HDD18ºC ≤ 4000
6A and 6B	Cold – Humid (6A) Dry (6B)	7200 < HDD65°F ≤ 9000	4000 < HDD18ºC ≤ 5000
7	Very Cold	9000 < HDD65°F ≤ 12600	5000 < HDD18ºC ≤ 7000
8	Subarctic	12600 < HDD65°F	7000 < HDD18ºC

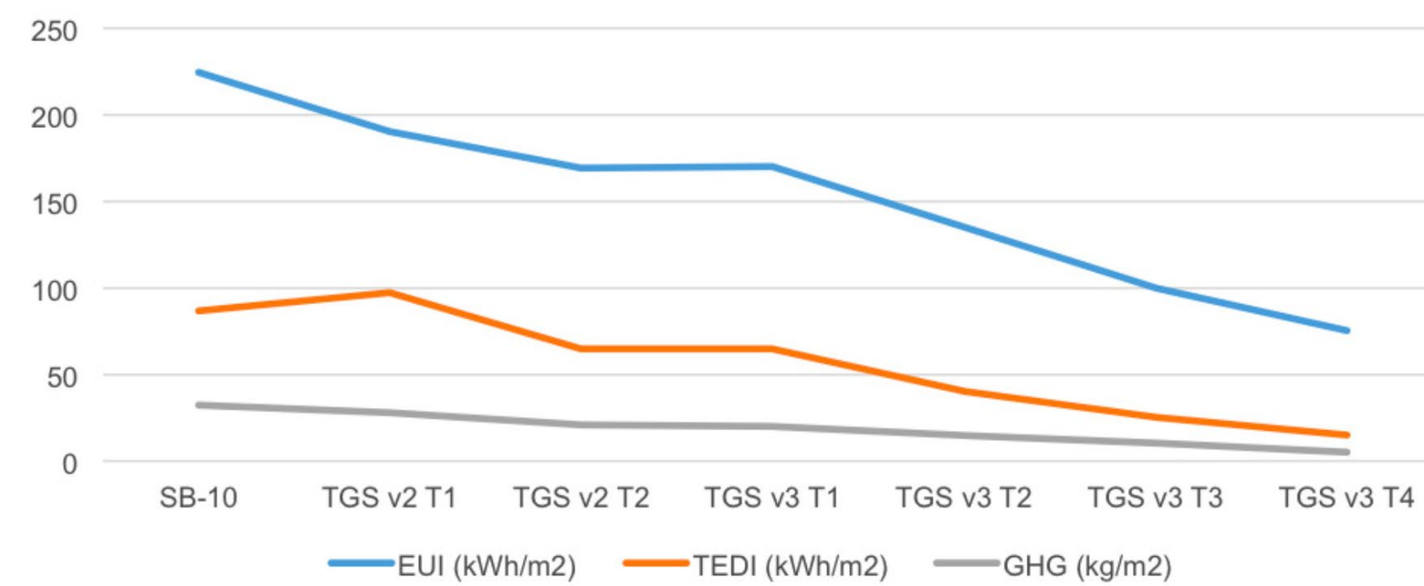
Thermal resilience design for hot and humid climates is challenging.

This guide focuses on thermal resilience design, specifically thermal autonomy and passive habitability, for ASHRAE Climate Zones 4, 5, 6, 7, and 8 inclusive, recognizing that while many of the passive measures are applicable to hot and humid climates, additional special measures are normally required.

This part of the design guide presents a generally extensible methodology for assessing thermal resilience at the schematic design stage where critical decisions about passive measures will largely determine the heating and cooling metabolism of the building. But it is important to appreciate that this methodology goes beyond building metabolism in that the passive measures and strategies influence all aspects of indoor environmental quality.

Thermal Resilience Makes for Better Buildings

Thermal autonomy and passive habitability are performance indicators highly correlated to energy efficiency, in particular annual heating and cooling energy demands, and peak heating and cooling energy demands. From these annual and peak energy demand metrics, thermal energy demand intensities may be derived. It is also possible to estimate the extreme minimum and maximum temperatures that will be experienced inside of a building with no active environmental conditioning systems. All of these metrics are important in planning and designing for resilience in buildings. Annual and peak energy heating and cooling energy demands indicate how much energy must be available and the capacity of energy conversion equipment. This is very critical in remote locations where there is no access to a centralized energy grid and a supply of energy for heating and cooling must be transported to the site and stored. Estimating internal temperatures in buildings that are unconditioned is helpful in determining strategies for the protection against freezing of vital infrastructure as well as selecting interior materials and finishes that are capable of undergoing numerous freeze-thaw cycles.

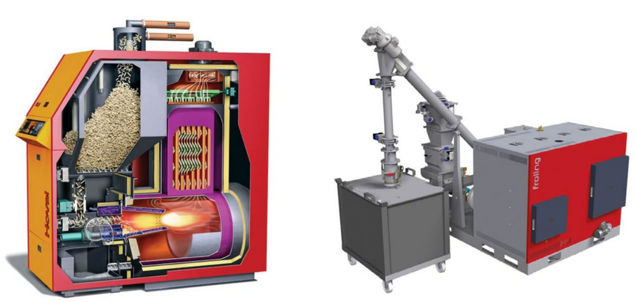


Passive measures are key to achieving near-zero emission buildings.
The graph above depicts the target progression (Tiers 1 to 4, T1 - T4) for multi-unit residential buildings (MURBs) from the current practices (TGS v2 T2) to proposed 2030 requirements (TGS v3 T4) under the latest version of the Toronto Green Standard (TGS v3). As improvements to active system efficiencies dwindle, the heavy lifting needed to attain near-zero emission targets must be performed by robust enclosures. [Source: Zero Emissions Buildings Framework. City of Toronto, March 2017.]

As importantly, in the case of passive habitability indicators, it is much easier to properly plan emergency measures protocols for buildings by knowing how long they can withstand prolonged power outages before steps to protect vital infrastructure must be taken. And finally, passive habitability analyses will indicate the degree of vulnerability of a building and whether or not active systems for emergency back-up power are warranted.

It is very important to understand that extended periods of passive habitability become ever more difficult to achieve as the prolonged extreme weather event gets hotter and colder. Passive measures have limitations and eventually the building interior will begin to approach the outdoor conditions. This is why this guide has not dealt with Climate Zones 1, 2 and 3 where predominantly hot weather passive habitability is extremely challenging to maintain during extended extreme heat wave conditions.

In large urban centres it may be reasonable to aim for two or three days of passive habitability assuming that power will normally be restored within that timeframe. As much as a week of passive habitability may be needed is some areas where energy infrastructure is difficult to access and service, and it will take more time to relocate people into warming/cooling places of refuge.



Thermal autonomy reduces energy use, the capacity of equipment, and on-site energy storage.
Bio-fuels exert a negligible carbon footprint, but unlike gas and electrical services, sufficient energy supplies must be stored on site. The wood pellet-fired combination boiler (left) and combined heat and power plant (right) are examples of active systems whose operating times and fuel conservation can be extended through high-performance passive measures in buildings. Enhanced thermal autonomy also reduces the annual operating times for such equipment, reducing wear while extending service life. Many of these technologies are being deployed for emergency back-up purposes as active systems that complement passive measures for thermal resilience.

Passive versus Active Systems in Buildings
With the exception of the simplest buildings, practically all buildings consist of both passive and active systems which ideally complement each other to achieve acceptable indoor environmental quality.

Passive Role
To moderate the indoor environment for the safety, health and well-being of the occupants without the appreciable consumption of non-renewable energy over the useful life of the building.

Active Role
To supplement the passive systems to the extent that is required to achieve the desired level of environmental quality, ideally with a minimum of entirely zero-carbon footprint energy sources.

Passive/Active Symbiosis
The passive and active systems should be so designed and integrated that a minimum threshold of habitable shelter is passively privileged in the absence of all active systems.

Architecture is rooted in passive systems.
It was not until the Industrial Revolution that buildings began to rely on active systems to provide adequate shelter, and this shift underlies the predominance of fossil fuels leading to greenhouse gas emissions and climate change.

Critical Aspects of Thermal Resilience

Whenever thermal autonomy and passive habitability are being used as indicators of thermal resilience, it is important to determine their critical aspects. For example, thermal autonomy during the heating season may be considered more important than during the cooling season. In this case, it is the amount of time and the intensity of space heating that is of greatest importance. On the other hand, if an electrical energy utility has issues related to peak power demands during periods of hot weather, then the intensity and duration of space cooling energy are critical, hence passive measures for hot weather thermal autonomy become dominant design considerations.

Analogous logic can be extended to passive habitability. It is widely acknowledged that more deaths are attributable to excessive exposure to extreme heat for the very young, the very old, and the gravely ill, than to exposure to cold indoor temperatures. Hot weather passive habitability may be the most critical thermal resilience design consideration in regions where the risks of extreme heat waves and coincident power outages are high. The opposite may be true in far northern regions where frequently interrupted energy supplies and/or prolonged power outages during cold weather render cold weather passive habitability as the most critical design consideration.

Climate change has been a disruptive factor affecting building design because there is a noticeable increase in the frequency and severity of extreme weather events. But there are also climatic regions that seldom if ever witnessed these types of extreme weather events in the past and this has made it necessary to forecast beyond historical weather data in assessing suitable thermal resilience measures in buildings. This is an ever more daunting challenge for design professionals that feel obligated to exercise due diligence and futureproof their building designs.

Passive measures help address sustainable development and climate change mitigation imperatives. *In a new city district of 116 hectares, the Bahnstadt Project in Heidelberg, Germany is being constructed to the Passive House Standard and is serviced by a renewable district energy system for satisfying thermal and electrical loads. [Photo: C40.org]*

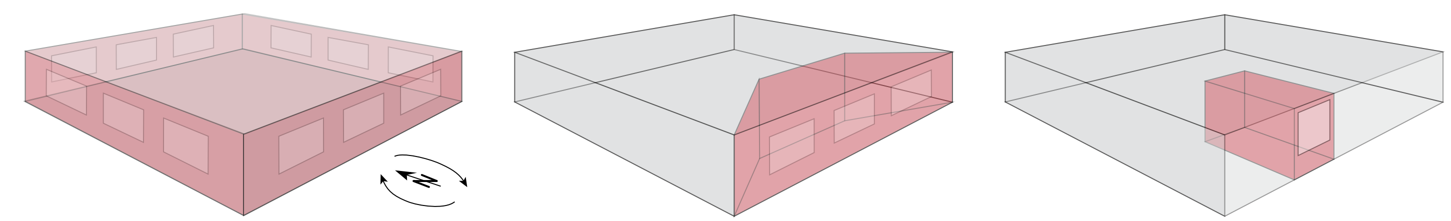
Thermal Resilience Modeling Conventions

Even by following these thermal resilience modeling conventions, it is still very challenging to capture critical relationships efficiently. Part of this challenge is related to ensuring that the critical aspects of a building design are properly addressed. The intended outcomes for thermal resilience design in buildings typically dictate what is critical to model. There are a number of potential issues and opportunities that can investigated through thermal resilience analysis.

- Extreme hot or cold weather passive habitability;
- Annual versus hot or cold weather thermal autonomy;
- Annual and peak space heating and cooling energy demands;
- Space heating and cooling load demand intensities conducive to low temperature HVAC systems;
- Energy supply storage requirements (remote and/or emergency facilities);
- Freezing potential during winter power outages.

Often, particular scenarios are considered, such as a prolonged power outage during an extended extreme weather event that affects vulnerable inhabitants - the ill, elderly and demobilized. The nature of the thermal resilience that is being sought by the designer will vary depending on whether every suite in a housing project, for example, will enjoy a minimum period of passive habitability, or if only a particular zone or facility within the building will serve as a warming and/or cooling centre (place of refuge).

Applications for Passive Performance Energy Models and Thermal Resilience Indicators and Metrics



Passive Performance Energy Models

- ***Whole Building*** - Model a typical floor to obtain performance indicators and metrics extensible to whole building. Assess strategies for solar orientation, shading, spectrally selective glazing by solar orientation, natural ventilation.
- ***Zone in Building*** - Passive habitability for warming/cooling place of refuge. Suitability for low temperature intensity space heating and cooling HVAC.
- ***Suite in Building*** - Identify unit with weakest thermal resilience (passive habitability and extreme maximum and minimum temperatures, freezing potential).

Passive Performance Indicators and Metrics

- Thermal autonomy (% of year)
- Passive habitability (hours to threshold temperature)
- Annual space heating and cooling energy demands (ekWh)
- Peak space heating and cooling energy demands (kW)
- Thermal energy demand intensity - TEDI (ekWh/m^2.year)
- Extreme maximum and minimum indoor temperatures (OC or OF)
- Space heating and cooling load intensities (W/m^2)
- Freezing potential (% risk, frequency and severity)
- Energy supply storage requirements (remote and/or emergency facilities)

Energy models reflect the type of thermal resilience being assessed. *Regardless of the indicator and metrics being assessed, it is advisable to keep the modeling as simple as possible to maximize comparative performance information between combinations of passive measures while expending minimum time and effort.*

Where every dwelling unit in a multi-unit residential building must achieve a minimum acceptable level of thermal resilience, then only the critical suites need to be assessed. For example, in the northern hemisphere, typically north-facing suites face the greatest challenges to achieve similar levels of thermal autonomy and passive habitability during winter as compared to south-facing suites that enjoy solar gains. South and west-facing suites normally face the greatest challenges during the summer months and controlling overheating requires a strategic combination of passive measures.

In general, it is advisable to assess the thermal resilience of individual suites or occupancies, followed by zones along entire floors and eventually the whole building. Given that a chain is only as strong as its weakest link, it is usually the most critical suite, occupancy or zone in a building that establishes the level of thermal resilience that is imparted to the entire building. While window characteristics such as U-value, solar heat gain coefficients and shading devices may vary by solar orientation, generally is found that opaque building enclosure assemblies remain fairly uniform over the entire building project, as do desired levels of airtightness. Where it becomes extremely challenging to achieve a minimum acceptable level of thermal resilience in a particular suite, zone or occupancy of a building, or that extending the passive measures for the enclosure to the entire building is unaffordable, then strategies and protocols for sheltering inhabitants in warming/cooling places of refuge may be a more feasible approach.

Thermal autonomy analysis is also helpful in establishing design criteria for low temperature space heating and cooling technologies. HVAC systems that incorporate technologies such as in-floor radiant heating and cooling systems and chilled beams are only effective in providing comfort if the space conditioning energy demand intensities are very low. Thermal resilience design can contribute to making responsible choices to combat climate change and promote low carbon climate change adaptation.

Low temperature space heating and cooling technologies rely on correspondingly low thermal energy demand intensities. *Passive measures are the key to a well-tempered indoor environment to maintain minimal indoor space conditioning energy demands that can be satisfied with low temperature systems. Low and no carbon thermal energy systems, such as geothermal and district energy systems based on renewable energy sources, are low exergy systems that operate within a low range of temperatures. They depend on the building enclosure to passively manage heat gains and losses within limited thresholds, especially in glazed perimeter zones.*

Minimum Effective Thermal Resistance Values and Airtightness Levels for Enclosures

An important step in the process of thermal resilience design is the selection of thermal efficiency levels for building enclosure component. At the schematic design stage, it is not necessary to develop actual enclosure assemblies and details - one the effective R-values / U-values need to be selected to begin energy modeling. It is also necessary to assume a level of enclosure airtightness with the understanding detailing of the air barrier system will take place during the design development stages.

As requirements for energy efficiency become more demanding, the primary role of the enclosure is becoming recognized as the most cost-effective means of attaining high-performance targets. The table below indicates recommended effective R-values (RSI values) for various enclosure components for use in residential buildings. Note these are effective R-values that account for thermal bridging effects.

Climate Zone	Wall	Vented Attic	Compact Roof	Basement Wall*	Exposed Floor	Slab Edge	Windows U (U_{SI})/SHGC	Sub-Slab
1	10 (1.76)	40 (7.04)	35 (6.16)	5 (0.88)	10 (1.76)	none	any	none
2	15 (2.64)	50 (8.81)	40 (7.04)	10 (1.76)	20 (3.52)	5 (0.88)	0.35 (2.0) / < 0.25	none
3	20 (3.52)	50 (8.81)	45 (7.93)	10 (1.76)	20 (3.52)	7.5 (1.32)	0.30 (1.7) / < 0.3	5 (0.88)
4	25 (4.40)	60 (10.57)	45 (7.93)	15 (2.64)	30 (5.28)	7.5 (1.32)	0.30 (1.7) / < 0.35	7.5 (1.32)
5	30 (5.28)	65 (11.45)	50 (8.81)	15 (2.64)	30 (5.28)	10 (1.76)	0.24 (1.4) / < 0.50	7.5 (1.32)
6	35 (6.16)	75 (13.21)	60 (10.57)	20 (3.52)	40 (7.04)	10 (1.76)	0.18 (1.0) / --	10 (1.76)
7	40 (7.04)	90 (15.85)	65 (11.45)	25 (4.40)	45 (7.93)	15 (2.64)	0.15 (0.9) / --	15 (2.64)
8	50 (8.81)	100 (17.61)	75 (13.21)	35 (6.16)	50 (8.81)	20 (3.52)	0.15 (0.9) / --	20 (3.52)

* Continuous insulation, interior or exterior, over full height of basement - sub-slab insulation as indicated.
-- for Window SHGC indicates any value acceptable, but > 0.50 preferred to take advantage of solar gains and daylighting.

Recommended R-values (RSI) by Climate Zone for High-Performance Residential Construction.
[Source: Building America Special Research Project: High R-Value Enclosures for High-Performance Residential Buildings in All Climate Zones. Building America Report 1005. John Straube, Building Science Corporation, Revised February 2011.]

Residential buildings demand high levels of thermal resilience in order to provide shelter to inhabitants during prolonged power outages coinciding with extended extreme weather events. High levels of thermal insulation and energy efficient windows and glazing combined with enclosure airtightness not only deliver thermal resilience and passive habitability, but also serve to protect vital infrastructure inside the building, such as potable water supply, from freezing. It is commonly reported that bursting water pipes in residential buildings during extreme cold weather events cause water damage to electrical service panels that eventually fail, in some cases burn out. Not only does this put occupants of the building in danger, it also cuts the supply of electricity and thus puts all building systems out of commission. The net result in large residential buildings is disabled elevators and water pumps serving higher levels, no heating, ventilation or domestic hot water, no operational lights, stoves, fridges or electrical appliances and equipment - often emergency signs and lighting in stairwells are compromised. While some of these problems arise from a lack of maintenance and poor facilities management practices, the susceptibility of an inferior building enclosure to the risks of freezing is very often a contributing factor. A thermally efficient building enclosure is key to resilience.

Climate Zone	Wall	Vented Attic	Compact Roof	Basement Wall*	Exposed Floor	Slab Edge	Windows U (U_{SI})/SHGC	Sub-Slab
1	10 (1.76)	30 (5.28)	15 (2.64)	5 (0.88)	10 (1.76)	none	1.2 (6.8) / < 0.25	none
2	10 (1.76)	40 (7.04)	20 (3.52)	5 (0.88)	20 (3.52)	5 (0.88)	1.2 (6.8) / < 0.25	7.5 (1.32)
3	15 (2.64)	40 (7.04)	20 (3.52)	5 (0.88)	20 (3.52)	7.5 (1.32)	0.6 (3.4) / < 0.25	10 (1.76)
4	20 (3.52)	40 (7.04)	20 (3.52)	5 (0.88)	30 (5.28)	7.5 (1.32)	0.40 (2.3) / < 0.4	15 (2.64)
5	20 (3.52)	40 (7.04)	20 (3.52)	5 (0.88)	30 (5.28)	10 (1.76)	0.35 (2.0) / < 0.4	15 (2.64)
6	20 (3.52)	40 (7.04)	20 (3.52)	10 (1.76)	30 (5.28)	10 (1.76)	0.35 (2.0) / < .40	15 (2.64)
7	20 (3.52)	40 (7.04)	20 (3.52)	10 (1.76)	30 (5.28)	15 (2.64)	0.35 (2.0) / --	20 (3.52)
8	20 (3.52)	50 (8.81)	20 (3.52)	10 (1.76)	40 (7.04)	20 (3.52)	0.35 (2.0) / --	20 (3.52)

* Continuous insulation, interior or exterior, over full height of basement - no sub-slab insulation unless slab is heated.
-- for Window SHGC indicates any value acceptable, but > 0.40 preferred to take advantage of solar gains and daylighting.

Recommended R-values (RSI) by Climate Zone for Steel-Framed, Commercial Construction.
[Adapted from ASHRAE 90.1-2016 Energy Standard for Buildings Except Low-Rise Residential Buildings.]

The table above indicates slightly lower effective R-values for the same components in steel-frame commercial buildings. The lower R-values reflect the fact that the thermal metabolisms of most commercial buildings are internal load dominated due to high heat gains from people, lighting, and equipment. As a result, the cost-effective levels of thermal insulation are balanced between heating and cooling demands, but this balance will shift as lighting and office equipment become much more energy efficient. In the event a commercial or institutional building is intended to provide a level of thermal resilience similar to that justified in residential occupancies, then the insulation levels and window quality should reflect the values indicated in the previous table.

Cost Effectiveness Versus Thermal Resilience

Energy codes are often based on cost effectiveness analyses that consider the costs associated with higher levels of enclosure thermal efficiency versus the savings in operation costs - typically, maintenance and repair costs associated with durability problems are not factored into the analyses. Thermal comfort is seldom considered and resilience is simply not a consideration in formulating minimum requirements for the building enclosure.

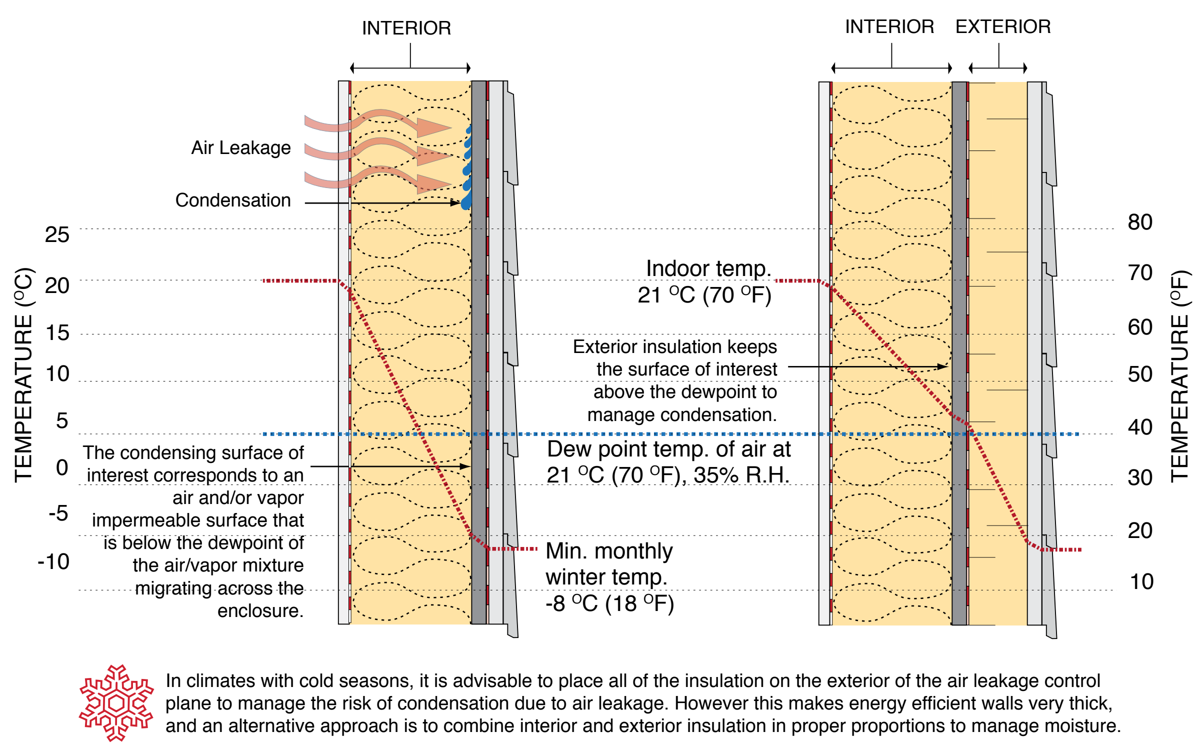
Performance paths in many energy codes permit the use of much lower levels of thermal insulation by trading off energy efficient lighting and HVAC equipment against the enclosure efficiency. This tends to result in buildings with larger sized HVAC equipment and enclosures that are often uncomfortable during extreme weather, hot and cold. There is an increasing awareness among the building science community that observing appropriate levels of insulation, as indicated in the previous tables, is a cost-effective means of achieving high-performance buildings that are more comfortable, robust and resilient.

If the costs for damages, deterioration, disruptions and inconvenience associated with buildings that have marginal resilience and experience prolonged power outages during extended periods of extreme weather are taken into account, then the thermal performance of building enclosures would be much higher than what is justified by energy savings alone. This line of argument reinforces the inherent incompatibility of energy economics criteria with the realities of building physics and climate change.

Thermal Resilience and Durability

It is widely understood that higher enclosure thermal insulation levels can increase the potential for moisture damage in building enclosures. The discussion that follows examines exterior wall assemblies, but the concepts can be extended to all enclosure components and assemblies.

Achieving exterior walls with higher effective R-values can be challenging because they become thicker as more insulation is added, and require different details for cladding attachment, structural penetrations, window trim, etc. When exterior walls with higher effective R-values are desired, or required by codes, these may be achieved by placing all of the insulation to the exterior of the wall structure and air barrier plane, or by placing insulation both within the wall cavity and the exterior. However, the ratio of exterior to interior insulation must be observed as indicated in the table that follows in order to manage the risk of condensation inside the wall.

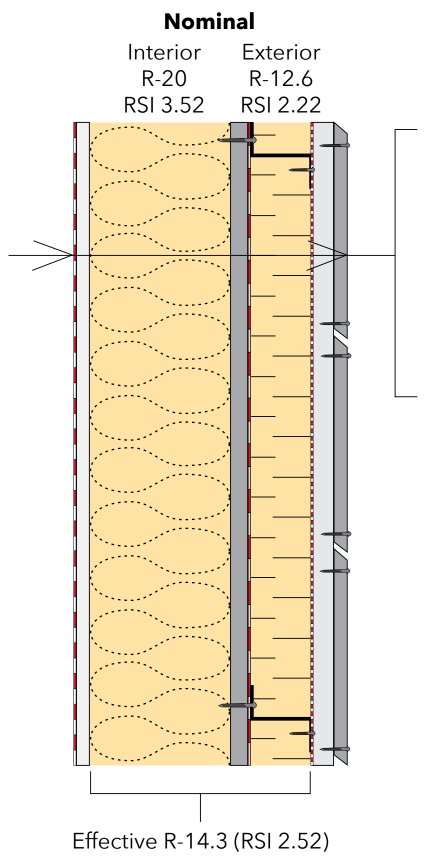


Continuous exterior insulation improves the thermal efficiency of walls. *It also helps manage moisture problems due to air leakage in cold climates.*

Interstitial condensation is a critical concern in cold climates where the potential for warm moist are migrating through the building enclosure along air leakage paths can lead to significant moisture accumulations, deterioration and the risk of mold growth. Based on extensive hygrothermal simulations, the table that follows indicates the required ratio of exterior (outboard) to interior (inboard) insulation to avoid condensation problems. Typically, the mean daily minimum temperature for the coldest month of the year, along with the expected indoor relative humidity, are used as the basis for selecting the proper exterior to interior insulation ratio. For example, in Toronto, Canada, the mean daily minimum temperature in January is -11.1 Celsius or 12 OF and if the indoor relative humidity was to be maintained at 40%, the ratio of exterior to interior insulation may be interpolated as 0.55.

Indoor	RH		20	25	30	35	40	50	60
Dew Point	°C		-3	0.0	2.5	4.7	6.6	9.9	12.7
	°F		26.6	32.0	36.6	40.5	44.0	49.9	54.8
$T_{OUTDOOR}$	°C	°F	Ratio of exterior to interior insulation (effective R-values)						
	0	32	0.00	0.00	0.12	0.23	0.32	0.47	0.60
	-5	23	0.08	0.19	0.29	0.37	0.45	0.57	0.68
	-10	14	0.23	0.32	0.40	0.48	0.54	0.64	0.73
	-15	5	0.33	0.42	0.49	0.55	0.60	0.69	0.77
	-20	-4	0.41	0.49	0.55	0.60	0.65	0.73	0.80
	-25	-13	0.48	0.54	0.60	0.65	0.69	0.76	0.82
	-30	-22	0.53	0.59	0.64	0.68	0.72	0.78	0.84
	-35	-31	0.57	0.63	0.67	0.71	0.74	0.80	0.85
	-40	-40	0.61	0.66	0.70	0.73	0.76	0.82	0.86

Hygrothermal analysis is key to maintaining enclosure durability. *Ratio of interior to exterior thermal insulation to manage the risk of condensation from the leakage of indoor air into the exterior wall assembly. [Source: High Performance Enclosures, by John Straube, Building Science Press, 2012.]*



Example: In a building located where the average daily minimum January temperature is 12 oF (-11.1 oC), and the indoor relative humidity is intended to be maintained at 40%, the ratio of exterior to interior insulation is given as 0.55. If the interior insulation in a 5.5 inch (140mm) wall cavity is R-20 (RSI 3.52), then the exterior insulation should be at least R-11.0 (RSI 1.94), based on nominal insulation values.

(Important Note: Assuming an insulated steel stud wall and metal cladding attachments, the overall effective thermal resistance of the wall will be significantly less than the nominal thermal resistance of the insulation layers, i.e., 20 + 12.6 = R-32.6 or RSI 5.74.)

Validated calculation methods that take 3-dimensional heat flows into account indicate the overall effective thermal resistance of the wall is only R-14.3 (RSI 2.52). This means that the thermal efficiency of this wall assembly, based on the nominal insulation values is 14.3/32.6 = 43.9%. The wall is durable but not suitable for thermal resilience purposes, and it also may not comply with codes.

Effective thermal resistance of building enclosure components is critical to resilience. *Recent research indicates that methods of construction and cladding attachment can significantly compromise the overall effective thermal resistance of exterior walls. Designing for resilience demands an enclosure that is thermally efficient and durable.*

Noting the example wall assembly in the previous figure, it is important to appreciate that while the potential for condensation has been properly managed, the overall effective thermal resistance of the wall is significantly less than the nominal thermal resistance of the insulation layers. While it is thermally more efficient to place all of the insulation on the exterior, it may make cladding attachment and window installation more difficult and costlier. This reinforces the important of selecting thermally efficient cladding attachments such that a higher percentage insulation effectiveness may be realized.

Avoid excessive cladding attachments causing thermal bridging. *The excessive use of steel cladding attachments can significantly reduce the overall effective R-value of opaque wall assemblies. It is important to ensure that measures to effectively manage moisture and air leakage are not undone by thermally inefficient opaque wall assemblies.*

Thermally efficient enclosures are practically achievable. *A continuous, structurally supported air/vapour barrier with two layers of insulation using point fasteners to minimize thermal bridging is an effective means of managing enclosure heat flows.*

Airtightness and Thermal Resilience

The need for airtightness in building enclosures goes beyond achieving thermal resilience. Controlling air leakage helps manage moisture migration across the building enclosure minimizing the risk of condensation leading to mold growth and deterioration. A great deal of energy is saved by managing air leakage and this also contributes to improving occupant thermal comfort. Building pressures are better controlled when a continuous air barrier system is provided and this helps manage air, odour and smoke movement in buildings.

Thermal autonomy and passive habitability require a continuous air barrier that does not allow air leakage rates to exceed 2 L/s.m2 @ 75 Pa (0.4 cfm/ft2 @ 1.57 psf) during whole building airtightness testing. It is important to model this level of airtightness correctly when conducting energy simulations. If airtightness is too low, it will be difficult to achieve acceptable thermal resilience results. Setting airtightness too high, beyond this threshold, will not result in any appreciable difference in performance. A sensitivity analysis of airtightness can be easily conducted to verify the veracity of the claim that beyond a certain threshold, airtightness does not measurably enhance performance. Additional references regarding air barriers and airtightness testing are provided in the latter sections of this guide.

Application	Metric	U.S.
Residential R-2000	1.5 ach* @ 50 Pa 0.7 L/s.m^2 @ 75 Pa	0.14 cfm/ft^2 @ 1.57 psf
Passive House	0.6 ach @ 50 Pa 0.28 L/s.m^2 @ 75 Pa	0.048 cfm/ft^2 @ 1.57 psf
Commercial Building NBCC, IECC, ASHRAE 90.1	2 L/s.m^2 @ 75 Pa	0.4 cfm/ft^2 @ 1.57 psf
Commercial Building U.S. Army Corps of Engineers	1.3 L/s.m^2 @ 75 Pa	0.25 cfm/ft^2 @ 1.57 psf

* ach - air changes per hour. The volume of air leaked per hour divided by the volume of the building.
75 Pa = 1.57 psf = 0.3" w.c. (H_2O)

Whole Building Airtightness Testing Standards

- CAN/CGSB 149.15 - Determination of the Overall Envelope Airtightness of Buildings by the Fan Pressurization Method Using the Building's Air Handling Systems
- The United States Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes
- ISO 9972:2006 - Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method
- ASTM E779 - Standard Test Method for Determining Air Leakage Rate by Fan Pressurization
- ASTM E1827 - Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door
- ATTMA - Measuring Air Permeance of Building Envelopes (Dwellings)
- ATTMA - Measuring Air Permeance of Building Envelopes (Non-Dwellings)

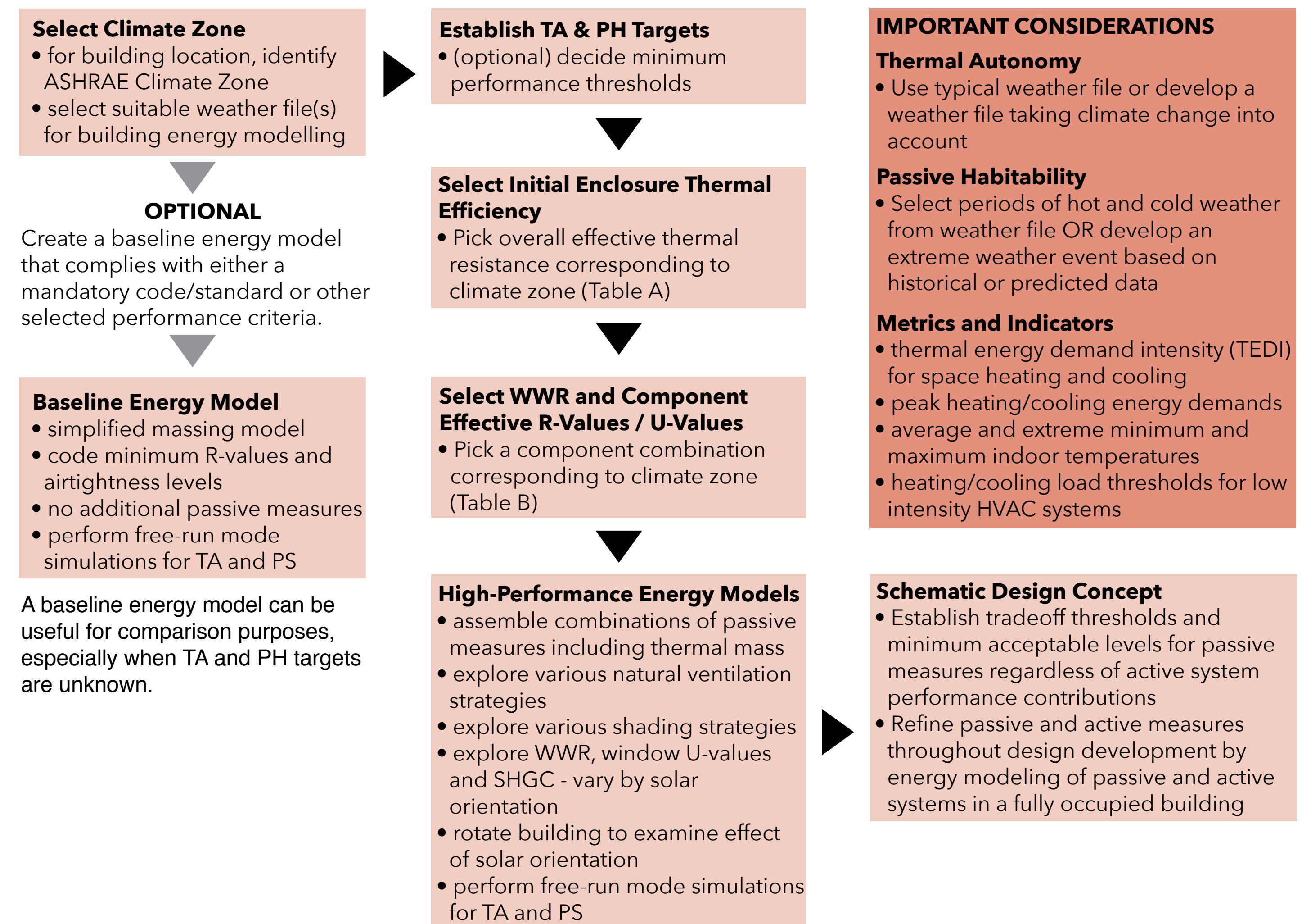
Airtightness is critical to achieving thermal resilience. *The chart above indicates various levels of airtightness (allowable air leakage rates) associated with high-performance building enclosures. Any one of these airtightness levels will contribute positively to enhanced thermal resilience, but higher levels of airtightness may be desirable to maintain long-term durability as the air barrier system ages.*

Modeling Thermal Resilience

There are several critical aspects to modeling thermal resilience. Accurately determining the effective thermal resistance of various enclosure components and assemblies is extremely critical as these values are inputs to energy simulation models. This aspect of thermal resilience modeling is not dealt with in this guide but references are provided in subsequent sections to guide proper thermal enclosure modeling. There is also an appendix on energy modeling complete with references to technical literature provided in this guide. The flowchart below depicts the recommended methodology for modeling thermal resilience and it is assumed the users of this guide possess the entry level of knowledge and experience needed to perform the required steps.

Thermal Autonomy (TA) and Passive Habitability (PH) Energy Modeling Methodology

Refer to the appendix on energy modeling and to references on thermal resilience design for more detailed information. Begin with a schematic design of the proposed building, or comprehensive building retrofit - follow the steps below.



__A methodology for modeling thermal autonomy and passive habitability has not been formalized.__ The chart above indicates various levels of airtightness (allowable air leakage rates) associated with high-performance building enclosures. Any one of these airtightness levels will contribute positively to enhanced thermal resilience, but higher levels of airtightness may be desirable to maintain long-term durability as the air barrier system ages.

The overall effective R-values appearing in Table A were generated over a period of time during which academic research and studies were conducted by the authors of this guide on behalf of various funding agencies. The plot of U = 1/R indicates how milder climates require lower levels of overall effective R-values for the enclosure. Note that levels beyond R-28 (RSI 5.0) deliver rapidly diminishing returns for thermal resilience in buildings, however, even higher values may be justified for enclosures without windows such as refrigeration storage facilities.

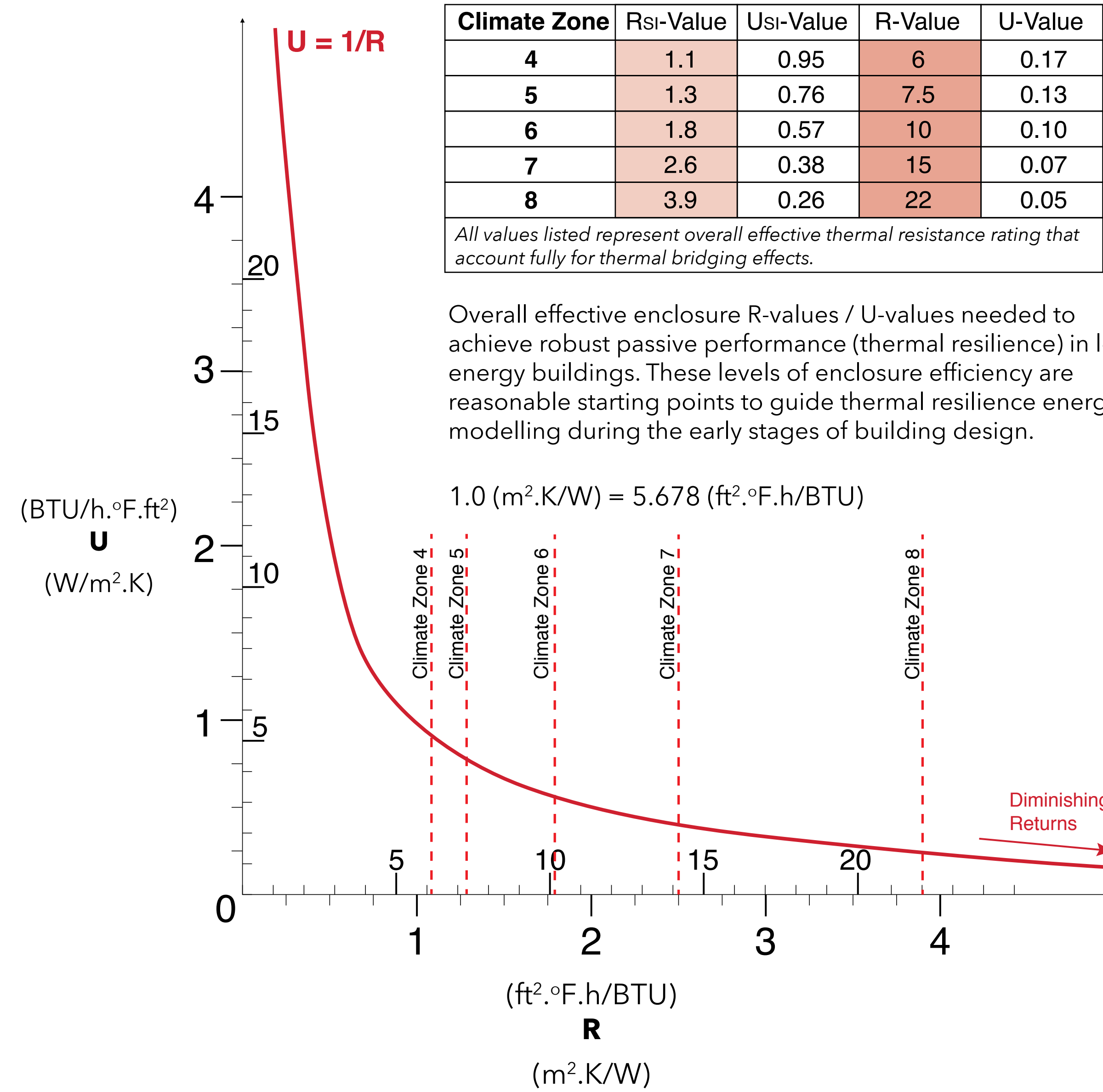
TABLE A - Minimum Recommended Levels of Enclosure Efficiency for Thermal Resilience Design

Climate Zone	RSI-Value	USI-Value	R-Value	U-Value
4	1.1	0.95	6	0.17
5	1.3	0.76	7.5	0.13
6	1.8	0.57	10	0.10
7	2.6	0.38	15	0.07
8	3.9	0.26	22	0.05

All values listed represent overall effective thermal resistance rating that account fully for thermal bridging effects.

Overall effective enclosure R-values / U-values needed to achieve robust passive performance (thermal resilience) in low energy buildings. These levels of enclosure efficiency are reasonable starting points to guide thermal resilience energy modelling during the early stages of building design.

1.0 (m².K/W) = 5.678 (ft².°F.h/BTU)



Overall effective thermal efficiency of the enclosure is a significant indicator of thermal resilience. *The overall effective R-values depicted above represent departure points for preliminary simulations and analyses corresponding to each ASHRAE Climate Zone. These are derived from extensive parametric simulations but should viewed as initial values, not as a substitute for more sophisticated and ongoing simulations.*

In order to proceed efficiently with energy modeling, select a window-to-wall ratio (WWR) and enclosure effective R-values from Table B corresponding to each climate zone covered by this guide.

TABLE B - WWR and Enclosure Component R-Values Corresponding to Enclosure Overall Recommended R-Values by Climate Zone

ZONE 4

Window-to-Wall Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%
Roof (RSI)	3.52	3.52	3.52	3.52	3.52	3.52	4.4	4.4	4.4
Walls (RSI)	3.35	3.35	3.35	3.52	3.52	3.52	3.52	3.52	3.52
Slab-on-Grade (RSI)	0.88	0.88	0.88	0.88	0.88	1.32	1.32	1.32	1.32
Windows (RSI)	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.7
Overall USI-Value	0.60	0.68	0.76	0.83	0.89	0.89	0.85	0.82	0.88
Overall RSI-Value	1.67	1.48	1.32	1.20	1.10	1.12	1.18	1.22	1.14
Overall R-Value	9.5	8.4	7.5	6.8	6.2	6.4	6.5	6.9	6.5

ZONE 5

Window-to-Wall Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%
Roof (RSI)	3.52	3.52	4.4	4.4	4.4	4.4	4.93	7.04	7.04
Walls (RSI)	3.35	3.35	3.35	3.52	3.52	3.52	4.4	4.93	4.93
Slab-on-Grade (RSI)	0.88	0.88	0.88	0.88	0.88	1.32	1.32	1.32	1.32
Windows (RSI)	0.5	0.5	0.5	0.6	0.6	0.6	0.8	0.8	0.9
Overall USI-Value	0.60	0.68	0.74	0.75	0.72	0.72	0.70	0.73	0.72
Overall RSI-Value	1.67	1.48	1.35	1.33	1.39	1.39	1.44	1.38	1.40
Overall R-Value	9.5	8.4	7.7	7.5	7.9	7.9	8.2	7.8	7.9

ZONE 6

Window-to-Wall Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%
Roof (RSI)	5.64	5.64	5.64	5.64	7.04	7.04	7.04	7.04	7.04
Walls (RSI)	3.52	3.52	3.52	3.87	4.4	4.4	5.64	5.64	5.64
Slab-on-Grade (RSI)	1.76	1.76	1.76	1.76	2.64	2.64	2.64	2.64	2.64
Windows (RSI)	0.5	0.5	0.6	0.7	0.8	0.8	0.85	0.9	1
Overall USI-Value	0.41	0.49	0.52	0.54	0.53	0.53	0.55	0.57	0.57
Overall RSI-Value	2.43	2.03	1.91	1.86	1.90	1.88	1.82	2.75	1.76
Overall R-Value	13.8	11.6	10.8	10.6	10.8	10.7	10.4	10.0	10.0

ZONE 7

Window-to-Wall Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%
Roof (RSI)	7.04	7.04	7.04	7.04	8.81	8.81	8.81	8.81	10.56
Walls (RSI)	4.4	4.93	4.93	4.93	5.64	5.64	5.64	5.64	7.04
Slab-on-Grade (RSI)	1.76	2.64	2.64	2.64	2.64	2.64	2.64	2.64	3.52
Windows (RSI)	0.5	0.6	0.8	1	1	1.2	1.5	1.5	1.5
Overall USI-Value	0.38	0.37	0.38	0.38	0.41	0.40	0.37	0.40	0.39
Overall RSI-Value	2.64	2.70	2.63	2.62	2.46	2.51	2.67	2.52	2.58
Overall R-Value	15.0	15.3	14.9	14.9	14.0	14.3	15.2	14.3	14.6

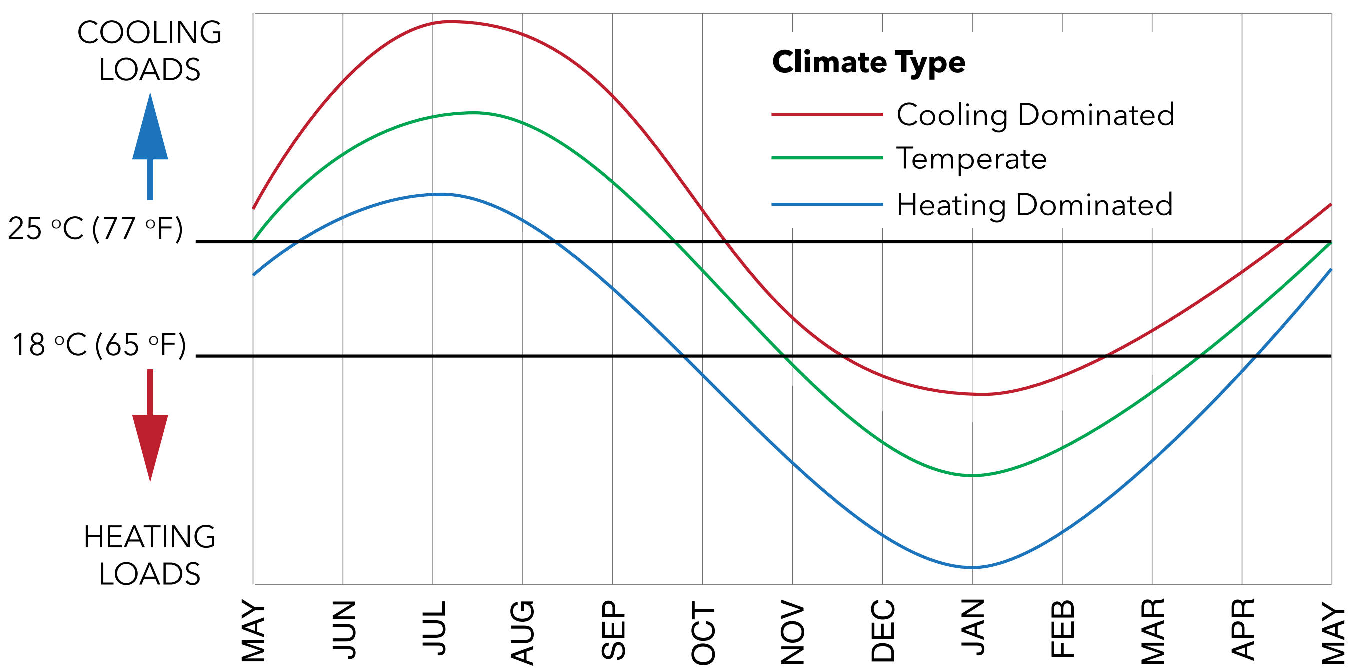
ZONE 8

Window-to-Wall Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%
Roof (RSI)	8.81	10.56	10.56	10.56	10.56	10.56	10.56	10.56	10.56
Walls (RSI)	5.64	7.04	7.04	7.04	7.04	7.04	7.04	7.04	7.04
Slab-on-Grade (RSI)	2.64	2.64	3.52	3.52	3.52	3.52	3.52	3.52	3.52
Windows (RSI)	1	1.2	1.2	1.5	1.5	1.5	1.5	1.5	1.5
Overall USI-Value	0.25	0.26	0.26	0.27	0.29	0.31	0.34	0.36	0.39
Overall RSI-Value	3.96	3.89	3.79	3.77	3.45	3.18	2.95	2.75	2.58
Overall R-Value	22.5	22.1	21.5	21.4	19.6	18.1	16.8	15.6	14.6

NOTES:
Use component effective thermal resistance levels as starting points for thermal resilience energy modelling.
Overall R-value based on building aspect ratio range of 1:1 up to 1:2 - re-calculate as required.
For buildings with basements, assume these are full-height insulated to same level as slab-on-grade.
Include skylight areas within window-to-wall ratios.

Simulation time and effort can be minimized by starting with a reasonable combination of building enclosure effective R-values for a given window-to-wall ratio. *The combinations tabled above correspond to recommended initial values for each climate zone. Note that in Zone 8 it is difficult to maintain the recommended overall effective R-value when the WWR exceeds 50%.*

The chart below may be employed to select suitable and effective passive measures that can be deployed according to a number of strategies. These will reveal critical thermal resilience relationships for individual suites, zones in a building, and for the entire building.



Once a number of combinations of various passive measures and design strategies have been modelled, it is very time and effort efficient to comparatively visualize their performance. Research has indicated that the type of energy modeling conducted for code compliance purposes yields results that are often overwhelming and unclear. The mixing of passive and active systems in an energy model makes the optimization of passive measures extremely difficult, if not impossible. By conducting energy simulations in free-run mode with no active or occupant interactions, the contributions of the passive measures can be clearly isolated and studied in depth.

Thermal Resilience Passive Measures

● Critical
● Recommended
○ Optional

* On all facades in hot climates, South & West facades in temperate climates.
** On South and East facades in cold climates.
*** On North facades in cold climates.

Climate Type	High Levels of Thermal Insulation	Continuous Air Barrier	High Performance Windows	40% < WWR > 60%	Low SHGC Glazing < 0.3 *	High SHGC Glazing > 0.5 **	Thermal Breaks for Balconies	Balcony Enclosures ***	Shading Devices	Natural Ventilation
Cooling Dominated	Recommended	Critical	Recommended	Recommended	Critical	Optional	Optional	Optional	Critical	Critical
Temperate	Recommended	Critical	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Critical	Critical
Heating Dominated	Critical	Critical	Critical	Critical	Optional	Critical	Critical	Critical	Critical	Critical

Passive measures for thermal resilience vary in effectiveness according to the type of climate. *This chart identifies critical passive measures by climate zone. It is important to appreciate that climate change is causing extreme weather events in one climate type that are normally associated with other climate types. Risks and consequences should be carefully considered when testing various passive measures during simulations.*

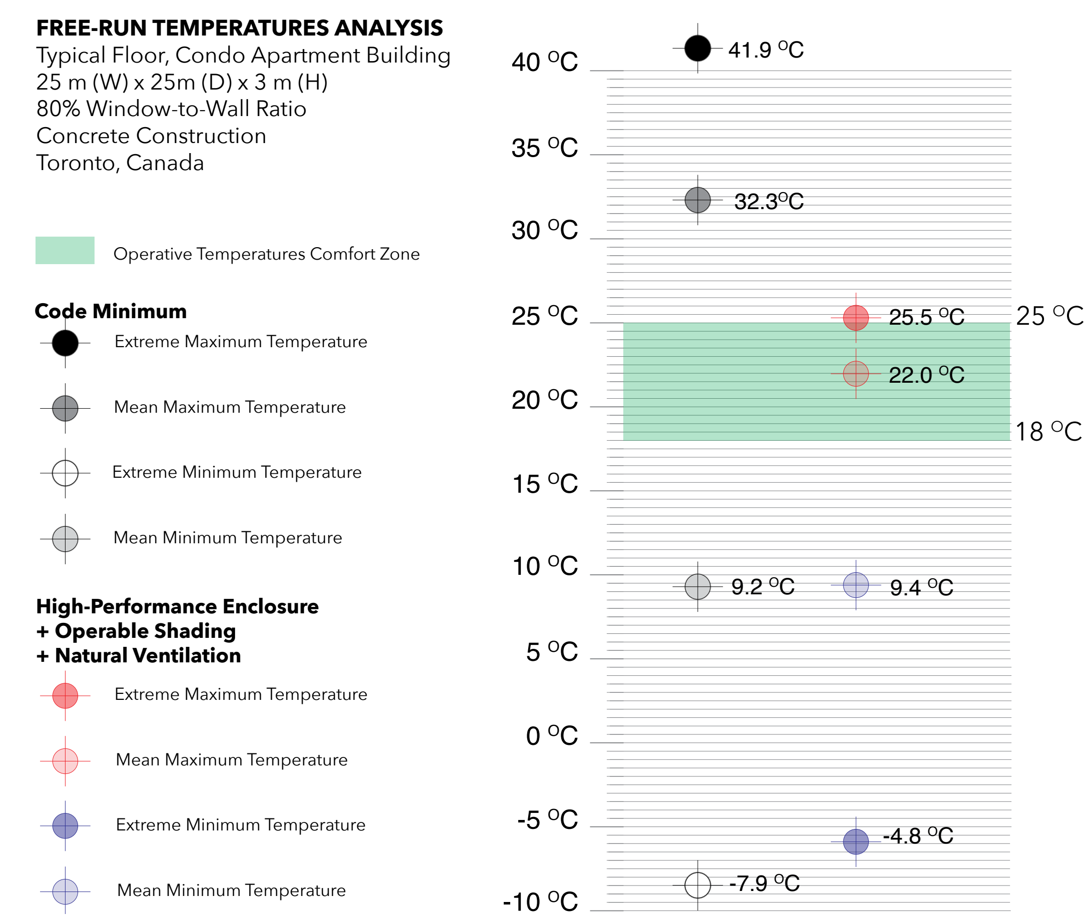
Visualizing Thermal Resilience

It is often debated as to whether or not the tabulation of numerical data is a form of visualization, but it is generally accepted that some types of numerical data are needed to inform the thermal resilience design process.

ENERGY DEMANDS FOR SPACE HEATING AND COOLING Typical Floor, Condo Apartment Building - 25 m (W) x 25m (D) x 3 m (H) Toronto, Canada		Annual Space Heating (kWh)	Space Heating TEDI (kWh/m2.yr)	Peak Heating Demand kW	Annual Space Cooling (kWh)	Space Cooling TEDI (kWh/m2.yr)	Peak Cooling Demand kW	Total Site TEDI (kWh/m2.yr)
40% WWR	Concrete Code Minimum Envelope	18,248	30.9	10.9	5,353	9.1	8.3	40.0
	Concrete High-Performance + Operable Shading + Natural Ventilation	10,035	17.0	6.1	0	0.0	0.0	17.0
	Wood Code Minimum Envelope	19,967	33.8	12.6	7,795	13.2	12.4	47.1
	Wood High-Performance + Operable Shading + Natural Ventilation	11,116	18.8	7.0	118	0.2	3.1	19.0
60% WWR	Concrete Code Minimum Envelope	22,144	37.5	13.9	8,485	14.4	11.7	51.9
	Concrete High-Performance + Operable Shading + Natural Ventilation	11,059	18.7	7.3	0	0.0	0.0	18.7
	Wood Code Minimum Envelope	25,790	43.7	16.3	13,641	23.1	17.6	66.8
	Wood High-Performance + Operable Shading + Natural Ventilation	13,950	23.6	8.7	285	0.5	4.8	24.1
80% WWR	Concrete Code Minimum Envelope	25,627	43.4	16.7	11,603	19.7	14.9	63.1
	Concrete High-Performance + Operable Shading + Natural Ventilation	12,064	20.4	8.5	21	0.0	1.6	20.5
	Wood Code Minimum Envelope	31,672	53.7	19.7	20,105	34.1	23.0	87.8
	Wood High-Performance + Operable Shading + Natural Ventilation	16,928	28.7	10.4	550	0.9	6.0	29.6

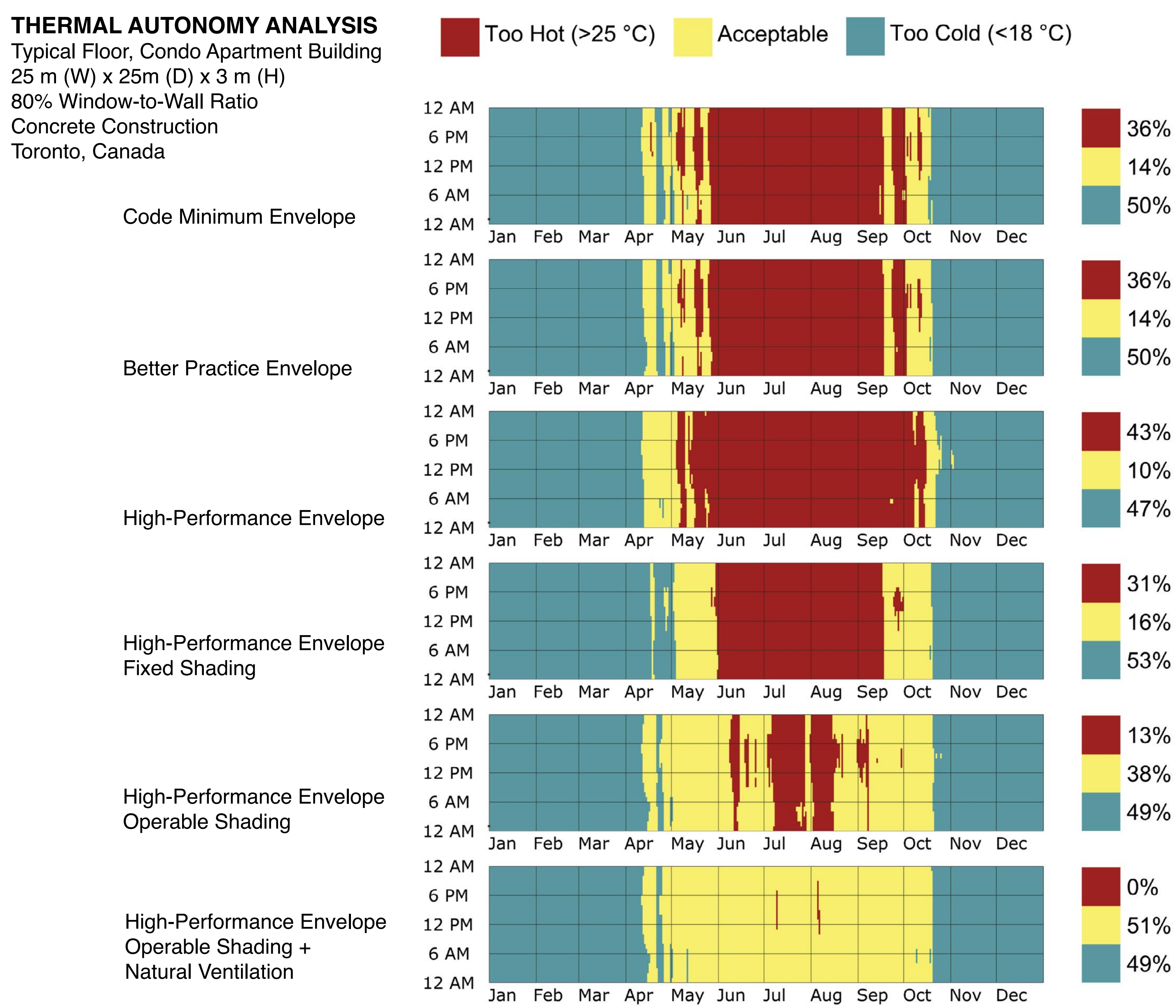
Tabulated data are necessary but insufficient to inform early stages of design. *Unlike code compliance, thermal resilience involves time-based metrics which are best conveyed graphically.*

Plotting free-run temperatures against the operative temperatures comfort zone provides additional information beyond the tabulated energy demand metrics. For example, there is a potential for freezing with either the code minimum or high-performance options, but a high-performance enclosure with operable shading and natural ventilation virtually eliminates the need for space cooling.



Examining critical performance metrics is necessary to appreciate thermal autonomy in a fuller context. *These data are extracted from the same energy model that generated the previous tabulated data. There is a dampening of temperature extremes by the high-performance building, operable shading devices and natural ventilation.*

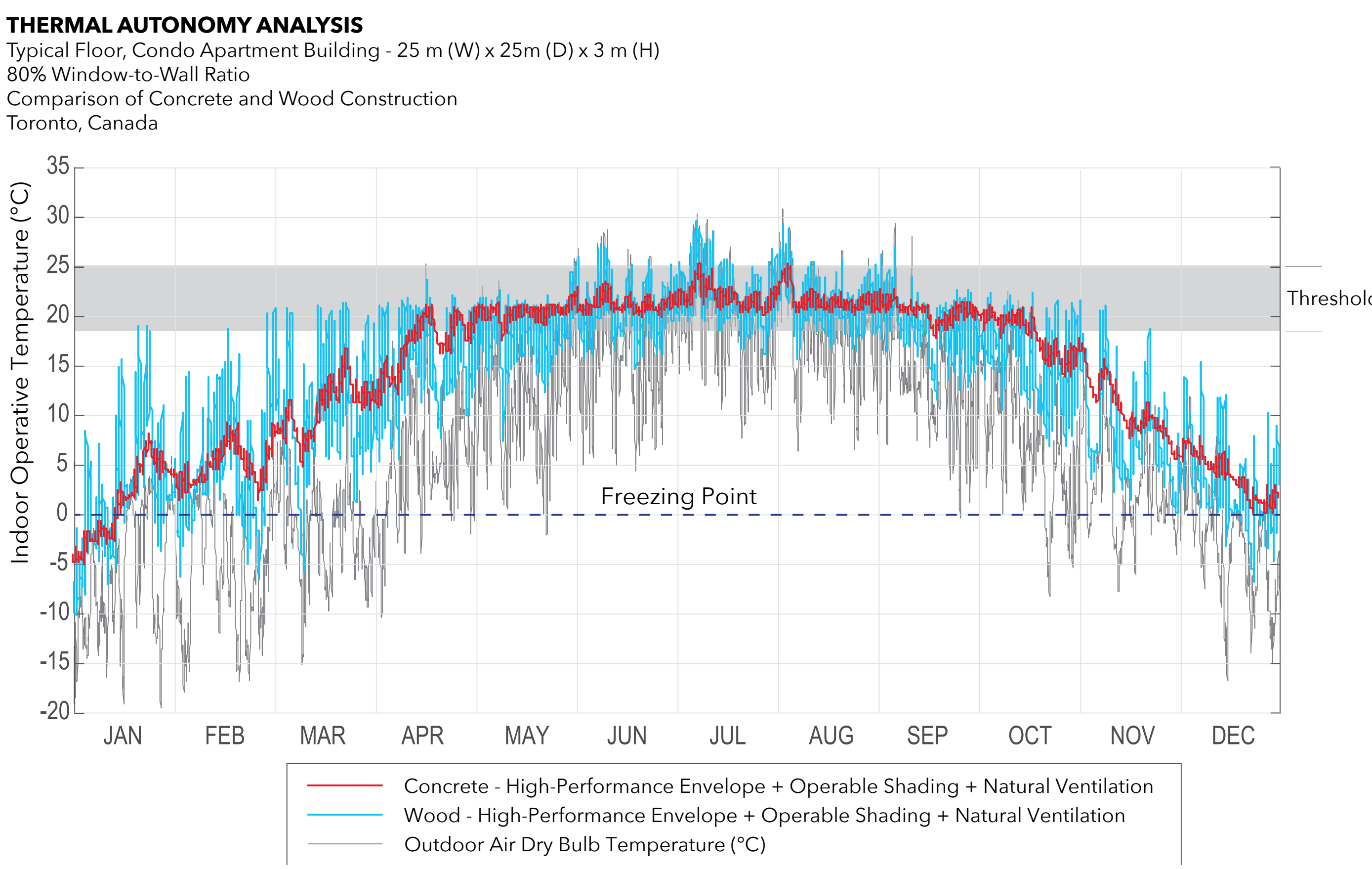
A very useful visualization technique for assessing thermal resilience involves the use of a carpet plot that indicates the "too hot", "acceptable", and "too cold" hours in each day over a typical weather year. When a progression of passive measure combinations is plotted, it is relatively easy to identify the trends as well as the particular contributions of various passive measures to cold weather and hot weather thermal autonomy.



A carpet plot makes for ease of comparing contributions between combinations of passive measures towards thermal autonomy. *However, the carpet plot does not indicate annual and peak energy demands, and the extreme minimum and maximum temperatures are also not displayed.*

Two important relationships emerge from this visualization. First, the percentage of time when it is too cold does not appreciably change regardless of the enclosure thermal efficiency. This may be due to the excessive 80% window-to-wall ratio. Second, the relationship between the high-performance envelope, operable shading and natural ventilation is synergetic with each measure significantly improving performance from 43% too hot down to practically 0% too hot. Something that is not indicated in this carpet plot is just how hot and cold it is inside the building on a daily, seasonal and annual basis

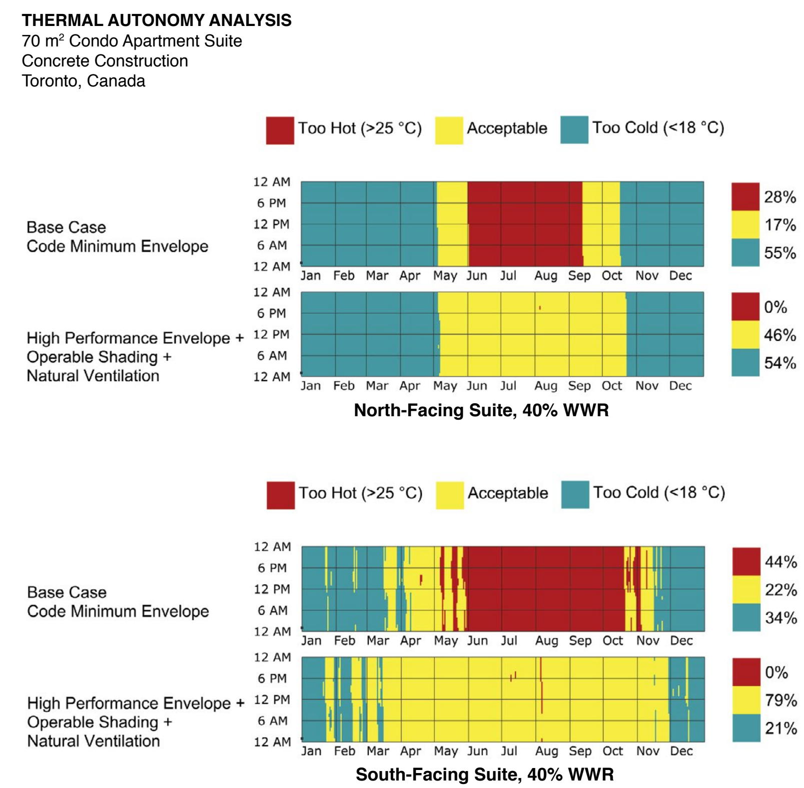
A plot of hourly free-run temperatures over a typical weather year provides critical information about the frequency and intensity of critical events, such as freezing.



Thermal autonomy analysis can be used to assess vulnerability to risks like freezing. *In the plot of hourly temperatures predicted in a "free-run" mode energy simulation, the daily temperature swings are much higher for the wood building structure versus the concrete building structure. Based on a normal weather data, the concrete building structure is only at risk of freezing for about the first half of January, whereas the wood structure has the potential for freezing over a three-month period.*

Unlike the carpet plot reflecting periods of acceptable and unacceptable thermal comfort, the hourly plot of free-run temperatures indicates fluctuations and extreme temperatures. The degree of thermal autonomy is not as conveniently summarized in numerical format, but the thermal response of the building can be more fully appreciated and explored.

The modeling of individual suites or zones in a building reveals important information about the impact of solar orientation on thermal resilience performance.



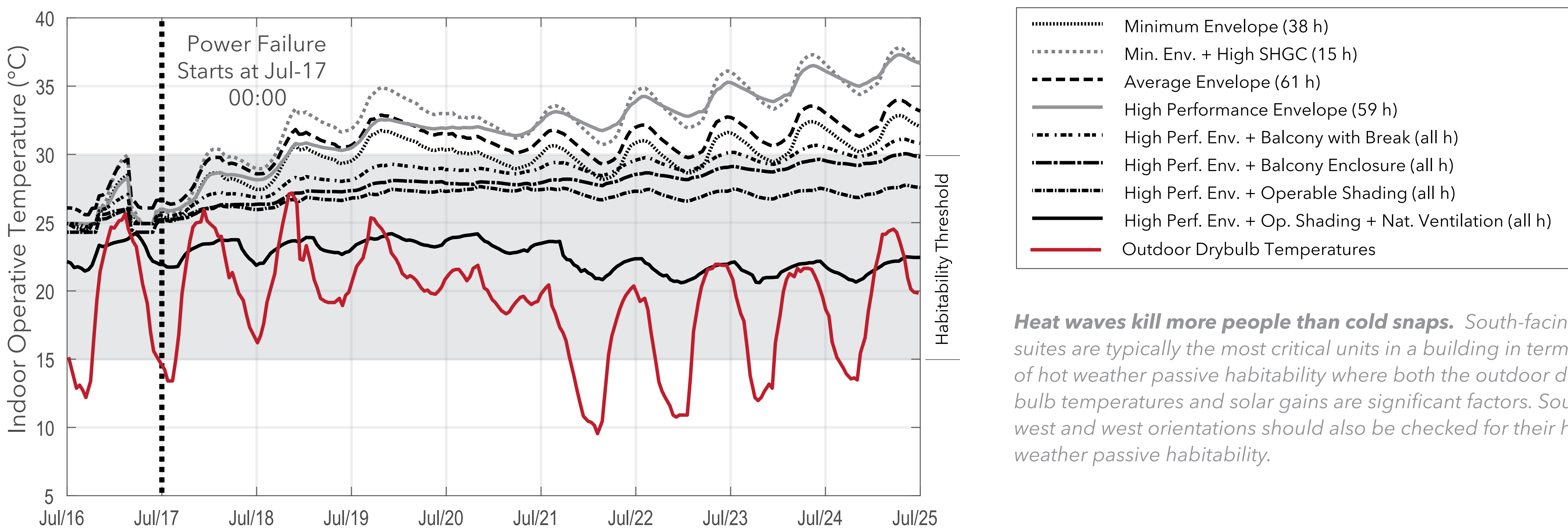
Solar orientation is a significant factor influencing cold weather thermal autonomy. *While both north and south-facing suites fitted out with a high-performance combination of passive measures display complete hot weather habitability, the cold weather passive habitability for the north-facing suite is virtually identical regardless of the passive measures that are deployed.*

It is interesting to note that from the modeling of the entire building presented earlier, its cold weather passive habitability trends towards the same level as the north-facing suite. This relationship holds for both the code minimum envelope and the high-performance envelope with operable shading and natural ventilation cases. This reveals that in cold climates, compartmentalization of zones with south-facing facades is an effective thermal autonomy strategy that also enhances passive habitability. Attempting to provide enhanced TA and PH for an entire building is normally not feasible unless the north facade has practically no windows, or a single-loaded corridor acts as a buffer zone between the northern exposure and south-facing zone.

Passive habitability analysis can provide even greater resolution for comparative assessments of passive measure strategies.

HOT WEATHER PASSIVE HABITABILITY ANALYSIS

70 m² Condo Apartment Suite North-Facing, 80% Window-to-Wall Ratio Concrete Construction Toronto, Canada



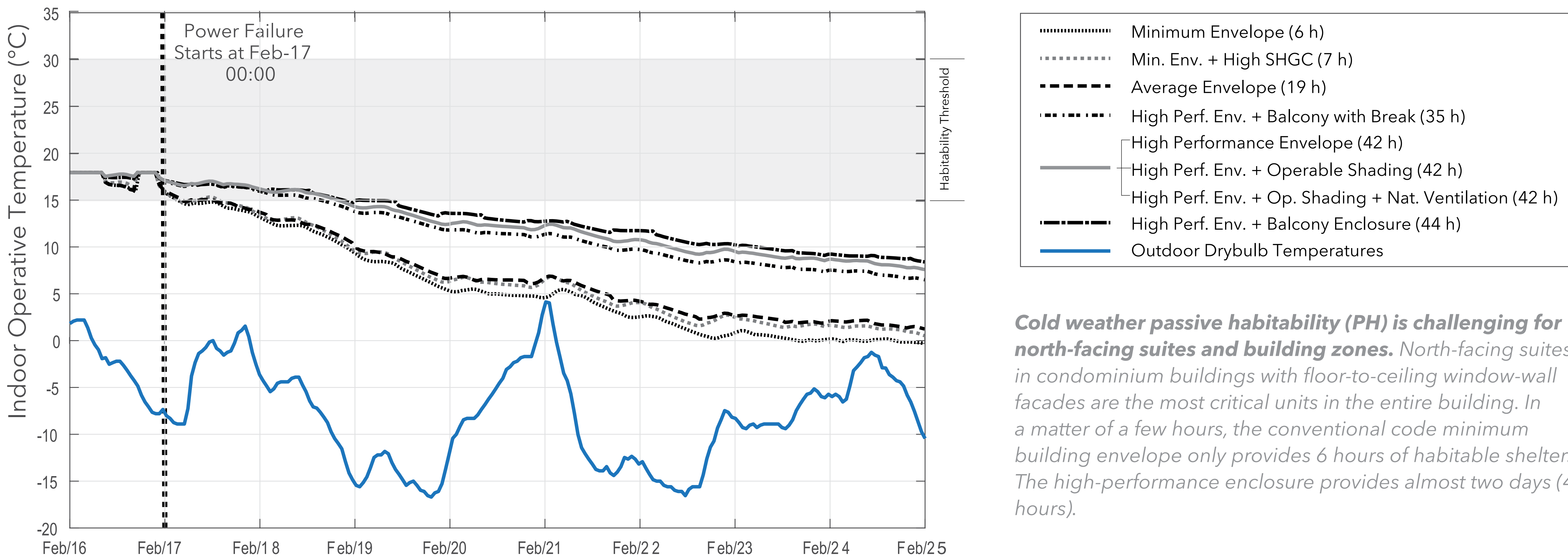
Heat waves kill more people than cold snaps. *South-facing suites are typically the most critical units in a building in terms of hot weather passive habitability where both the outdoor dry bulb temperatures and solar gains are significant factors. South-west and west orientations should also be checked for their hot weather passive habitability.*

Note that the high-performance envelope by itself does not perform any better than a better practices envelope simply because the higher efficiency windows retain heat accumulations. A buffer zone (balcony enclosure) improves performance, but the most significant reductions for interior temperatures are provided by operable shading and natural ventilation. While this set of simulations demonstrates that hot weather passive habitability is achievable even with high window-to-wall ratios, the weather data reflect normal temperatures. A more extreme and extended heat wave would require all of the passive measures to be deployed to remain at the upper habitability threshold.

Cold weather passive habitability is very challenging in cold climates depending on the solar orientation of a suite or zone. It also is affected by whether or not the suite or zone is effectively compartmentalized, or if airflows and heat energy transfer across adjacent spaces.

COLD WEATHER PASSIVE HABITABILITY ANALYSIS

70 m² Condo Apartment Suite North-Facing, 80% Window-to-Wall Ratio Concrete Construction Toronto, Canada



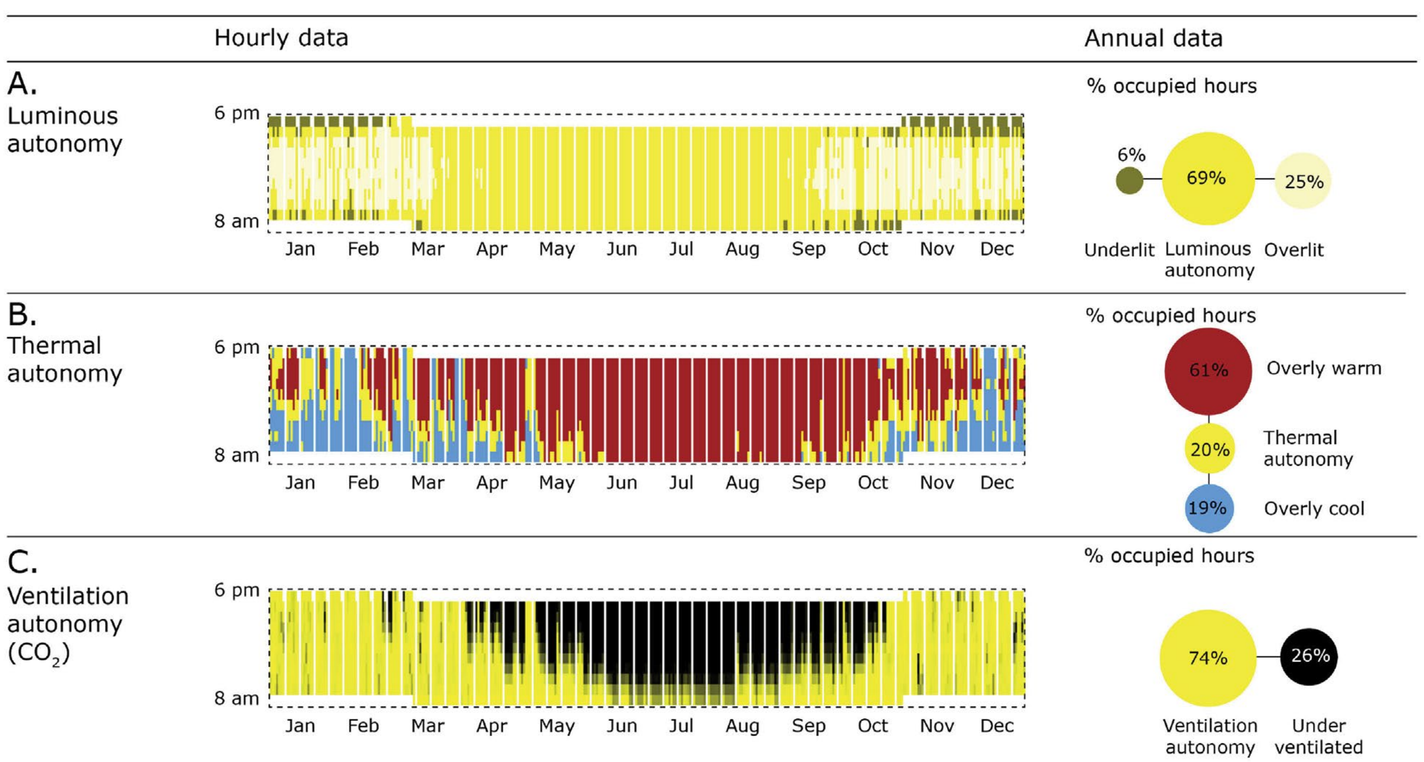
Cold weather passive habitability (PH) is challenging for north-facing suites and building zones. *North-facing suites in condominium buildings with floor-to-ceiling window-wall facades are the most critical units in the entire building. In a matter of a few hours, the conventional code minimum building envelope only provides 6 hours of habitable shelter. The high-performance enclosure provides almost two days (44 hours).*

The very same set of passive measure combinations yield dramatically different cold weather habitability results. This can be expected for north-facing suites/zones in most of Climate Zone 6 where an absence of solar gains is evident in a constantly declining indoor temperature profile.

Beyond Thermal Resilience

The quest for thermal resilience cannot be allowed to compromise the quality of the indoor environment. Access to light and air along with comfortable accommodations must all be integrated within a robust framework of resilience.

Once appropriate thermal resilience measures and strategies have been decided at the early stages of design, it is important to retain them throughout the design development process when features that are invisible, such as high levels of thermal insulation and airtightness, are "value-engineered" out of the equation. And it is also critical not to trade-off passive measures against active systems which do nothing to enhance thermal resilience.



Hourly autonomy map and annual summary – Phoenix, AZ; A. Luminous autonomy (based on the UDI-a, 300–3,000-lux model); B. Thermal autonomy (based on the adaptive-comfort model); and C. Ventilation autonomy (based on CO2 concentration; ASHRAE 62.1).

Thermal resilience and well performing buildings are not mutually exclusive. The sad reality remains that many indigenous and vernacular forms of architecture from centuries ago provided a higher level of thermal resilience than many of our contemporary architectural expressions. This guide is intended to promote more robust and resilient passive features in buildings and to help everyone proactively address the challenges of climate change adaptation. It is hope thermal resilience will eventually find its way into codes and standards to be viewed as a fundamental health and safety requirement for all buildings.

Contemporary building performance simulation seeks to address all aspects of indoor environmental quality.
The above analysis of an office building in Phoenix, Arizona indicates that measures to combat overheating are needed without compromising relatively high levels of daylighting and ventilation autonomy. [Source: ¬¬¬Won Hee Ko, Stefano Schiavon, Gail Brager, Brendon Levitt (2018). Ventilation, thermal and luminous autonomy metrics for an integrated design process. Building and Environment 145, pp.153-165.]

Thermal Resilience Resources

A number of thermal resilience resources are available for convenient downloading. By clicking on the links below, a folder will downloaded to your computer and each folder contains a number of resources that are related to thermal resilience.

Thermal resilience begins with thermally efficient enclosures and windows. A number of publications, presentations and guides provide a helpful collection of related resources.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Enclosures&Windows.zip

Air barrier detailing and whole building airtightness testing are essential to thermal resilience in buildings, and this folder contains helpful publications related to airtightness.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Airtightness.zip

The early stages of design represent the most advantageous time to incorporate pasive measures to enhance the thermal resilience of buildings. A number of papers outline this opportunity.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Early-Stage-Design.zip

Combined heat and power (CHP) is now being incorporated in multi-unit residential buildings (MURBs) as a substitute for emergency back up power systems, providing both heat and electrical energy during prolonged power outages.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/MURBS-CHP.zip

General resilience measures in MURBs are documented in this folder.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/MURBS&Resilience.zip

Resilient building design is an emerging field of research and practice.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Resilient-Building-Design.zip

Techniques and approaches to modelling thermal resilience are presnted in a collection of papers on this this subject.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Thermal-Resilience-Modelling.zip

Vulnerable populations are at risk due to thermal stress, both cold and heat, and this collection of publications explains the key issues an pevention strategies.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Thermal-Stress.zip

Climate change is affecting weather and this series of publications deals with how to model changing weather to help future proof buildings.

https://pbs.daniels.utoronto.ca/faculty/kesik_t/TRDG/Weather&ClimateChange.zip

Appendix A

Guide for Energy Modelling

This appendix is intended to provide guidance on energy modelling associated with thermal resilience design of buildings, and serves as a supplement to the chapter on Thermal Resilience Modelling. It focuses on passive measures in buildings that contribute to thermal autonomy (TA) and passive habitability (PH). The targeted audience is energy modelling practitioners, but it may also prove helpful to inform building performance simulation studies in programs of architecture and engineering.

Buildings are prosthetic devices intended to shelter humans in environments conducive to their health and well-being. There may not be a one-to-one correspondence between human health indicators and building performance, but it is interesting how modern medicine has developed highly meaningful and reliable indicators of health. For the most part, heart rate, blood pressure, cholesterol, blood sugar and body mass index can inform physicians about the health status of their patients. Is it possible to develop a simple set of metrics and indicators that can provide a useful assessment of building performance?

Research in passive measures related to the area of thermal resilience indicates there are a number of indicators and metrics that are very meaningful. Many of these are highly correlated to attributes such as energy efficiency and thermal comfort. However, as noted earlier, unlike more conventional energy performance metrics, it is important to appreciate that TA and PH are indicators - they are relatively, but not absolutely, meaningful. It will take a great deal of time and effort to validate the accuracy of TA and PH indicators in real buildings, but they are nonetheless comparatively significant indicators that are highly useful during the early stages of building design.

Thermal resilience modelling is imperfect, but still very useful. *Predictions about how long it takes pipes to freeze after a power failure in winter are imprecise, but the risks associated with various levels of thermal control can be comparatively assessed to inform prudent preventive measures. [Photo courtesy Insurance Adjusters Canada Inc.]*

General Principles

It is important to recognize that it is the DNA of a building, which is almost entirely decided when it is conceived (designed), that will determine its life cycle performance. Nurture throughout construction and during occupation can maintain a building and help it achieve its maximum performance potential, but its upper performance limit is decided by its DNA. And this DNA is expressed through form and fabric - not through active system technologies. The guiding principle in energy modelling intended to support thermal resilience design is to focus exclusively on passive measures as these are the only strategies available when active environmental conditioning systems have failed. The sections that follow are based on key aspects of the energy modelling process, as follows:

- Types of simulation model(s);
- Indicators and/or metrics of interest;
- Modelling conventions for passive systems;
- Weather file(s) selection; and
- Visualization of thermal resilience.

Implicit in this process is the assessment of risk and consequences which is beyond the scope of this publication. The additional costs associated with enhanced thermal resilience must be carefully considered in relation to the damages stemming from disruption of habitable building conditions, health impacts on inhabitants, freezing and overheating, etc.

Resilience is becoming a critical consideration. *Problems in large high-rise apartment buildings forced massive evacuations of tenants during the winter of 2018/19 in Toronto's St. Jamestown neighbourhood. The social and economic costs are very high compared to those associated with preventive measures.*

Simulation Models, Indicators and Metrics

Thermal resilience as it relates to space heating and cooling may be assessed according to the interests of the designer and/or building owner. Thermal resilience is not binary rather it is a continuum offering different levels of thermal resilience that may address various issues and concerns. The table below outlines the types of simulation models and associated indicators and metrics that are available.

Type of Simulation Model	Useful Indicator or Metric
Whole Building - Model a typical floor to obtain performance indicators and metrics extensible to the whole building. Assess strategies for solar orientation, shading, spectrally selective glazing, natural ventilation, etc. **Zone in Building** - Passive habitability for warming/cooling place of refuge. Suitability for low temperature intensity space heating and cooling HVAC. **Suite in Building** - Identify unit with weakest thermal resilience (passive habitability, extreme maximum and minimum temperatures, freezing potential, etc.)	• Thermal autonomy (% of year) • Passive habitability (hours/days to threshold temperature) • Annual space heating and cooling energy demands (ekWh) • Peak space heating and cooling energy demands (kW) • Thermal energy demand intensity - TEDI (ekWh/m^2.year) • Extreme maximum and minimum indoor temperatures (OC or OF) • Space heating and cooling load intensities (W/m^2) • Freezing potential (% risk, frequency and severity) • Energy supply storage requirements (remote and/or emergency facilities)

Thermal resilience can inform various aspects of building performance. *This table indicates three types of simulation models corresponding to different design concerns. The associated indicators and metrics may be useful to any one of these models depending on the level of thermal resilience that is being investigated. Risks and consequences should inform the framework for testing various passive measures during simulations.*

Important Note: Thermal energy demand intensity (TEDI), which is often a concern associated with the desire to reduce greenhouse gas emissions, remains a fuzzy metric as it is currently defined in certain building energy standards. It is commonly calculated considering both the building enclosure transmission losses and the ventilation loads. The problems associated with including ventilation loads are manifold. First, the occupancy of a building can change over time and hence the ventilation loads will correspondingly increase or decrease to reflect occupancy. The building enclosure thermal and airtightness characteristics remain virtually constant while the ventilation rates of a building can change significantly over time. Second, increases in energy recovery efficiency of ventilation systems may potentially be traded off against building enclosure passive measures. From the perspective of thermal autonomy and passive habitability, it is not desirable to employ metrics that permit active systems to compromise passive performance. In this guide and all of the supporting research leading up to its publication, thermal energy demand intensity is calculated as transmission losses (conduction, convection, radiation, and air leakage) through the enclosure only. Mechanical ventilation is an active system that is not operational during extended power outages and is better dealt with in energy efficiency standards through requirements for energy recovery and ventilation effectiveness.

Thermal autonomy (TA) (Levitt, Ubbelohde et al. 2013) is the fraction of annual hours that are too warm, comfortable, or too cold. This can be defined using the Fanger thermal comfort model, a.k.a. the PMV-PPD model (ASHRAE 2017), or using operative temperature thresholds. If the Fanger model is used, the comfort range is defined as 80% of occupants being satisfied, which corresponds to a predicted mean vote (PMV) of +/- 0.84 (about "slightly cold" to "slightly warm"). If operative temperature thresholds are used, a range which could be considered comfortable - 18°C (64.4°F) to 25°C (77°F) – may be used. Operative temperature is approximately the average of the air temperature and mean radiant temperature. It properly accounts for very warm or very cold exterior surfaces and will generally penalize poorly insulated wall assemblies or glazing units.

To assess thermal autonomy, a building is put into "free-running" mode where all of the active system and occupancy inputs are turned off in an energy model and the thermal performance of the building is simulated for a typical weather year. The number of hours where the indoor operative temperature is between 18°C and 25°C is compared to the entire year which comprises 365 days X 24 hours per day = 8,760 hours. For example, if a free-running simulation indicates that the building is between 18°C and 25°C for 4,500 hours, then the thermal autonomy is expressed as a passive fraction of 4,500/8,760 = 51.4%.

Passive habitability (PH), in contrast, focuses only on the extreme periods of the year and assesses the length of time after a power failure before which a building becomes uninhabitable. These metrics indicate if and when evacuation of a building or space will be necessary following a power failure during an extreme weather event.

Heating passive habitability (HPH) is the time between when heating is shut off (because of failure) and when the indoor operative temperature reaches 15°C (59°F) from an original heating setpoint of 21°C (70°F). The HPH threshold is based on the effect of low temperatures on elderly morbidity (Collins 1986).

Cooling passive habitability (CPH) is the time between when mechanical cooling is shut off (because of failure) the indoor operative temperature reaches 30°C (86°F) from a cooling setpoint of 24°C (75°F). This temperature is consistent with other standards, for example the United Kingdom National Health Service used about 30°C (86°F) as a daytime health warning trigger (Anderson et al. 2013).

Annual space heating and cooling energy demand is assessed using transmission losses (conduction, convection, radiation, and air leakage) through the enclosure only. These may include the consideration of natural ventilation effects. This metric provides an indicator of the level of thermal energy efficiency provided by the enclosure itself.

Peak space heating and cooling energy demands are calculated as transmission losses (conduction, convection, radiation, and air leakage) through the enclosure only.

Thermal energy demand intensity (TEDI) is calculated as transmission losses (conduction, convection, radiation, and air leakage) through the enclosure only. This metric is derived from the annual space heating and cooling energy demands, dividing them by the conditioned floor area of the building.

Extreme maximum and minimum indoor temperatures are obtained from thermal autonomy analysis. The extreme temperatures predicted by "free running" energy modelling help identify passive mitigation measures. It is also useful to calculate mean-minimum and mean-maximum temperatures by averaging the daily minimum and maximum temperatures over the heating and cooling seasons, respectively. This provides an indicator that is correlated to the required intensity and run times of active systems.

Space heating and cooling load intensities are important considerations when assessing the deployment of low intensity heating and cooling HVAC technologies. This is one metric that may require additional consideration of the influence of building occupancy associated with the number of persons, lighting and equipment loads.

Freezing potential is an indicator that is obtained from observing the frequency (# of hours) and severity (below-freezing temperatures) of indoor temperatures obtained from thermal autonomy analysis. The risk may be expressed as a percentage of the time during the heating season when indoor temperatures will reach below the freezing point. Alternatively, a freezing potential index analogous to heating degree-days may be calculated.

Energy supply storage requirements for remote and/or emergency facilities may be obtained by parsing the annual space heating and space cooling energy demands to assess the amount of energy storage required. For example, in a remote facility that must remain heated in between delivery periods for energy (e.g., wood pellets), this metric will provide a reasonable estimate of the amount of energy storage required.

Thermal resilience indicators and metrics are relative, not absolute. Their most significant utility is derived from comparing between design alternatives having different combinations of various passive measures.

Passive Versus Active Systems and Occupant Behaviour

Conventional energy modeling and simulation seldom provide indicators that speak to the performance of passive building systems. This is because during the energy modeling process, physical attributes of the building enclosure and external phenomena in the form of weather data are mixed in with active system operations and assumed occupant behaviour. The final results are unable to separate passive and active system effects. Put simply, passive systems represent the intrinsic quality of the building asset, whereas active systems are optional and transient components that supplement passive system performance according to occupancy and building usage.

Energy models produce results that reflect both passive and active system performance. The active system performance (HVAC, lighting, plug loads, etc.) is largely determined by occupancy of the building and the assumed occupant behavior. Passive systems, such as natural ventilation and daylighting, are not easy to integrate within energy models, hence the performance simulation results are limited to energy demands and do not distinguish between contributions by passive and active features of the proposed building design.

When performance indicators such as passive habitability are considered, it is only the performance of the passive systems that matters because it is assumed the active systems are down. The overall effective U-value of the enclosure, its airtightness, thermal storage capacity, daylighting (solar gains) and natural ventilation are the only factors that need to be considered by designers interested in assessing passive performance. It may also be argued these are the only performance indicators that can be measured or tested in-situ with reasonable accuracy to assess the quality of the physical building asset. From a life cycle perspective, it is the passive systems that will endure long after active system components may have been replaced several times, and the occupancy patterns and operating schedules of the building vastly altered over time, as buildings become re-purposed or adaptively re-configured.

However, occupant behaviour is an important consideration in thermal resilience design. Occupants may be classified as either passive or active. Passive occupants do nothing to mitigate outdoor weather conditions. They do not adjust shading devices, they do not open windows and their clothing levels remain constant. Active occupants will alter their clothing levels by putting on a sweater or changing into shorts and short sleeved shirts, as the conditions may require. They also will engage passive features such as shading devices and operable windows to improve their comfort.

Occupant behaviour can be modelled by assigning schedules and/or control parameters to shading devices and operable windows. For passive occupants, windows remain closed and shading devices remain fixed. But for active occupants, ideal behaviour may be modelled by having shading devices adjusted (e.g., external roller shades) based on outdoor temperatures and incident solar gains. Windows may be opened to promote natural ventilation and cooling based on indoor and outdoor temperatures.

Active occupant interactions with passive features are important to assess at the early stages of design since they involve fundamental strategies for empowering occupants to control their comfort.

Modelling Tools and Techniques

To prepare a simulation model (e.g., in EnergyPlus or other simulation tools) for assessing thermal resilience using the previously described indicators and metrics, several steps are needed. Note that regardless of the simulation tool, it must be capable of reporting raw hourly indoor temperatures and it must also allow HVAC schedules to be adjusted.

The thermal gains from equipment, appliances, lighting, and occupants should be set to zero. This is generally a conservative assumption that resolves uncertainty associated with these parameters and is also generally the case for times of power or system failure.

For thermal autonomy, the heating, cooling, and mechanical ventilation also need to be deactivated for the entire year.

For passive habitability simulations, the heating, cooling, and ventilation need to be suddenly cut off. This can be achieved using two methods: (1) by setting the setpoints to extreme values, at the time of simulated system failure, such that the heating does not become activated in the winter and cooling does not become activated in the winter; or (2) by scheduling the heating, cooling, and ventilation to shut off suddenly. Two important notes: first, the heating, cooling, and ventilation should be allowed to run normally prior to the failure (this is what sets the PH analysis apart from the TA); and second, mechanical ventilation must be deactivated after failure, as would occur if an electrical power outage occurred, or the HVAC system failed.

The model may include the entire building or merely representative spaces (e.g., a room facing each cardinal direction). For representative rooms, the interior surfaces can be set as adiabatic to model the presence of other adjacent spaces that are exposed to the same conditions (e.g., power failure). If the whole building is modelled, care should be taken to analyze the results to identify the space-specific, area-weighted, or worst-case resilience within the building.

Often, particular scenarios are considered, such as a prolonged power outage during an extended extreme weather event that affects vulnerable inhabitants - the ill, elderly and demobilized. The nature of the thermal resilience that is being sought by the designer will vary depending on whether every suite in a housing project, for example, will enjoy a minimum period of passive habitability, or if only a particular zone or facility within the building will serve as a warming and/or cooling centre (place of refuge).

Where every dwelling unit in a multi-unit residential building must achieve a minimum acceptable level of thermal resilience, then only the critical suites need to be assessed. For example, in the northern hemisphere, typically north-facing suites face the greatest challenges to achieve similar levels of thermal autonomy and passive habitability during winter as compared to south-facing suites that enjoy solar gains. South and west-facing suites normally face the greatest challenges during the summer months and controlling overheating requires a strategic combination of passive measures.

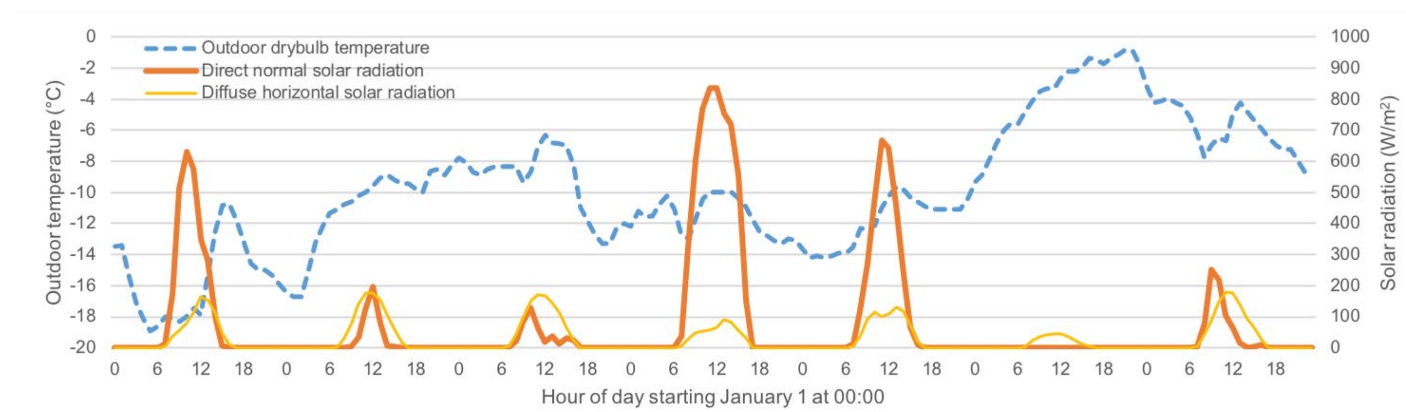
By modelling combinations of passive measures and varying parameters such as U-values, solar heat gain coefficients, window-to-wall ratios, etc., it is possible to reveal significant relationships that may be further investigated by sensitivity analyses.

Weather Data

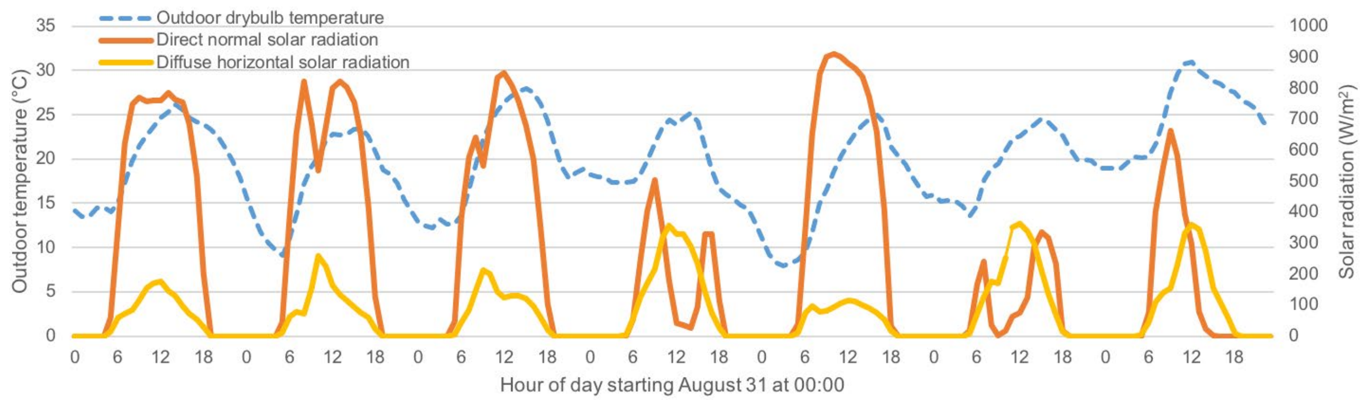
Weather data are critical to meaningful thermal resilience metric quantification. The Typical Meteorological Year (TMY) weather files (such as EWP or CWEC weather files) can be used for quantifying both metrics. The whole year (8,760 hours) is used for passive survivability. In contrast, only brief periods of about a week, are used for passive habitability. Specifically, the periods should be chosen as worst-case for the heating and cooling season. The heating period should be characterized by an extended period of cold outdoor temperatures and mostly cloudy days. The cooling period should be characterized by warm temperatures (perhaps the warmest of the year) and a string of clear days, if possible. The presence of such periods depends on the weather file and is a matter of sound judgment.

Moreover, the period can be chosen according to the building or room design. For instance, west-facing spaces are most susceptible to overheating with peak summer temperatures and sunny conditions, whereas south-facing spaces are often more susceptible to overheating in early autumn, when conditions are mild and there are a number of consecutive sunny days. The passive habitability period depends on the building. By definition, it can be as long or short as required for the indoor operative temperature to reach the threshold. This duration depends on both building design and climate. For instance, high-performance buildings tested in mild climates may require much longer than a week to reach the PH thresholds. Thus, the PH period must be determined on a case-by-case basis. To better inform the judgment required in selecting periods for PH analysis, it is helpful to first perform and visualize the TA results on an annual basis.

Examples of weather data to be used in passive habitability analysis for Toronto, Canada are provided in the following two figures. It is highly recommended to use engineering judgement when selecting periods from the annual weather file. Note that both periods have the presence of some anomalies that make them less severe (i.e., sunny days within the HPH week and cloudy cooler days within the CPH week). In some cases, more or less than a week period is required depending on the severity of the weather in a particular geographic location. For example, if the concern goes beyond habitability to include the risk of freezing, it may take more than a week before a suite, a space, or the entire building experiences below-freezing temperatures.



Selection of cold weather event from typical weather file is usually not the most extreme condition to be tested. *The weather period for testing heating passive habitability shown above (Jan. 1 – Jan. 7, Toronto, Canada) is much warmer than historical extreme cold weather events. It is also important to consider the influence of extended periods of overcast versus clear sunny weather.*



Dry bulb temperatures are not the only consideration when selecting a weather period for testing cooling passive habitability. *The data above (Aug. 31 – Sept. 6, Toronto, Canada) indicate sunny conditions with relatively low sun angles that cause solar gains to penetrate deep within a building. Not shown is the influence of outdoor relative humidity, which when combined with insolation effects, may represent an extreme weather period in terms of heat stress on vulnerable populations.*

Climate Change and Future Weather

The future impacts of climate change on weather data are forecast to be quite significant, but also very different across climate zones. While the global warming trend sees average global temperatures rising recent experience has indicated that periods of extreme cold may also result from this phenomenon. Means of creating weather files to account for climate change are well documented and these can also account for urbanization impacts associated with the urban heat island effect (Crawley 2007). An important factor to consider with climate change is the life cycle energy savings associated with energy utility incentive programs and how these may differ significantly between space heating and cooling. (Drury and Gattie-Garza 2016)

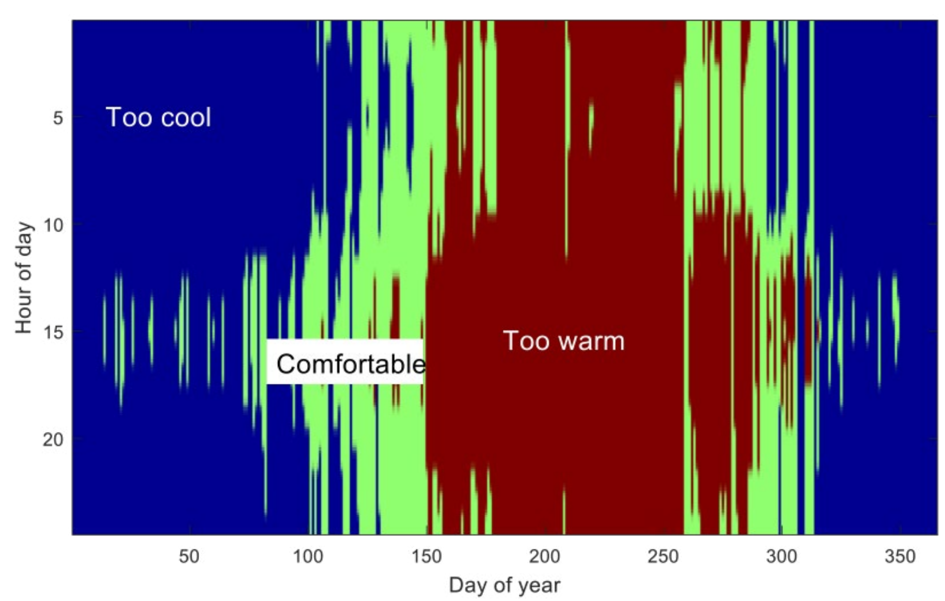
Given the lack of precision among the various climate change prediction models and how these may in turn affect weather data for a particular location, a probabilistic approach has been found to be a practical means of approaching this problem (Nik and Arfvidsson 2017). Far more difficult is the nagging problem of extreme weather events and how to properly reflect these in weather data (Stephenson 2008). This implies that while modelling thermal autonomy can reasonably account for long term weather shifts due to climate change, the same cannot be said about passive habitability. To further complicate matters, an aging population requires more evidence-based heat indices to be applied to assessments of passive habitability (Holmes, Phillips, and Wilson 2016).

Whatever may be witnessed in our future weather patterns, it is very important to make some account of climate change in thermal resilience modelling, but at the same time to reach a consensus among the energy modelling community that allows a fair comparison between different buildings across a single weather location. This is not to suggest that gaming weather data is yet another way to enhance the thermal resilience rating of buildings, rather than as a minimum, weather data used in thermal resistance analyses should always accompany the results, or be available upon request. This is a reasonable protocol until a broader consensus can be forged.

Visualization of Thermal Resilience

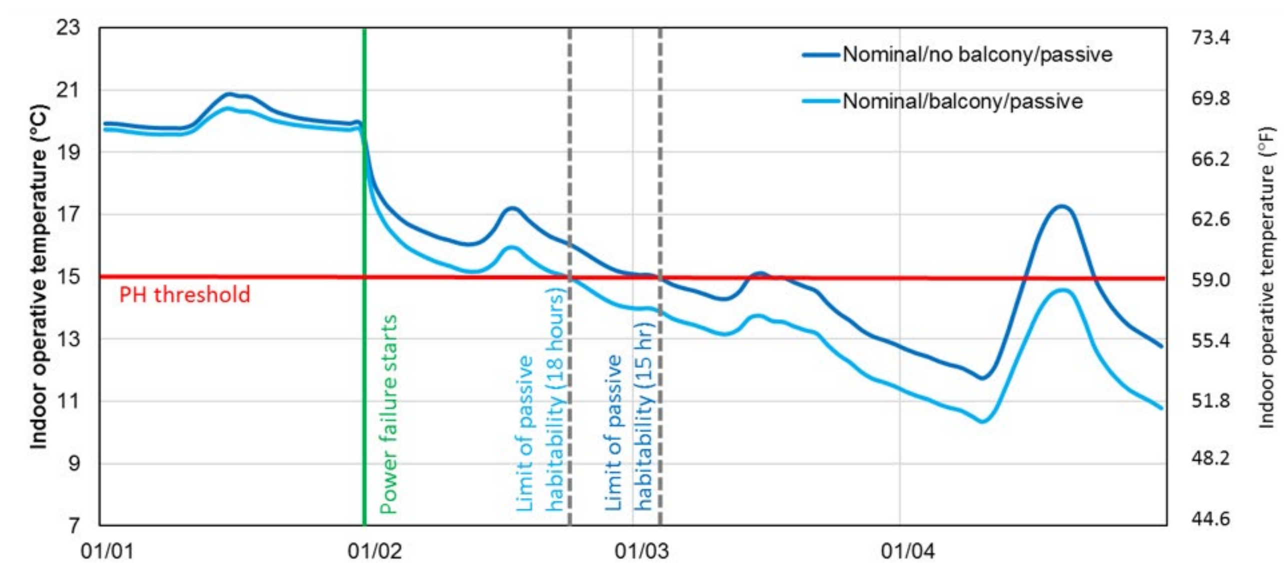
Once a number of combinations of various passive measures and design strategies have been modelled, it is very time and effort efficient to comparatively visualize their performance. Research has indicated that the type of energy modelling conducted for code compliance purposes yields results that are often overwhelming and unclear. The mixing of passive and active systems in an energy model makes the optimization of passive measures extremely difficult, if not impossible. By conducting energy simulations in free-running mode with no active or occupant interactions, the contributions of the passive measures can be clearly isolated and studied in depth.

Data visualization is an art that must prioritize the end use and end user. For comparing many building designs, a high-level metric may be preferred. For interpreting the results of just several designs, a time series to understand the time-based metrics is likely more valuable. Examples of visualizing thermal autonomy and passive habitability are depicted in the two figures that follow.



Carpet plots typically depict thermal autonomy showing periods that are too cool, comfortable, and too warm each day throughout of the year. *This carpet plot indicates that overheating occurs for 24 hours over a large number of consecutive days in summer months - inadequate natural ventilation does not provide effective night time cooling to reduce temperatures. The number of hours in each period are 3956, 1905, and 2899, respectively, for this particular building and climate, indicating a thermal autonomy of 21.7%.*

Interpreting the visualized results from thermal resilience simulations is more important than the visualization technique itself. This does not imply the visualization technique is secondary, rather that it should assist in conveying the information that corresponds to the key issues of interest. A plot of hourly temperatures provides information that a carpet plot of three temperature criteria cannot. It is preferable to generate a variety of visualizations of the data in order to reveal as many critical relationships as possible.



Fixed shading devices are not always beneficial. *Heating passive habitability for two different designs – a south-facing condominium unit with and without a balcony where the inhabitants are assumed to be passive. The results show that balconies act like horizontal shading devices and reduce solar gains that could help extend the passive habitability during the heating season. Operable/adjustable shading devices have the advantage of offering utility in both heating and cooling seasons.*

It is also advisable to begin visualizations of results by considering just one design parameter at a time. In the passive habitability visualization above, only two cases are examined where a single variable is either deployed or absent. Working with a single variable, such as having a balcony or not, has the advantage of isolating the influence of this design parameter. Once all of the parameters have been individually investigated, it is possible to consider combinations of passive measures to see which yields the best overall performance.

Standardizing Thermal Resilience Ratings

Experience in conducting numerous thermal resilience analyses indicates that eventually a subset of feasible passive measures for a given building typology in a particular climate zone emerge. This is not to suggest that the objective of thermal resilience modelling is to produce formulaic recipes for robust and resilient buildings. The purpose of this process is to generate minimum levels of desired and/or acceptable performance corresponding to a combination of passive measures that represent a baseline as the design process proceeds, and eventually the energy modelling of active systems is incorporated.

In order not to unintentionally compromise passive measures by trading them off against active system efficiencies, it is helpful to establish a framework of critical passive performance indicators that provides a basis of comparison against the best in class and code minimum levels of passive performance, as shown in the example below. It may even be expanded to include non-thermal passive performance parameters going forward. This framework acknowledges that energy efficiency is a tactic to be deployed towards the larger objective of resilient and sustainable buildings which will depend on durable, robust, low embodied energy buildings and decarbonized energy sources.

Critical Passive Performance Indicators

Proposed Apartment Building - Typical Floor (600 m²)

Toronto, Ontario, Canada	
WMO ID	71266
Latitude	43°40'00.000" N
Longitude	79°24'00.000" W
Elevation (m)	112.5
Degree Days (18 °C)	3498.2
Heating Design Temperature	-18 °C
Cooling Design Temperature	31 °C
Annual Daylight Hours	4643.4
Bright Sunshine Hours	2066.3

Proposed/Existing Design ▼

Best in Class ▽

Code Minimum (maple leaf)

U_{eff} (W/m².K) - Overall effective enclosure U-value.

TEDI (eKWh/m².yr) - Thermal energy demand intensity.

PCD (kW) - Peak space cooling energy demand.

PHD (kW) - Peak space heating energy demand.

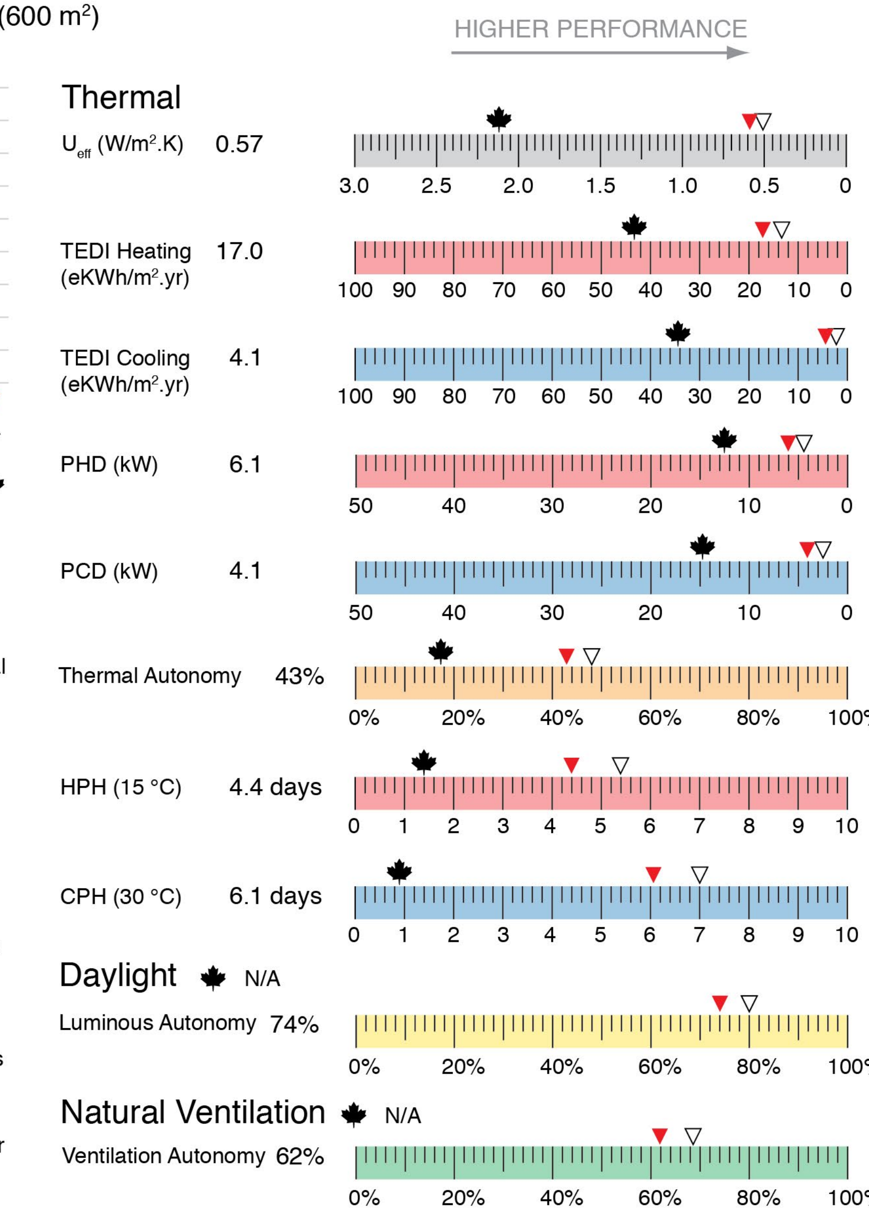
Thermal Autonomy (%) - Fraction of time during a typical weather year when a building can passively maintain comfort conditions within a range of operative indoor temperatures between 18°C and 25°C (64°F and 77°F).

HPH (hours/days) - Heating passive habitability is the time from when heating is shut off (because of failure) and the indoor operative temperature reaches 15°C (59°F) from an original heating setpoint of 21°C (70°F).

CPH (hours/days) - Cooling passive habitability is the time from when mechanical cooling is shut off (because of failure) and the indoor operative temperature reaches 30°C (86°F) from a cooling setpoint of 24°C (75°F).

Luminous Autonomy (% Occupied Hours) - Useful daylight illuminance expressed as the percentage of occupied daytime hours where the illuminance level falls within range of 300 to 3000 lux for autonomous hours (UDI-a 300 to 3000 Lux).

Ventilation Autonomy (% Occupied Hours) - Minimum air flow rate based on ASHRAE 62.1 requirements for a specified occupancy that is provided by natural ventilation to conditioned spaces.



Comparative ratings are highly informative. *Showing how a proposed design compares against minimum and best in class performance enables designers and owners to make informed decisions. At some point in the future these ratings may become standardized to promote consumer education and the advancement of minimum levels of acceptable passive performance.*

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Appendix B

Active Systems Considerations for Enhanced Thermal Resilience

This appendix acknowledges there are many cases where passive systems are unable to provide the level of thermal resilience needed to adequately shelter our populations. The intention here is to provide a framework for selecting practical mitigation strategies that involve active systems and technologies.

The key considerations related to thermal resilience is how long habitable shelter can be maintained before supporting infrastructure is restored? This question involves the following considerations:

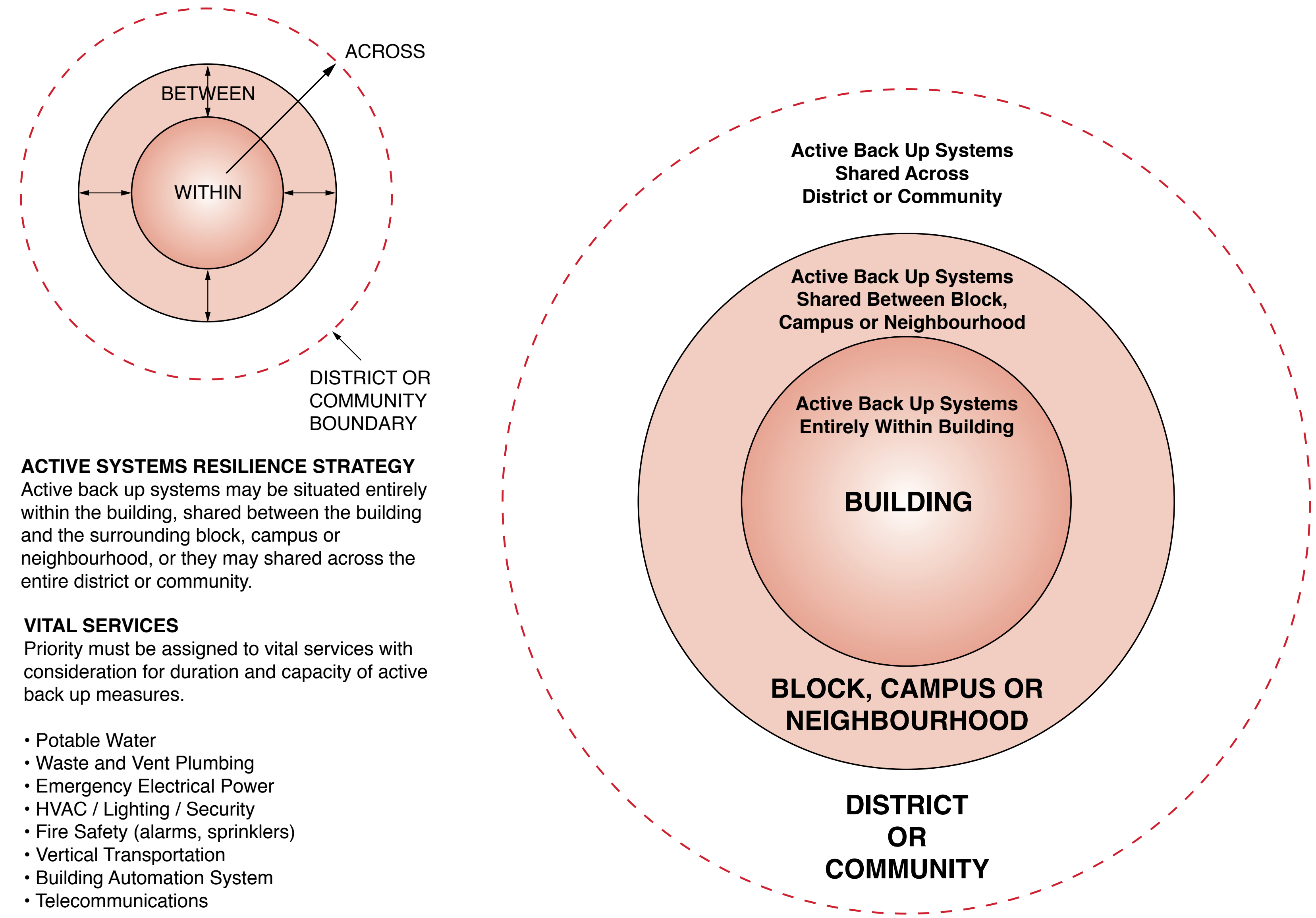
- Survivability depends upon water, food, shelter and sanitation - having a habitable shelter without access to food and water, and nowhere to go to the bathroom, is not a complete resilience solution.
- The capacity and timing of emergency response is a critical factor. A massive earthquake in the cold of winter that destroys all vital infrastructure is a different challenge than the failure of an electrical transformer serving a neighbourhood. The former may require weeks or months of active back up systems support while the latter only a matter of hours.
- The types and levels of vital services along with the duration these need to be supported by active back up systems must be sufficient. Alternatively, an evacuation plan will be needed to rescue and re-locate vulnerable populations.
- Social networks bind together communities and render them resilient. Active back systems can also fail hence community emergency measures must educate and engage social networks for effective outreach.

Traditional technologies prior to centralized services infrastructure were inherently resilient. *Products are still available today that provide autonomous capabilities for lighting, heating and cooking, but they are better suited to remote locations rather than large urban settlements. [Photo courtesy Canada Wood Stoves.]*

Guiding Principles

Resilience must always be planned within a specific context. Strategies for a remote research station that is only accessible by air will necessarily differ from measures for buildings located in large urban regions. Long term disruptions of energy and water supplies can place severe stress on a community and its vulnerable citizens. People who have mobility challenges, suffer from serious illness, and/or live alone without caregivers are among the most vulnerable individuals. Low income families may not have the means to temporarily evacuate an area undergoing disaster or crisis. Some thought should be given to enhancing energy and water security so that housing developments and critical service (warming/cooling) centres are able to function until recovery is possible.

Robust passive measures may not always prove sufficient, and so it is important to formulate resilience strategies that account for vital essential services. It is important to resolve whether the building will remain autonomous, or if it will be supported in some ways by the surrounding neighbourhood and community. Taking an inventory of emergency measures in a community and coupling this information to a scenario-based planning approach is very helpful in developing appropriate resilience strategies.



Robust passive measures reduce the capacity of active back up systems. *This relationship holds true for building, neighbourhood and community-scale resilience strategies.*

Helpful Resources

For a fuller perspective on resilience, download the **Resilience Planning Guide.**

https://pbs.daniels.utoronto.ca/faculty/kesik_t/Resilience/Resilience-Planning-Guide-v1.0-2017-11-19.pdf