Thermal Resilience

Professor Ted Kesik. Ph.D., P.Eng.

UNIVERSITY OF TORONTO

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

Daniels

Acknowledgements

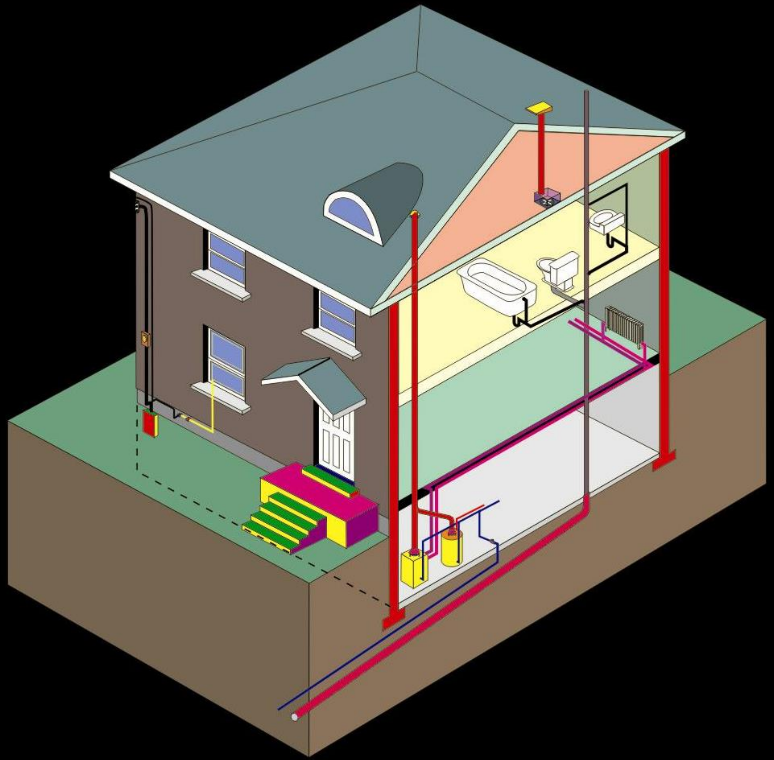
This technical research presented in this lecture has been made possible through the generous financial support of ROCKWOOL North America.

ROCKWOOL™

Special thanks to Co-Researcher, Dr. Liam O’Brien, Associate Professor, Architectural Conservation and Sustainability, Carleton University and Dr. Aylin Ozkan, Research Associate, University of Toronto.

It is also important to acknowledge the countless individuals and organizations that have directly or indirectly contributed to the advancement of energy modelling and the thermal resilience design of buildings.

Buildings Are Anthropomorphic Prostheses



Building Envelope
(Skin, Fat, Hair, Nails)

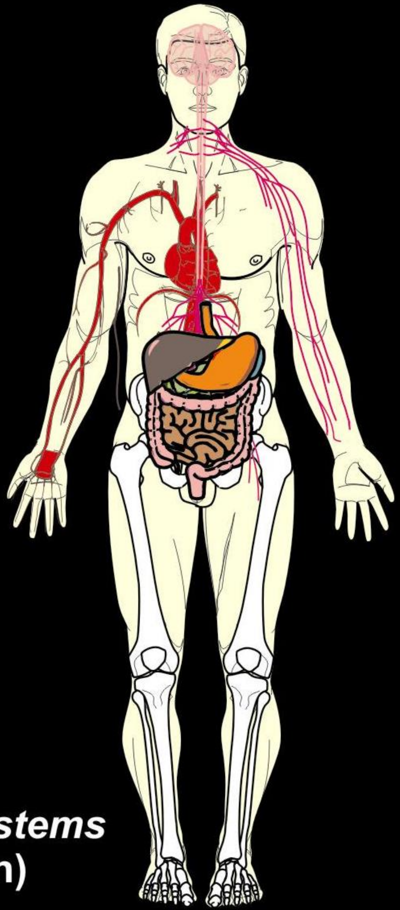
Structure
(Skelton, Muscles)

Mechanical System
(Circulatory and Respiratory Systems)

Electrical System
(Nervous System)

Energy and Sanitary Plumbing
(Digestive System)

Alarms, Security, Communications, and Building Automation Systems
(Sensory Organs & Brain)

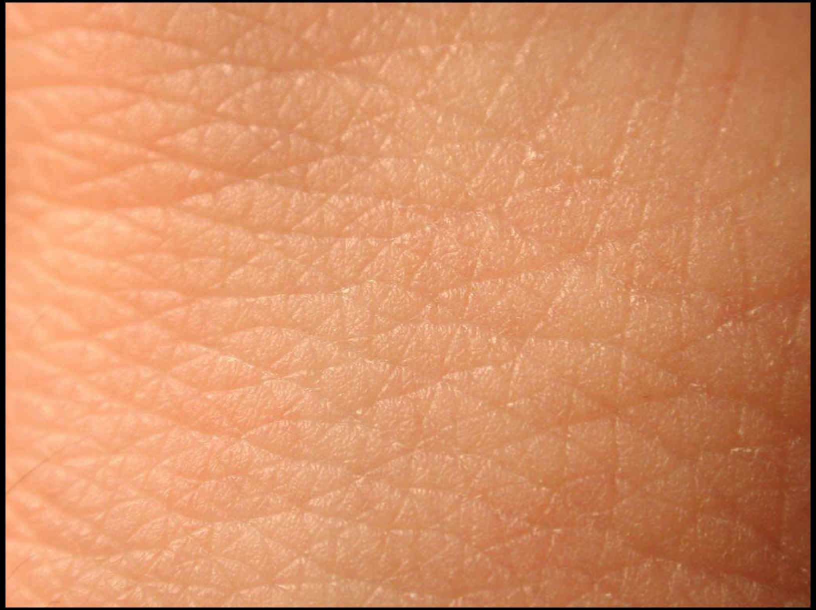


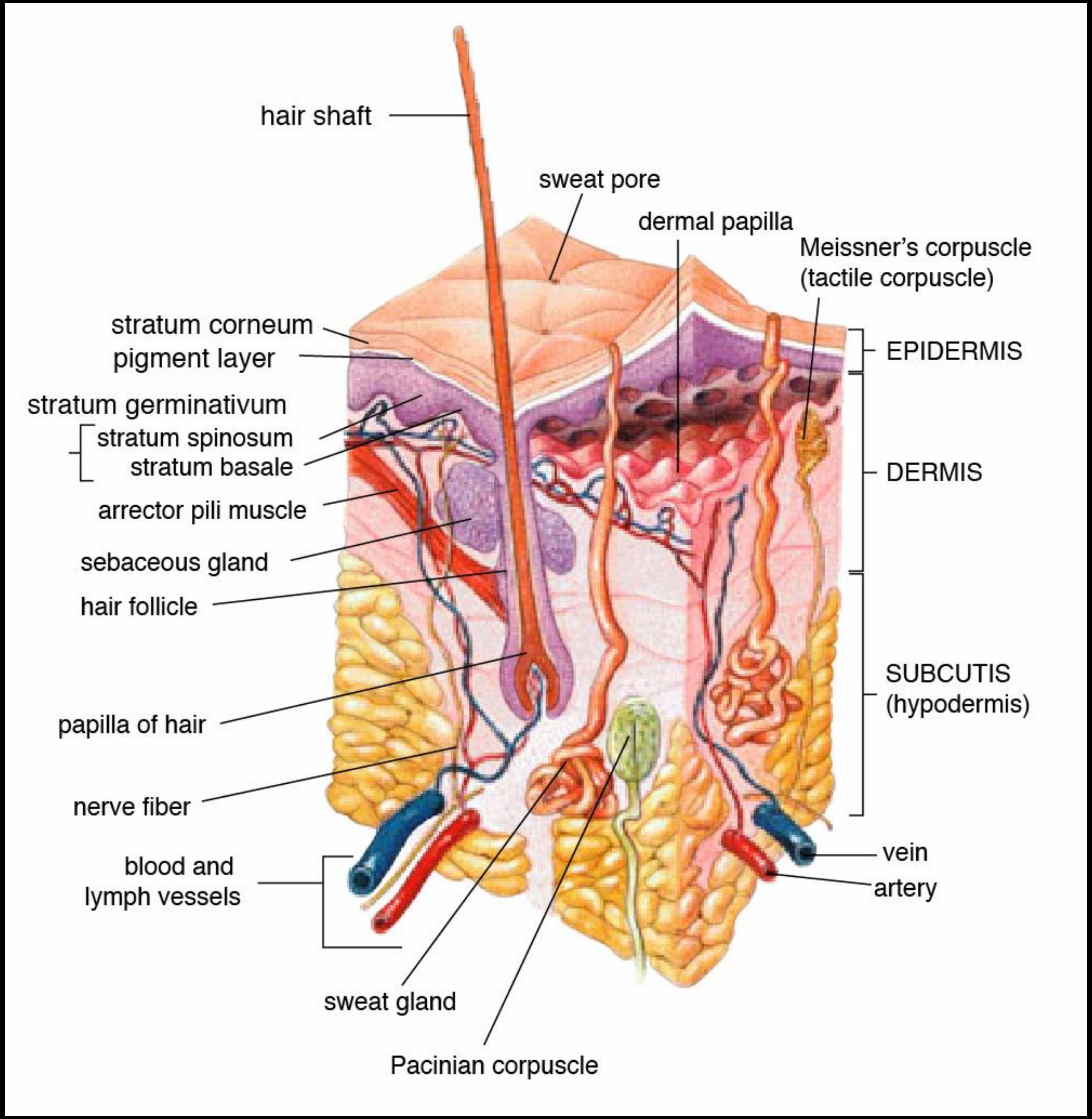
BUILDING

BODY

Humans live inside skins.

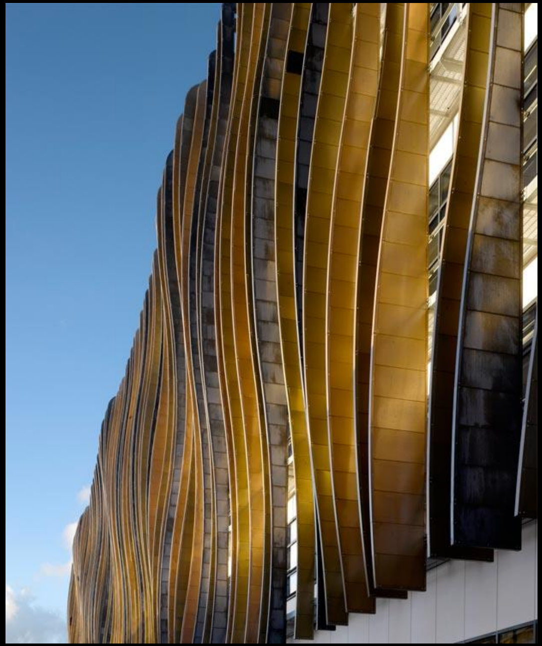
The first skin is the one we are born with.





The second skin is the one we wear and we do so for many reasons that go beyond function, style and comfort – such as status or safety/survival.

And the third skin is our building enclosure once intended for shelter, but



now for much more than just keeping

the outdoors out.

And if you experience health problems, contract a rare disease or get into a bad accident, you may end up in a fourth skin.

Take away the façade and what have you got?

They sure don’t make facades like they used to, eh?

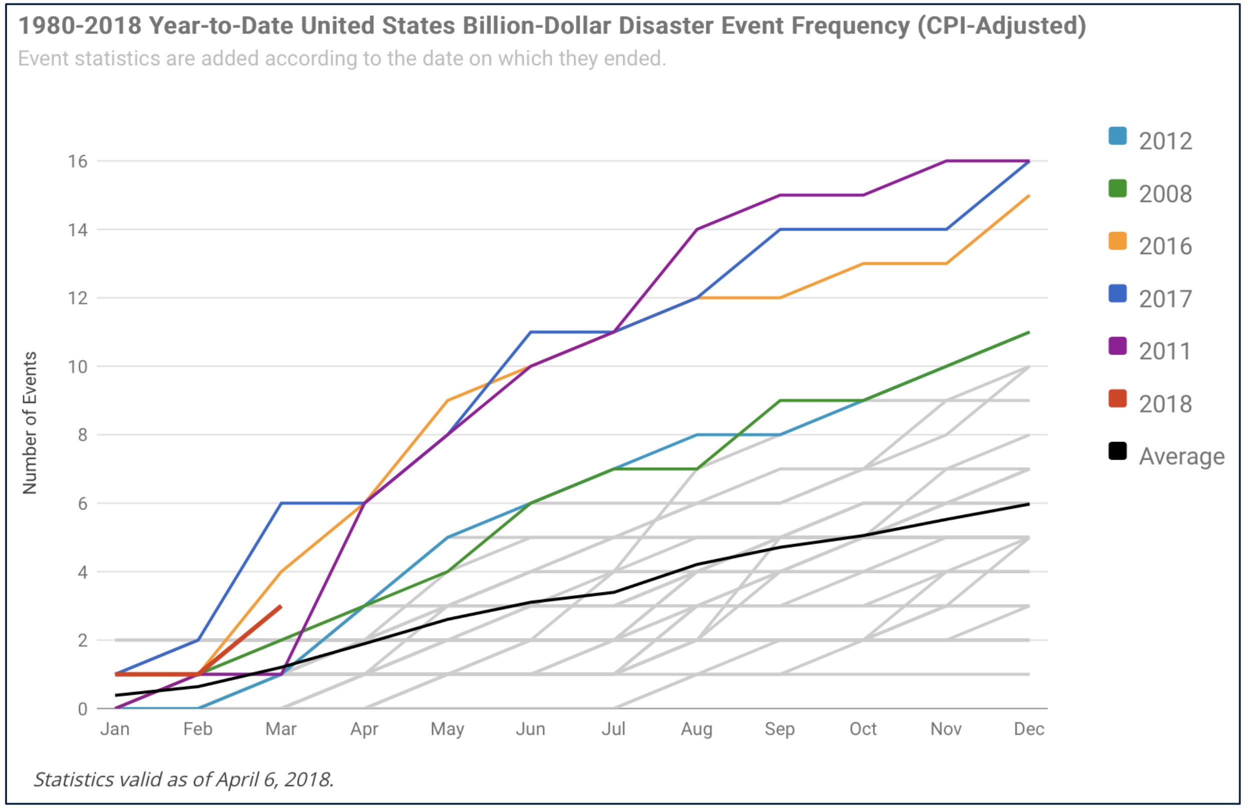
A façade in New York collapses during Hurricane Sandy.
Thank God the velvet paintings were spared.

The $1 Trillion Storm: How a Single Hurricane Could Rupture the World Economy by Geoff Diembicki

A Florida condo building damaged by Hurricane Andrew in 1992.
Photo by Steve Starr/Corbis via Getty

The BIG Picture

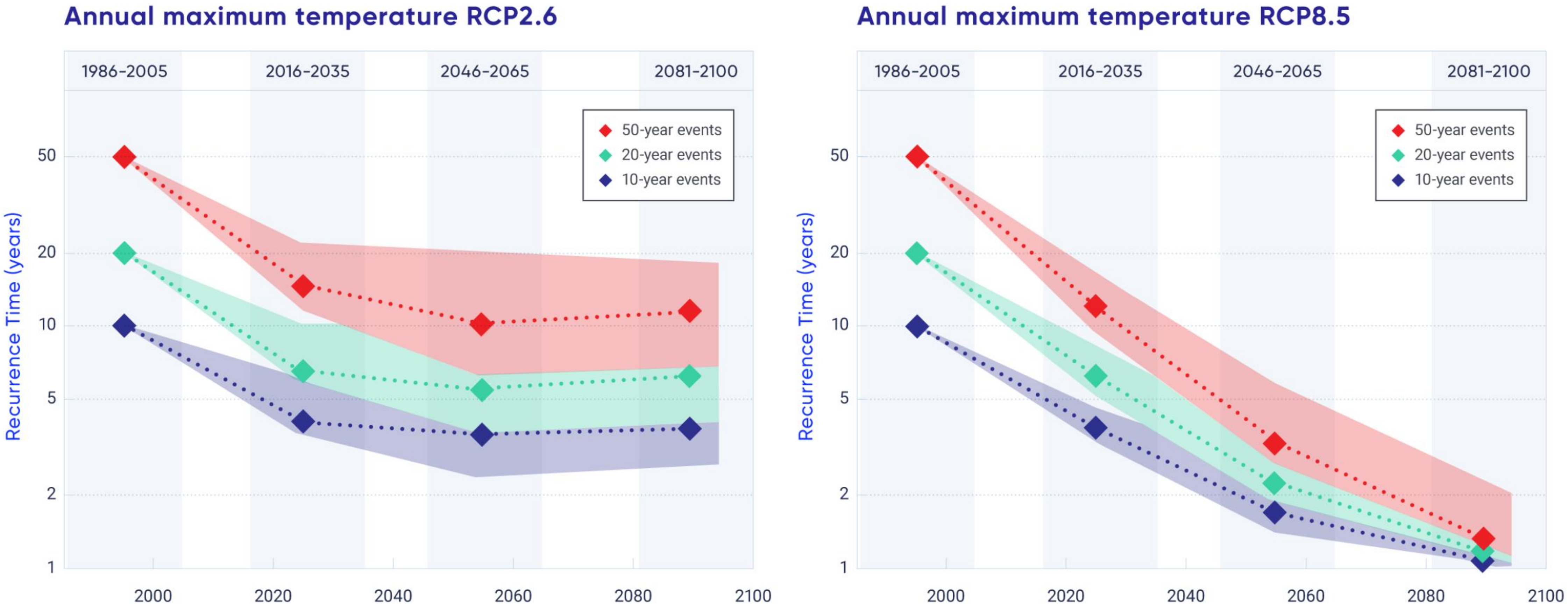
Climate Disasters are Escalating



Source: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2018). https://www.ncdc.noaa.gov/billions/

- NOAA data indicates a sharp increase in billion-dollar weather and climate disasters that have affected the United States.
- Most of these climate disasters knock out power for extended periods of times.
- Often these events occur during periods of extreme heat and cold.
- Buildings are unable to deliver shelter needs under these conditions.

Extreme Weather Events Will Be More Frequent and Severe



Projected changes in recurrence time (in years) for annual highest temperatures that occurred, on average, once in 10, 20, and 50 years in the late 20th century across Canada.
Source: Bush, E. and Lemmen, D.S., editors (2019): *Canada's Changing Climate Report*; Government of Canada, Ottawa, ON. 444 p.

Wildfires Can Be Unstoppable

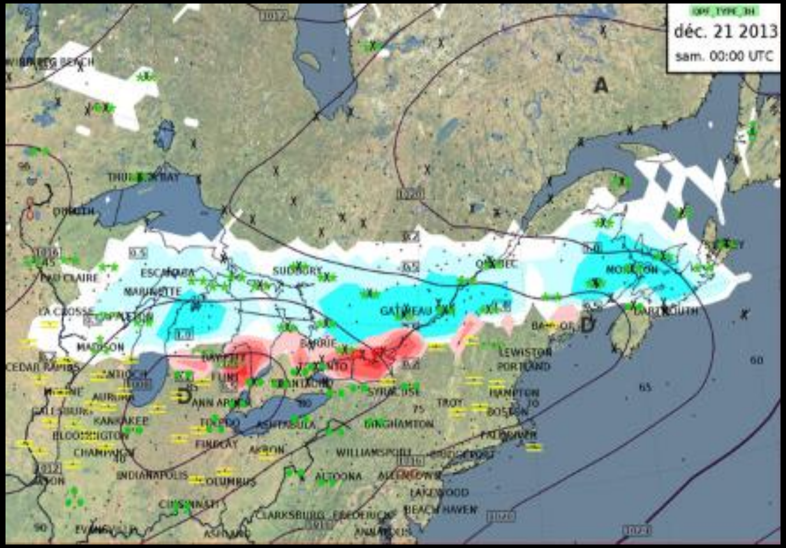
Freezing Rain Can Be Deadly

A large North American storm complex impacted the northeastern United States and Canada from December 20 to 23, 2013.

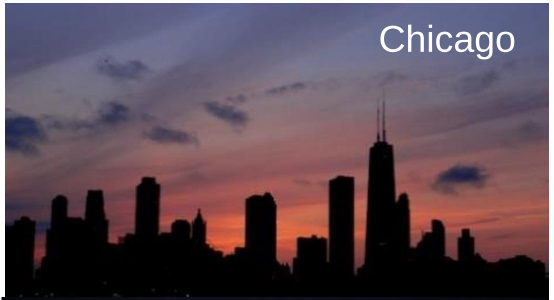
- The storm produced freezing rain and snow to the affected areas which caused massive damage to electric power transmission and trees.

- Many residents had to abandon dwellings that had no heating and quickly became too cold to inhabit.

- The storm resulted in 27 deaths, loss of power to over a million residents and over $200 million in damages.

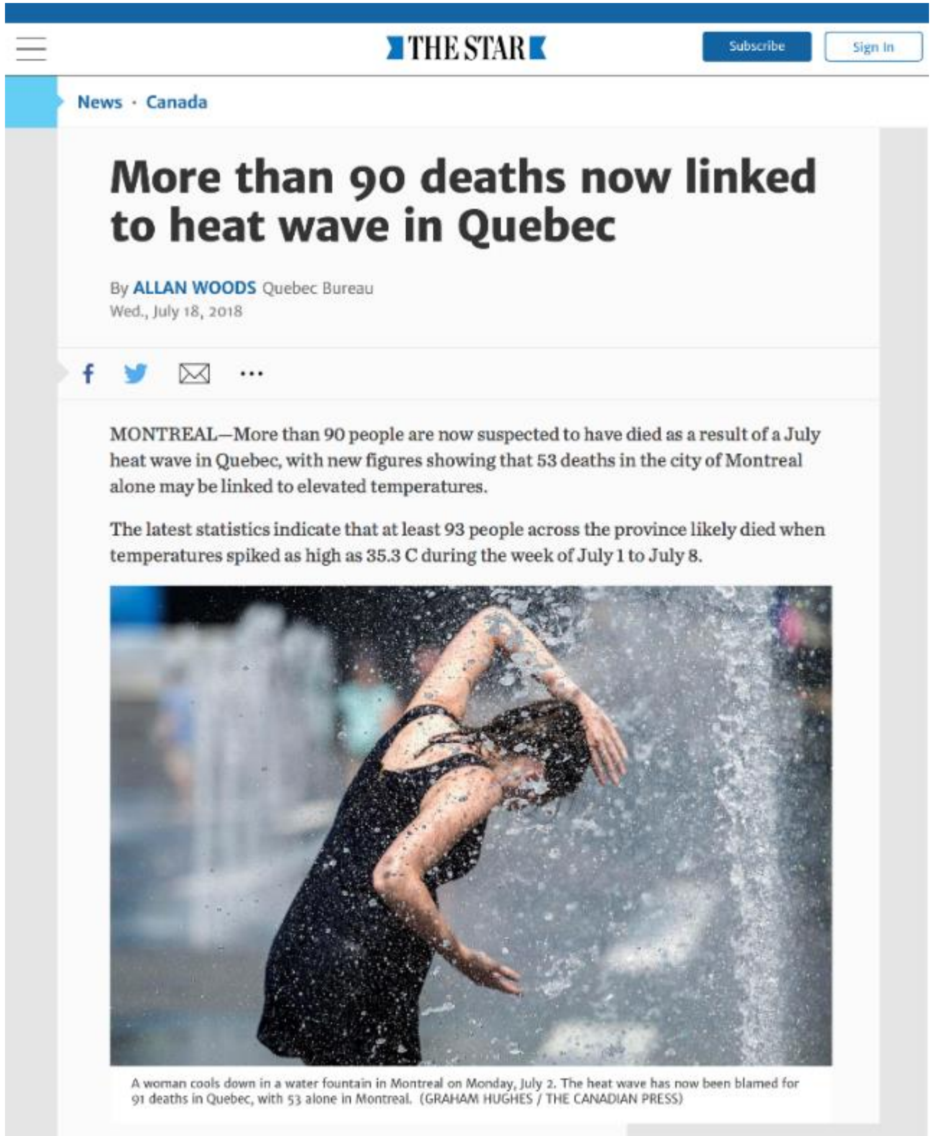


Beware Power Outages During Heat Waves



- Northeast blackout of 2003 is the ninth-largest major power outage in the world affecting 55 million people.
- The outage lasted from 1 to 5 days during a period of extreme hot weather.

Heat Waves Kill More People Than Fires



THE STAR

Subscribe Sign In

News · Canada

More than 90 deaths now linked to heat wave in Quebec

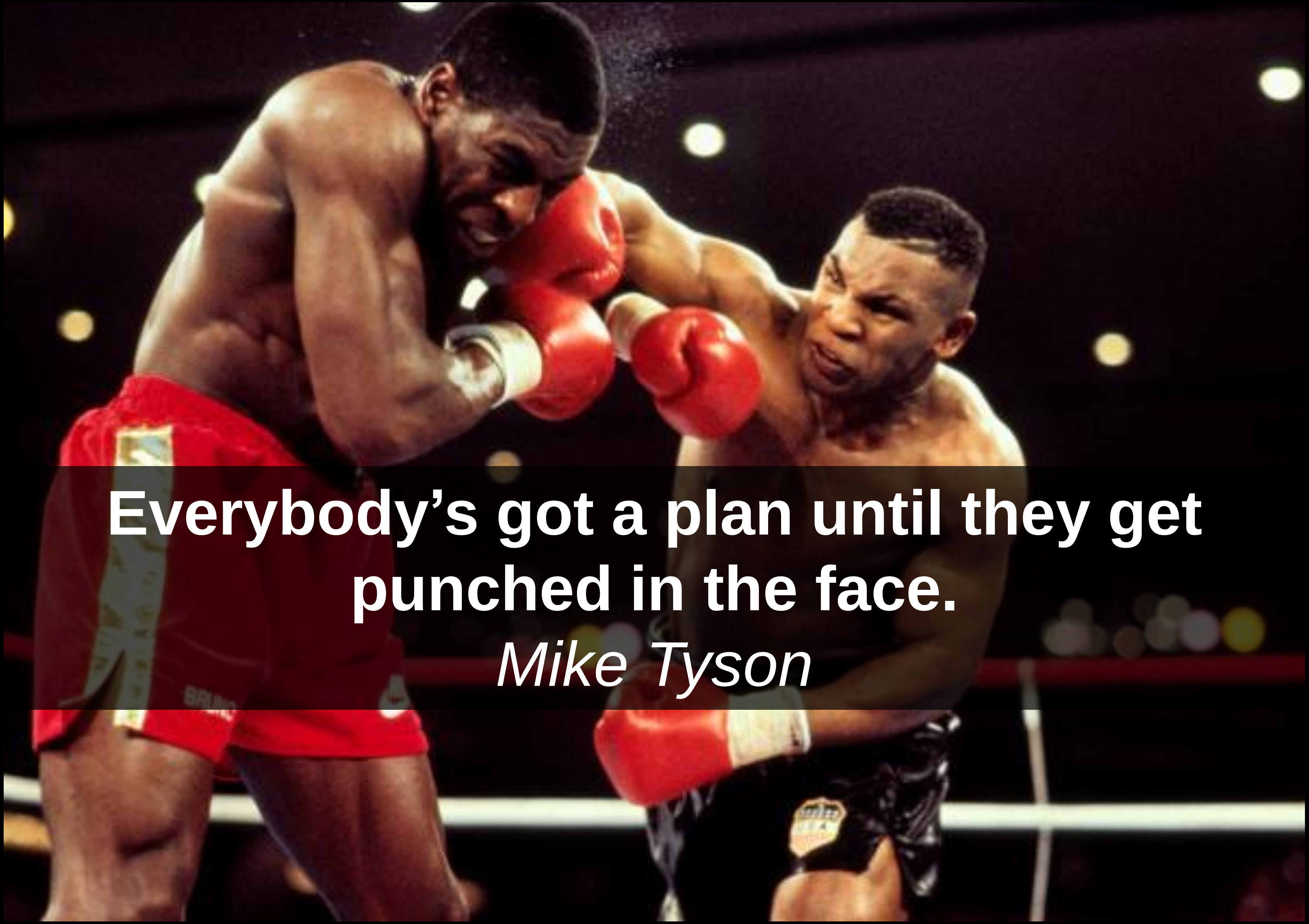
By ALLAN WOODS Quebec Bureau
Wed., July 18, 2018

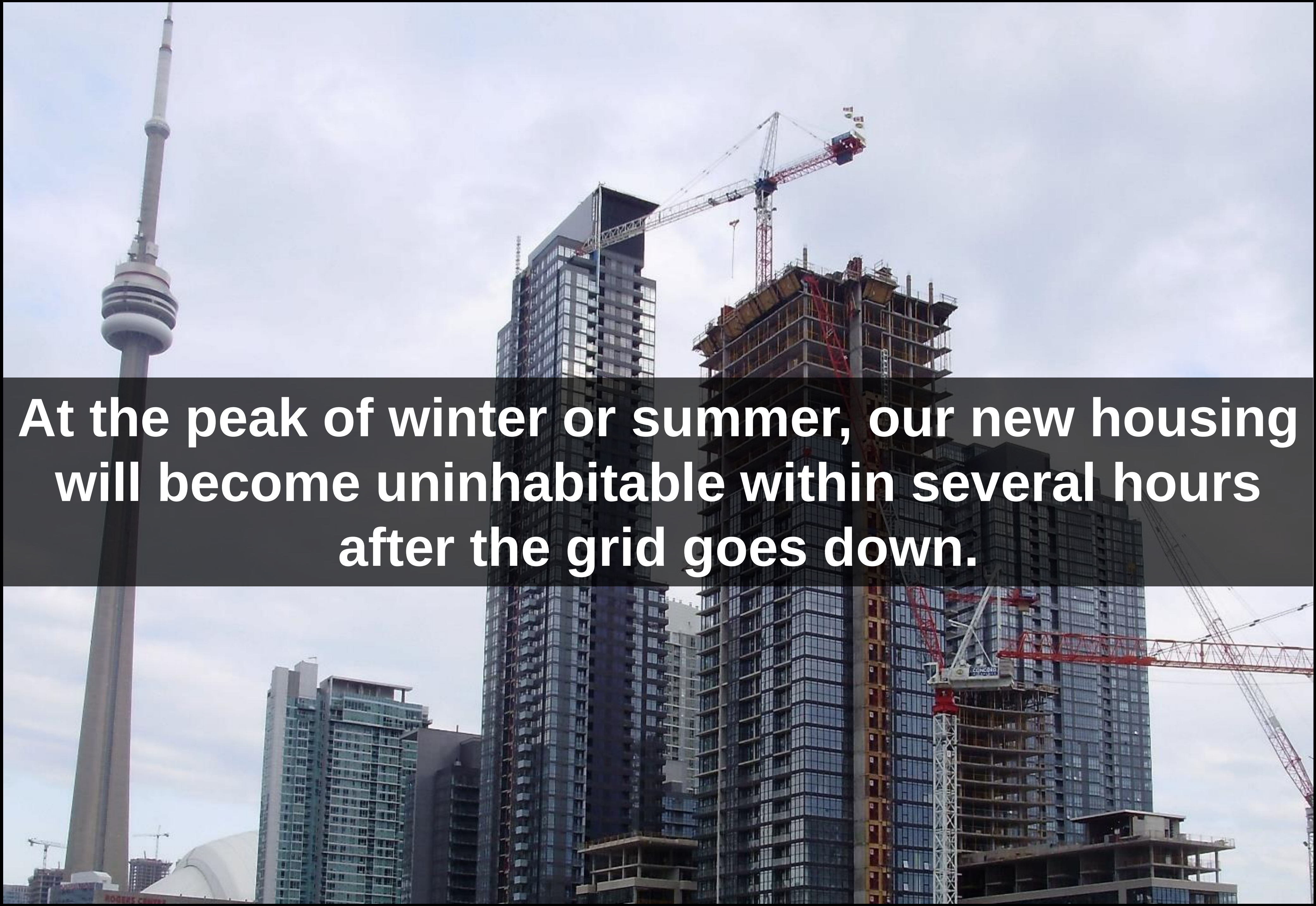
MONTREAL—More than 90 people are now suspected to have died as a result of a July heat wave in Quebec, with new figures showing that 53 deaths in the city of Montreal alone may be linked to elevated temperatures.

The latest statistics indicate that at least 93 people across the province likely died when temperatures spiked as high as 35.3 C during the week of July 1 to July 8.

A woman cools down in a water fountain in Montreal on Monday, July 2. The heat wave has now been blamed for 91 deaths in Quebec, with 53 alone in Montreal. (GRAHAM HUGHES / THE CANADIAN PRESS)

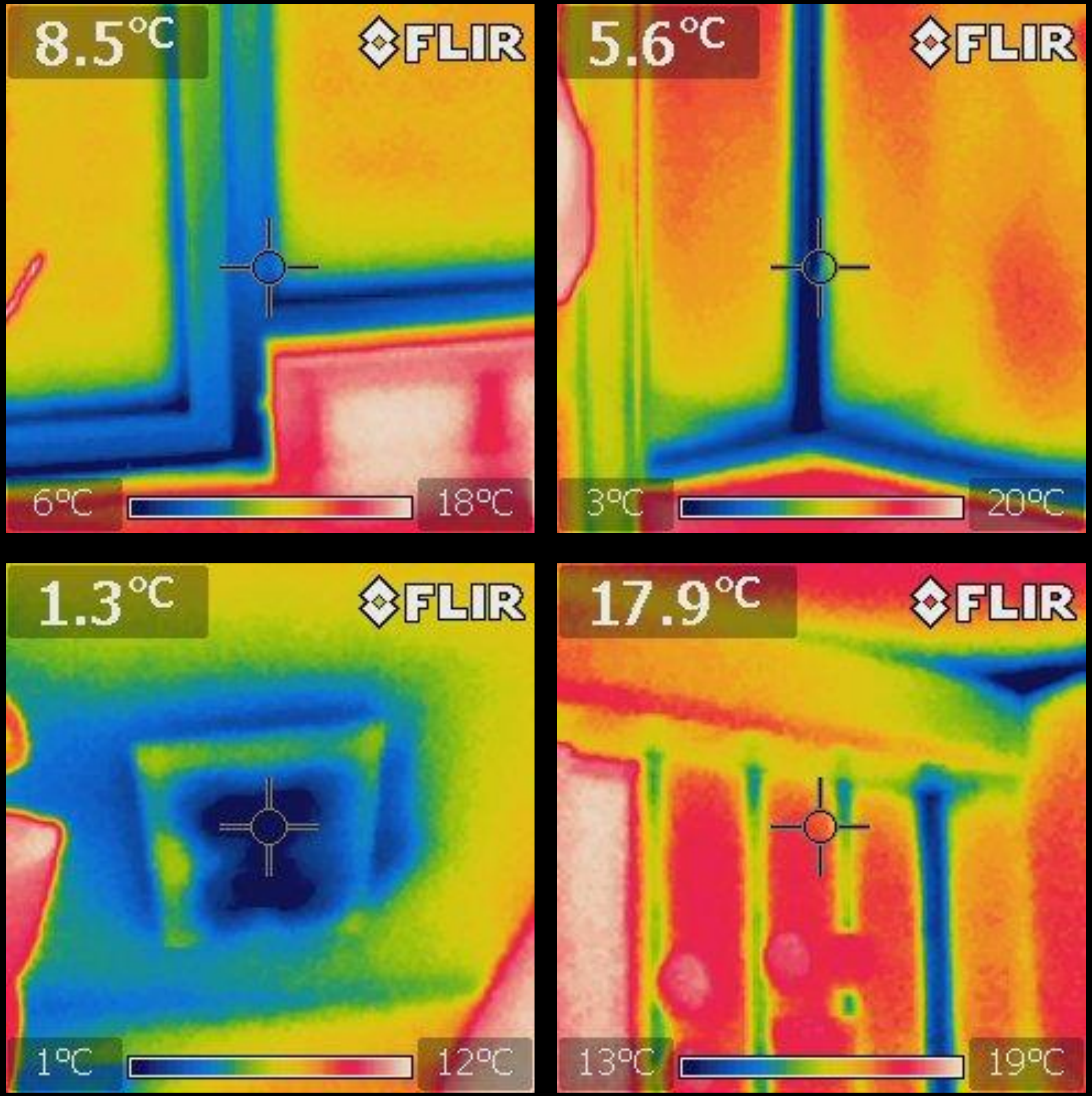
More people died in this summer’s heat wave than in the Grenfell Tower fire disaster.


Everybody’s got a plan until they get punched in the face.
Mike Tyson


At the peak of winter or summer, our new housing will become uninhabitable within several hours after the grid goes down.

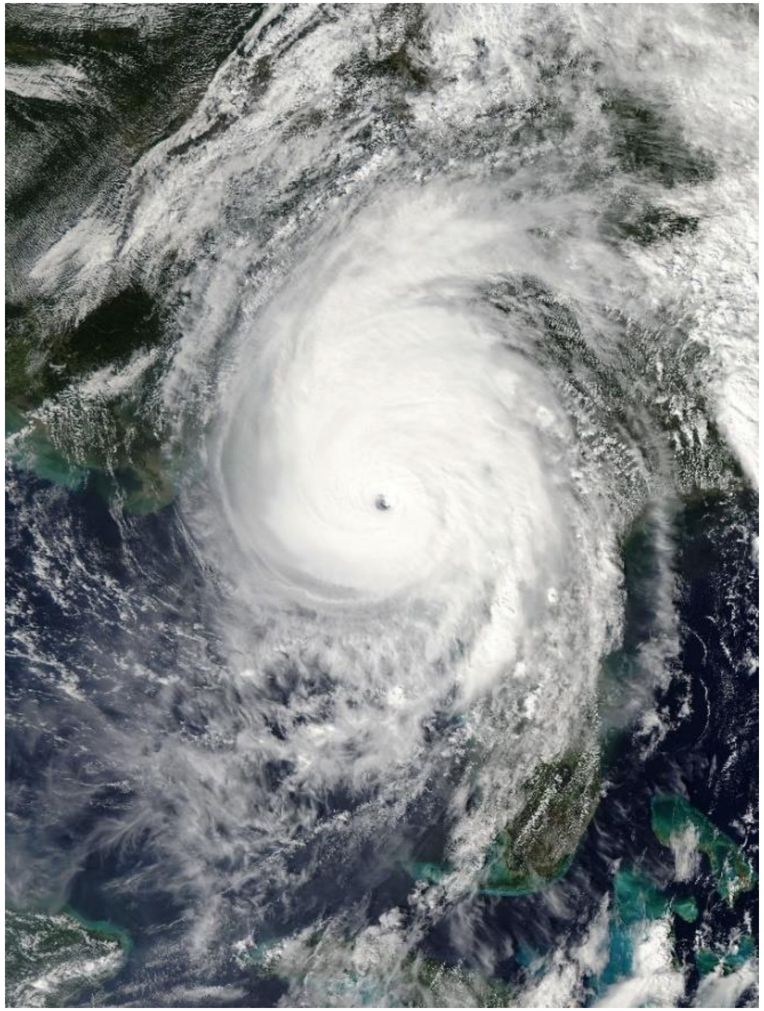
Extreme weather reveals inferior enclosures.

Code violations for condensation control are widespread.



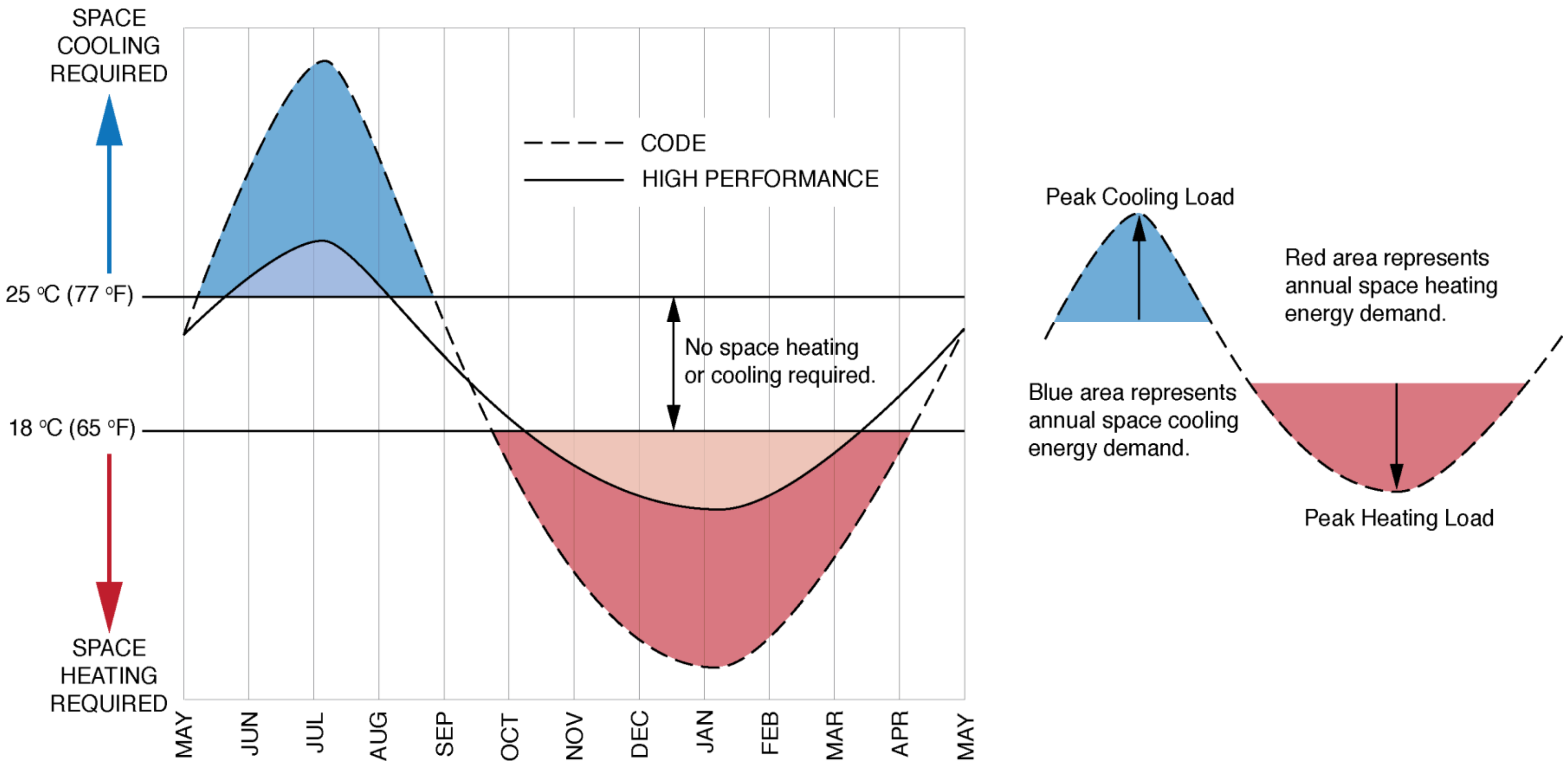
Source: Professor Liam O'Brien, Carleton University
Field Investigator: Isis Bennet.

Futureproofing

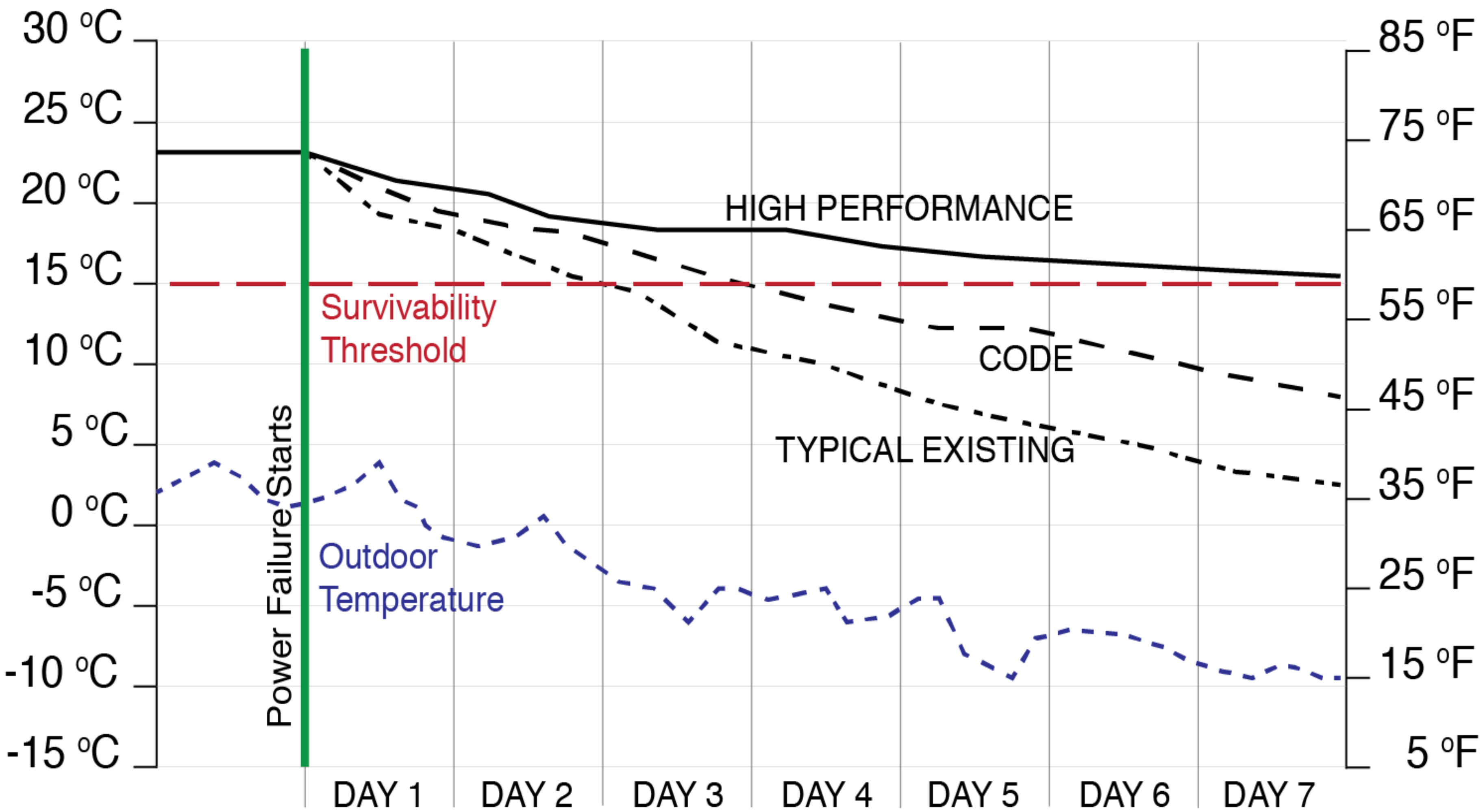


- Our communities will continue to "*get punched in the face*" as the frequency and severity of extreme weather events keeps dramatically increasing.
- Infrastructure delivering vital services to our communities is aging and therefore more susceptible to failure.
- Resilience is a critical and cost effective strategy that is easy to deploy and will help keep inhabitants safe.
- It will also help preserve the integrity and value of our building assets.

Nothing contributes more to building resilience than passive systems, and the most important passive system in a building is the enclosure / façade.



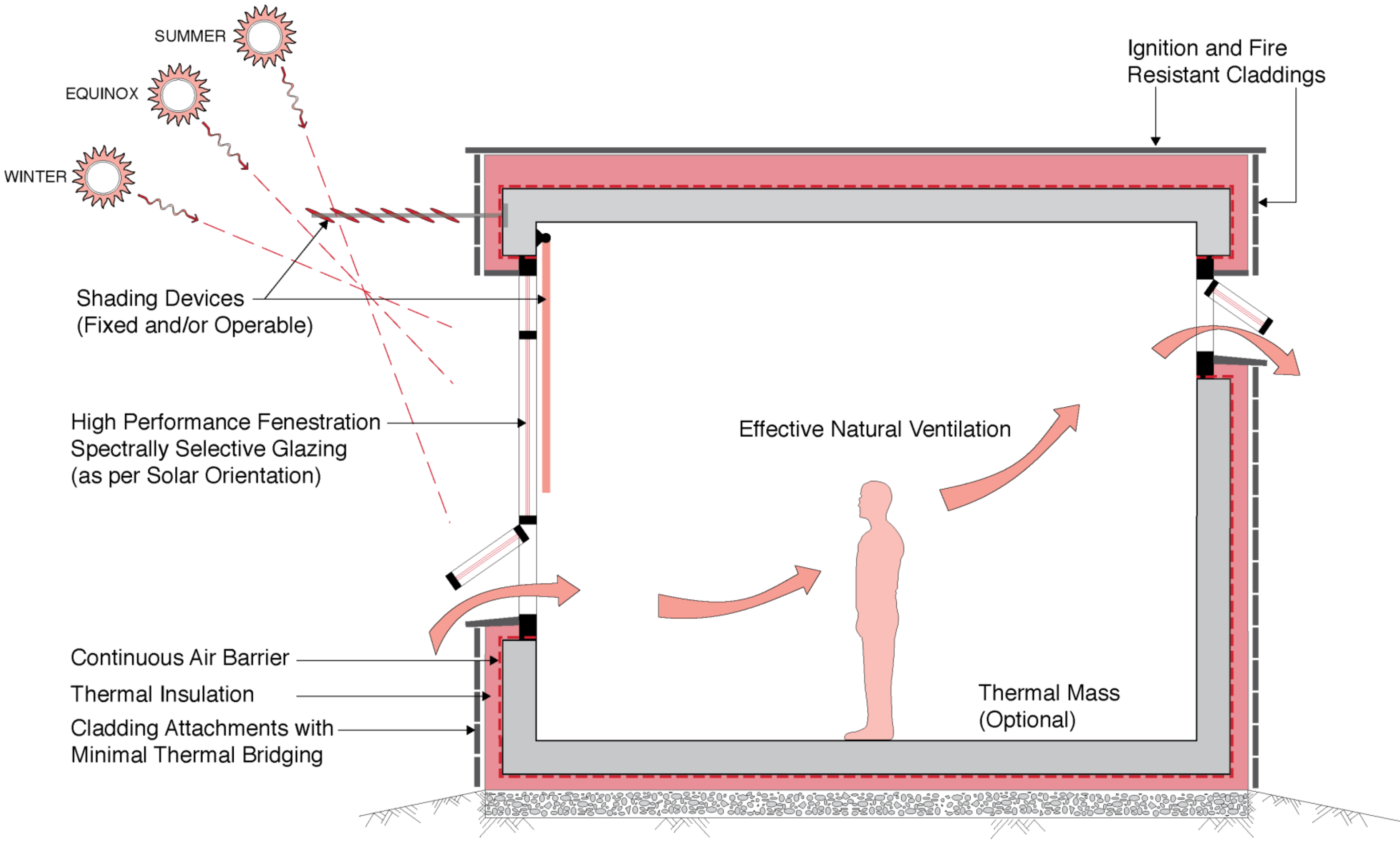
Thermal autonomy *is a measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs.*



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

Thermal Resilience Recipe

- High levels of thermal insulation
- Appropriate window-to-wall ratio
- Efficient windows & SHGC
- Continuous air barrier system
- Shading devices
- Natural ventilation



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.

Thermal Insulation

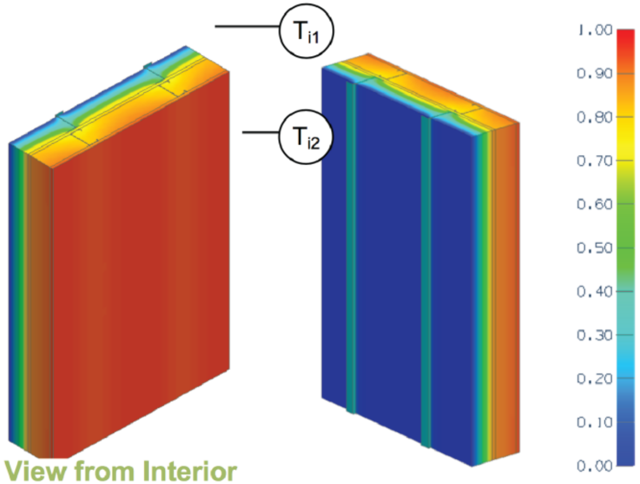
Insulation Type	RSI-value m².K/W per 25 mm	R-value °F.ft².hour/BTU per inch
Cellulose	0.56 - 0.65	3.2 - 3.7
Fiberglass	0.44 - 0.65	2.5 - 3.7
Mineral Fiber Wool	0.63 - 0.70	3.3 - 4.0
Extruded Polystyrene	0.88 - 0.95	5.0 - 5.4
Expanded Polystyrene	0.63 - 0.77	3.6 - 4.4
Urethane Spray Foam, low density	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.

Thermal Bridging

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



View from Interior

View from Exterior

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.

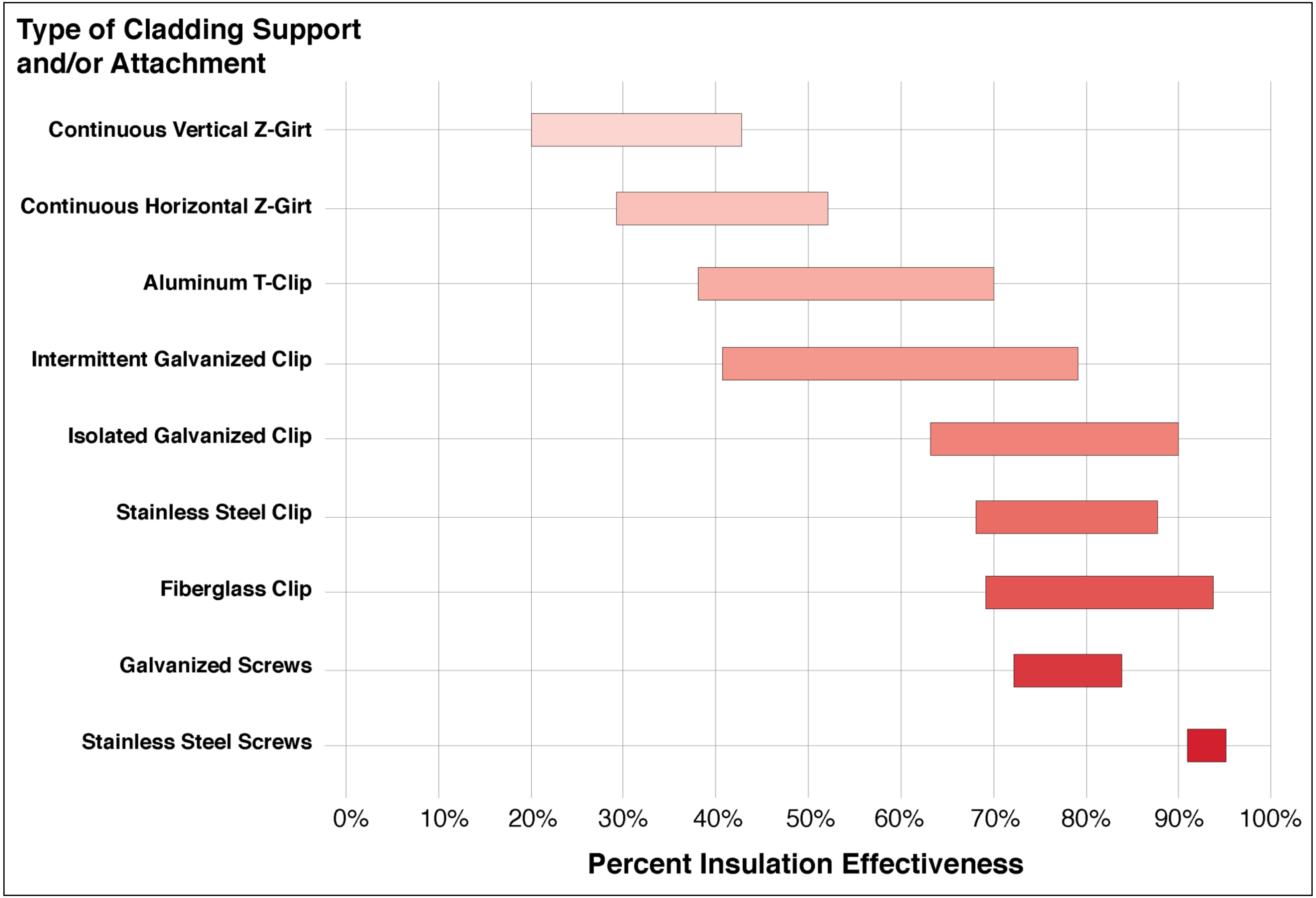
Nominal (1D) vs. Assembly Performance Indicators

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

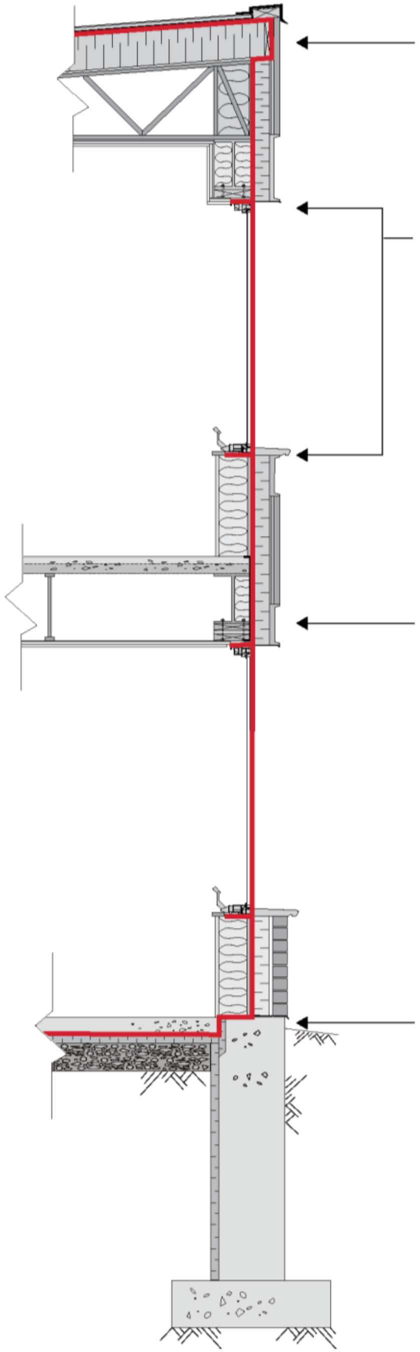
Temperature Indices

	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


Type of Cladding Support and/or Attachment
Continuous Vertical Z-Girt
Continuous Horizontal Z-Girt
Aluminum T-Clip
Intermittent Galvanized Clip
Isolated Galvanized Clip
Stainless Steel Clip
Fiberglass Clip
Galvanized Screws
Stainless Steel Screws
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent Insulation Effectiveness

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 depressuriztion is the only means of confirming that air impermeable materials 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 tying 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

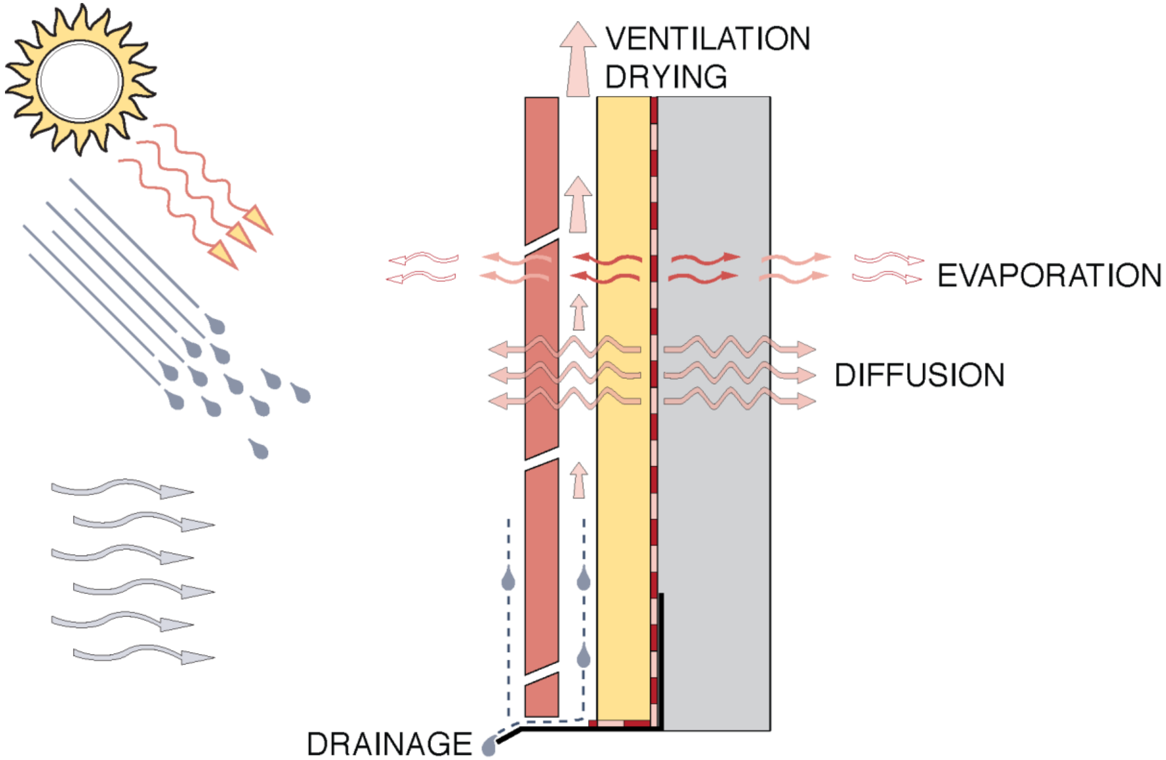
Foundation and Slab to Wall Transition
- formulation of air barrier strategy that is practical in terms of sequencing to allow for interconnection at transitions by durable materials that can withstand abuse during construction
- selection of a forgiving system where the control of soil gas by sub-slab 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

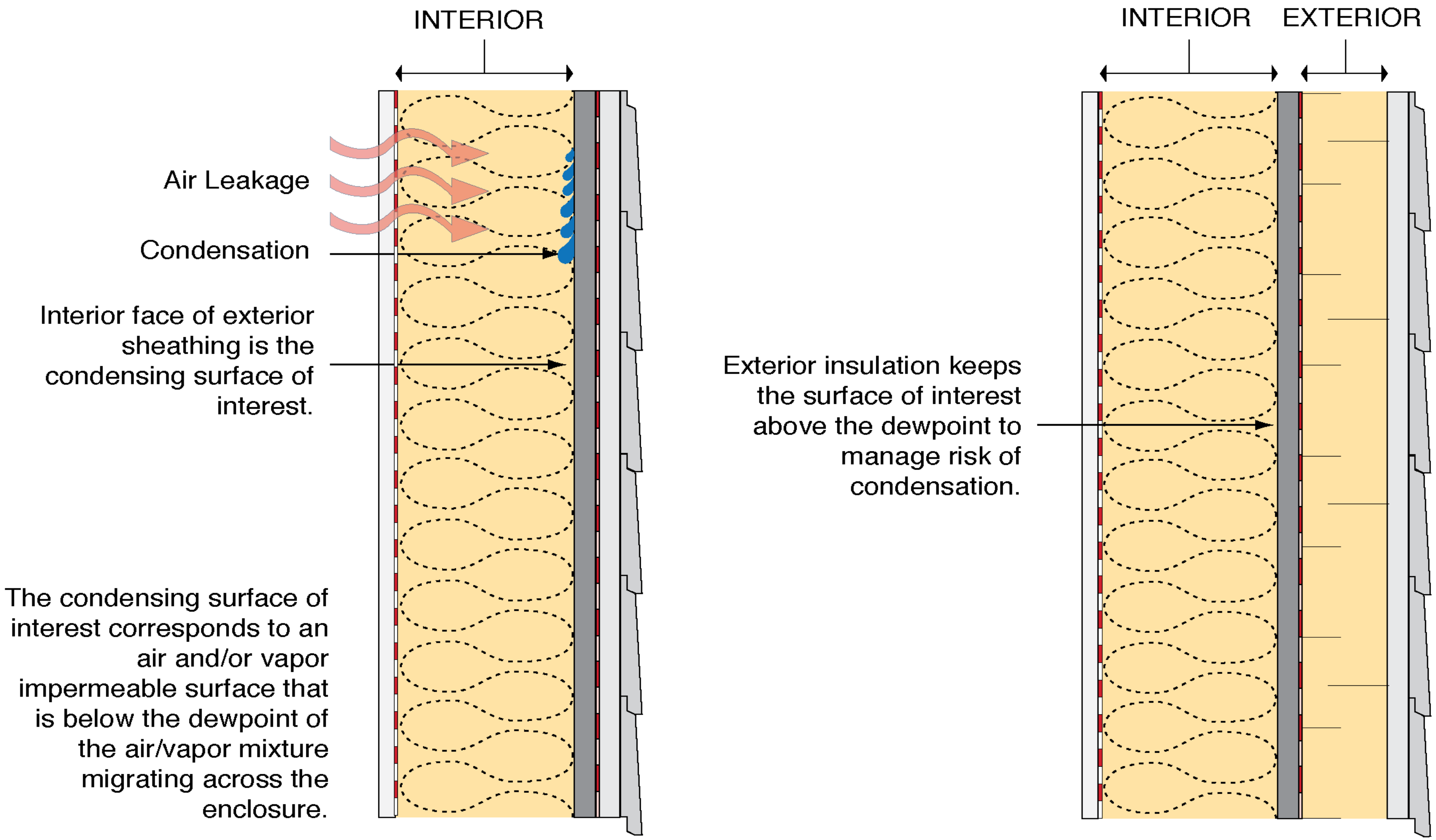
Application	Metric	U.S.	Test Method
Material	0.02 L/s.m² @ 75 Pa	0.004 cfm/ft² @ 1.57 psf	ASTM E 2178-13 Standard Test Method for Air Permeance of Materials
Assembly	0.2 L/s.m² at 75 Pa	0.04 cfm/ft² @ 1.57 psf	ASTM E 2357-17 Standard Test Method for Determining Air Leakage of Air Barrier Assemblies
Whole Building	2 L/s.m² at 75 Pa	0.4 cfm/ft² @ 1.57 psf	ASTM E779-10 (2018) Standard Test Method for Determining Air Leakage Rate by Fan Depressurization

Class	Permeance (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 to 10	60 - 600	Semi-permeable
none	Over 10	Over 600	Permeable

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

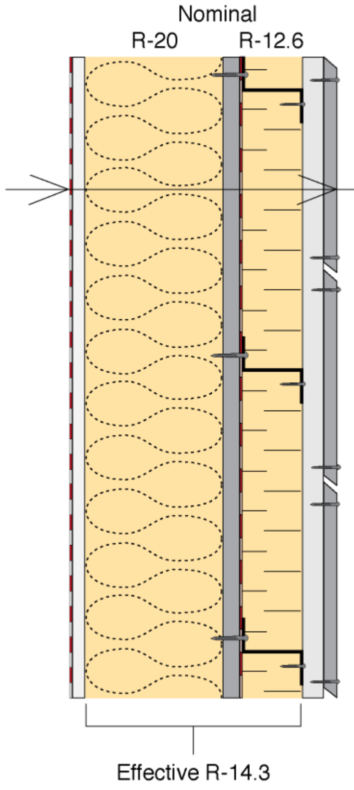
Building enclosures should be designed to dry out easier than they get wet. This is often easier said than done in climate zones with high precipitation exposure and low drying potentials. The vapor permeability of air barriers is among the many critical factors affecting hygrothermal performance.





In climates with cold seasons, it is advisable to place all of the insulation on the exterior of the air leakage control plane to manage the risk of condensation due to air leakage. However this makes energy efficient walls very thick, and an alternative approach is to combine interior and exterior insulation in proper proportions to manage moisture.

Indoor	RH		20	25	30	35	40	50	60
Dew point	°C		-3.0	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



Example: In a building located where the average minimum January temperature is 14 °F, and the indoor relative humidity is intended to be maintained at 40%, the ratio of exterior to interior insulation is given as 0.54 in Table 3. If the interior insulation in a 5.5 inch wall cavity is R-20, then the exterior insulation should be at least R-10.8.
(***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.*)
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. This means that the thermal efficiency of this wall assembly, based on the nominal insulation is 14.3/32.6 = 43.9%. This is less than half of the nominal insulation R-value and may not comply with codes.

Windows

Overall Window U-value =

Frame U-value X
% Frame Area

+

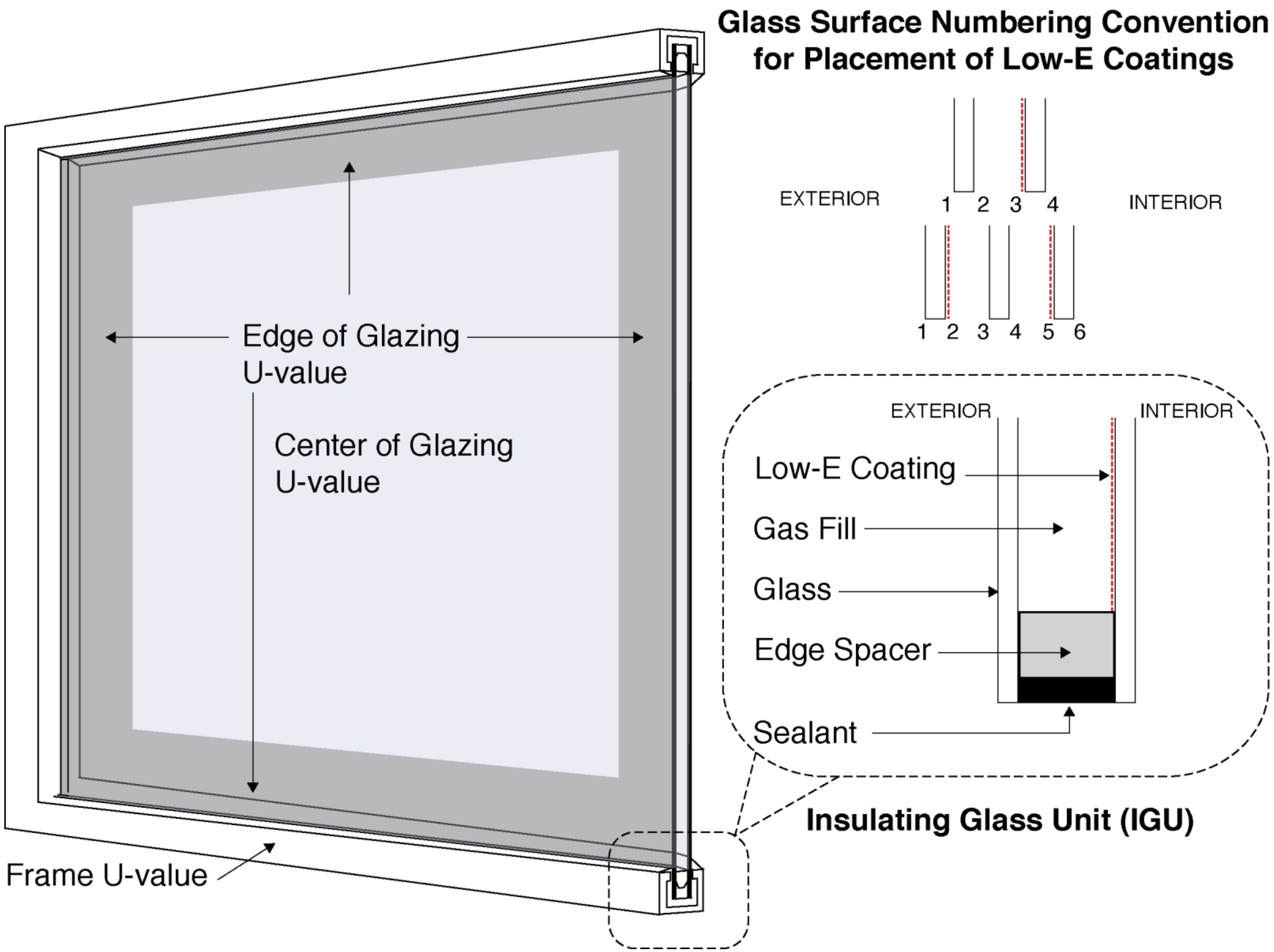
Center of Glazing U-value X
% Center of Glazing Area

+

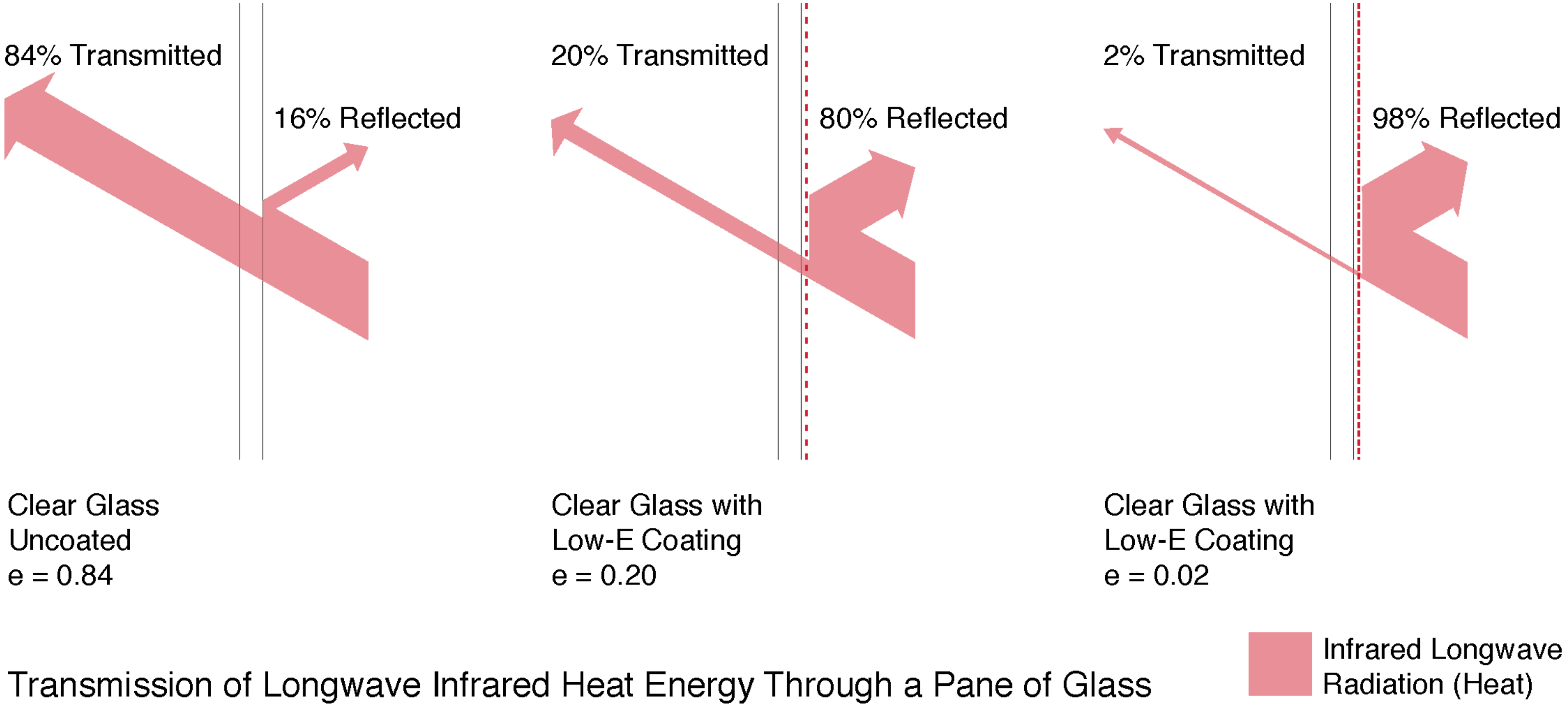
Edge of Glazing U-value X
% Edge of Glass Area

Note: Edge of glazing area is a
2.5 inch (63.5 mm) wide
perimeter strip.

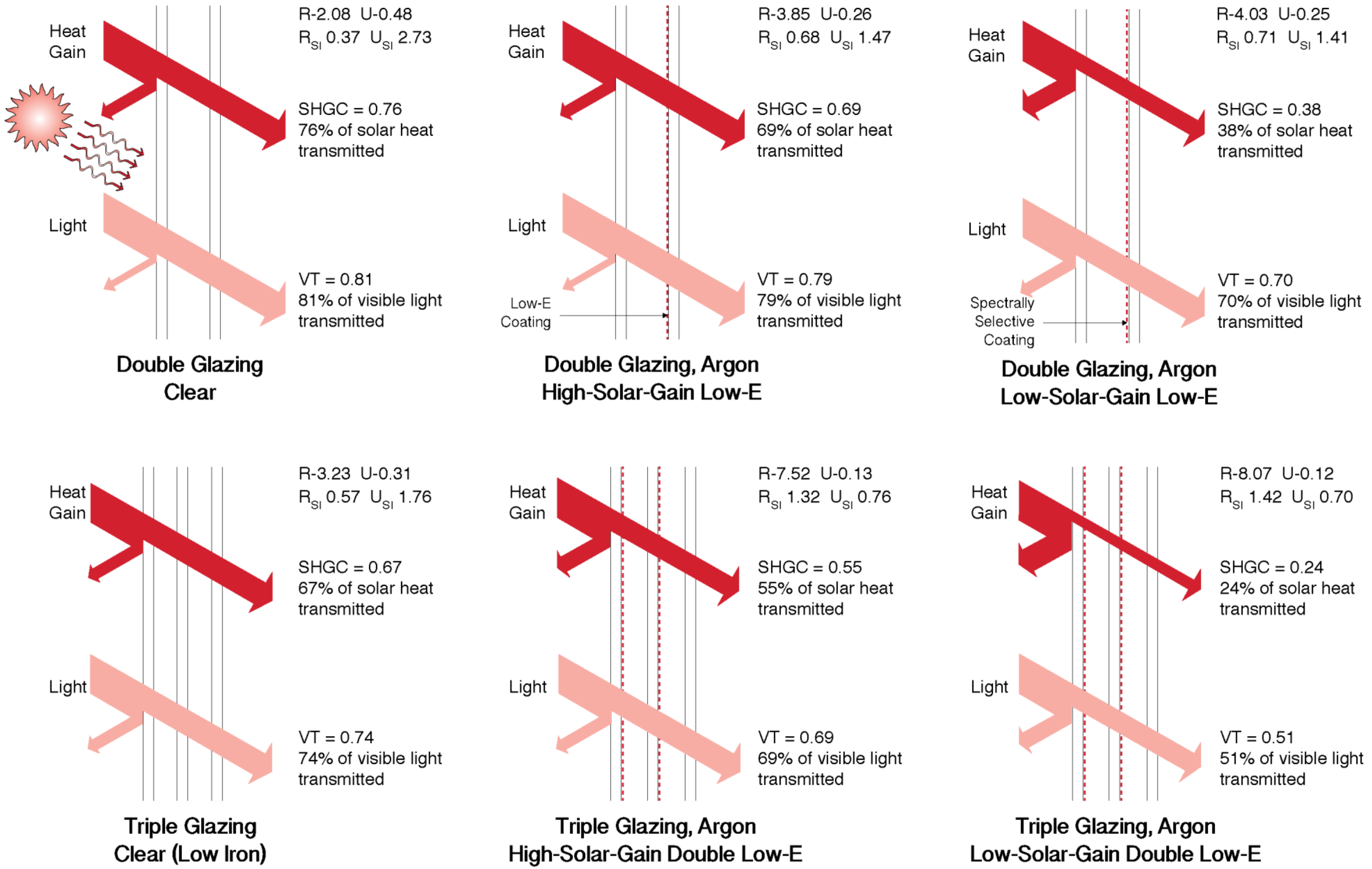
Overall R-value = 1/U-value



Spectrally Selective Glazing



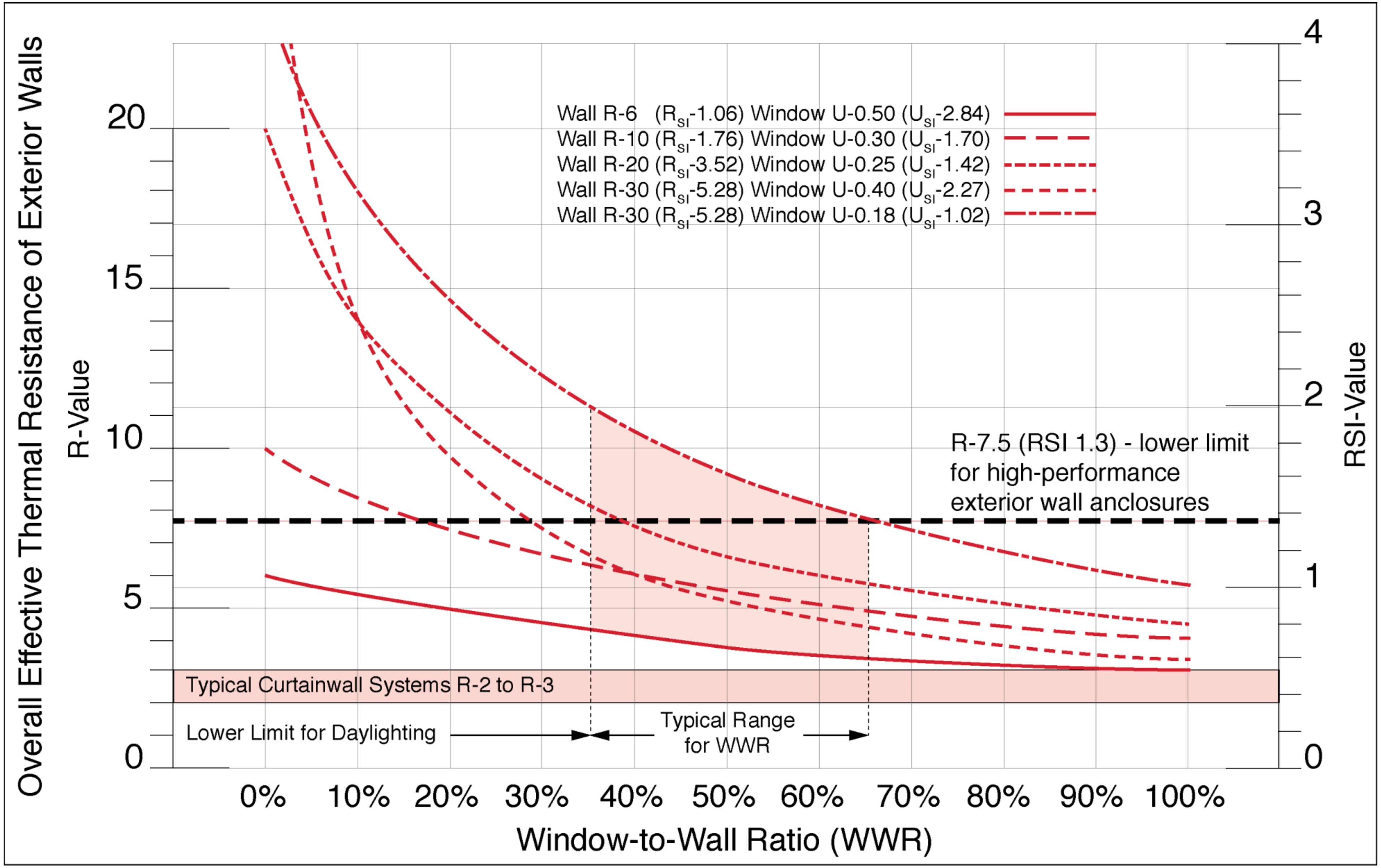
Transmission of Longwave Infrared Heat Energy Through a Pane of Glass



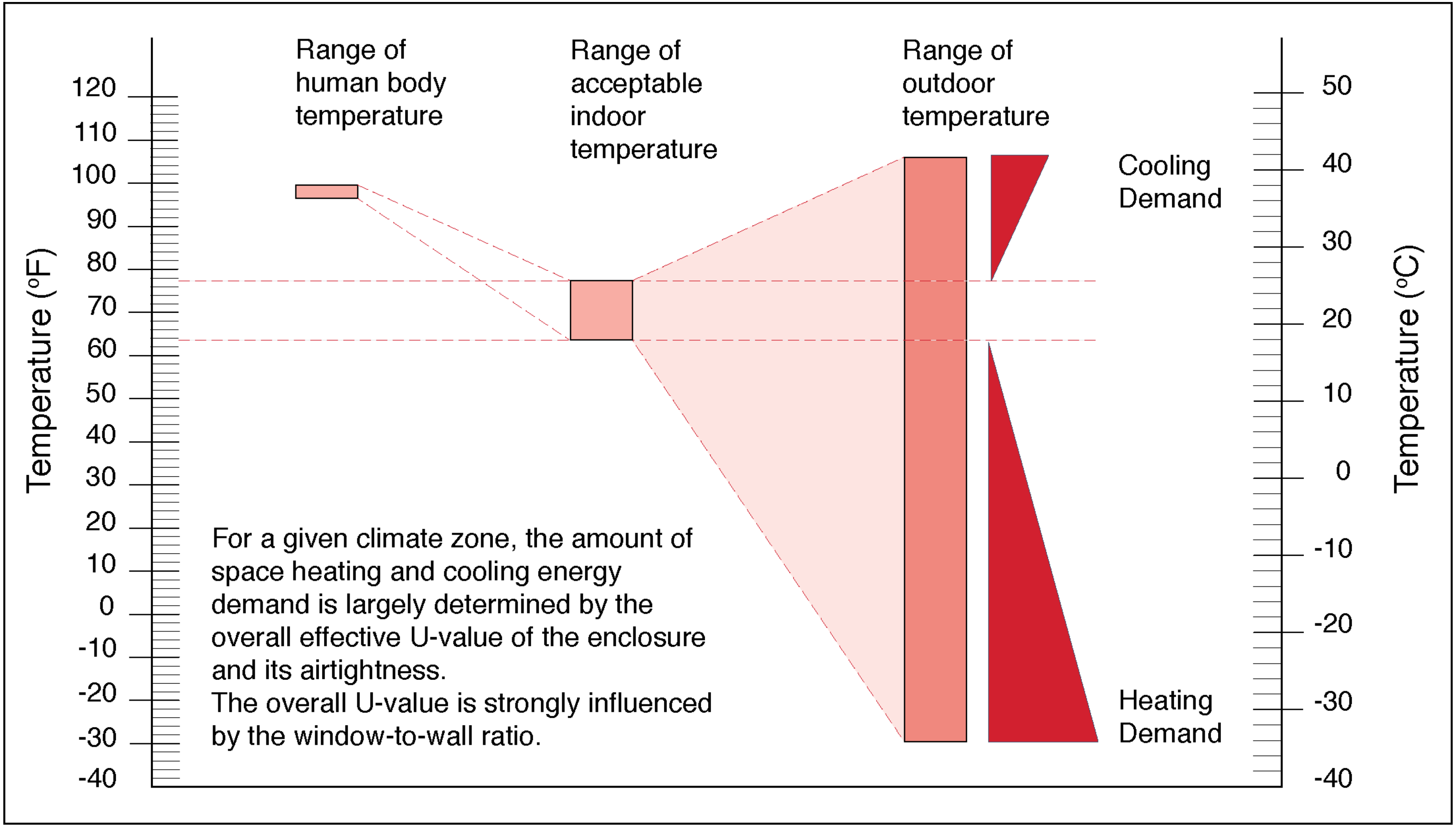
Heat Gain
Light
R-2.08 U-0.48
R_{SI} 0.37 U_{SI} 2.73
SHGC = 0.76
76% of solar heat transmitted
VT = 0.81
81% of visible light transmitted
Double Glazing
Clear
Heat Gain
Light
Low-E Coating
R-3.85 U-0.26
R_{SI} 0.68 U_{SI} 1.47
SHGC = 0.69
69% of solar heat transmitted
VT = 0.79
79% of visible light transmitted
Double Glazing, Argon
High-Solar-Gain Low-E
Heat Gain
Light
Spectrally Selective Coating
R-4.03 U-0.25
R_{SI} 0.71 U_{SI} 1.41
SHGC = 0.38
38% of solar heat transmitted
VT = 0.70
70% of visible light transmitted
Double Glazing, Argon
Low-Solar-Gain Low-E
Heat Gain
Light
R-3.23 U-0.31
R_{SI} 0.57 U_{SI} 1.76
SHGC = 0.67
67% of solar heat transmitted
VT = 0.74
74% of visible light transmitted
Triple Glazing
Clear (Low Iron)
Heat Gain
Light
R-7.52 U-0.13
R_{SI} 1.32 U_{SI} 0.76
SHGC = 0.55
55% of solar heat transmitted
VT = 0.69
69% of visible light transmitted
Triple Glazing, Argon
High-Solar-Gain Double Low-E
Heat Gain
Light
R-8.07 U-0.12
R_{SI} 1.42 U_{SI} 0.70
SHGC = 0.24
24% of solar heat transmitted
VT = 0.51
51% of visible light transmitted
Triple Glazing, Argon
Low-Solar-Gain Double Low-E

Window Type	U-Value (BTU/hr.ft^2.°F)	R-Value (hr.ft^2.°F/BTU)	U_{SI} (W/m^2.K)	R_{SI} (m^2.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	0.79
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 Coatings	0.18	5.57	1.02	0.98	0.24	0.51

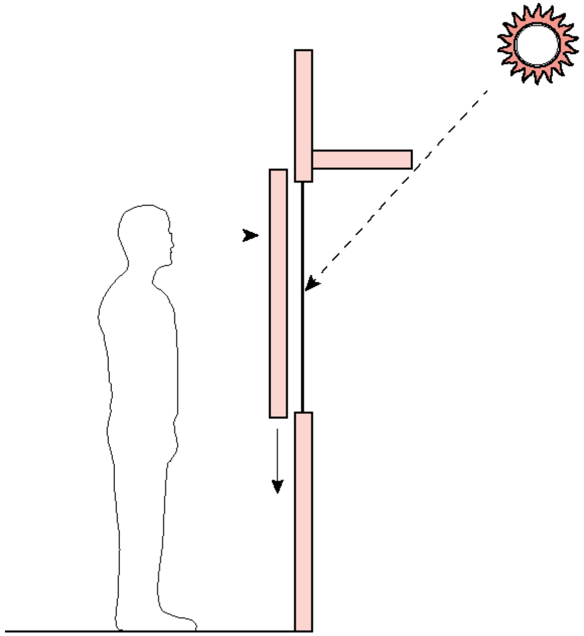
Advances in window technology have produced products that provide net energy gains on an annual basis for certain solar orientations and climate zones. Unlike only several decades ago, designers can tune building energy performance with the intelligent selection of window technologies.

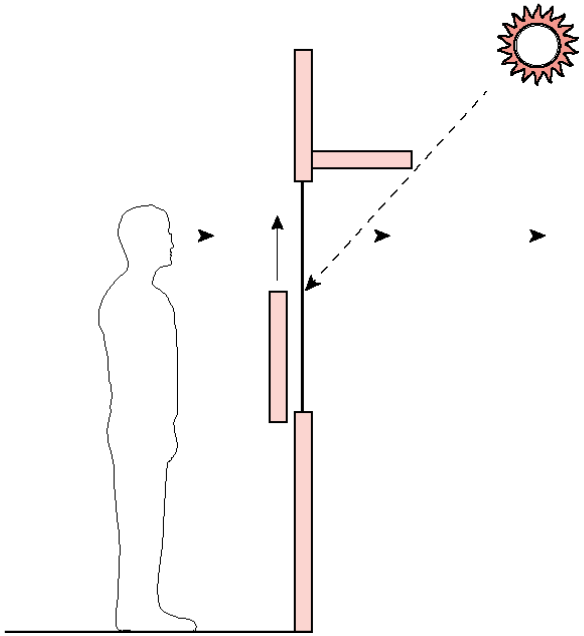


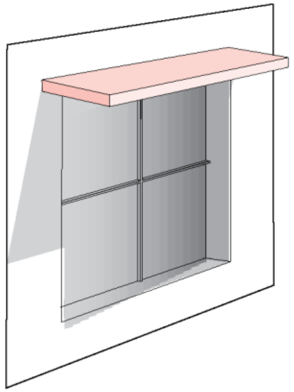
The window-to-wall ratio is a critical building enclosure design parameter. The influence of window-to-wall ratio on wall enclosure overall effective R-value for various combinations of opaque walls and windows reveals that highly glazed buildings can never be thermally resilient.


Range of human body temperature
Range of acceptable indoor temperature
Range of outdoor temperature
Cooling Demand
Heating Demand
Temperature (°F)
Temperature (°C)
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
50
40
30
20
10
0
-10
-20
-30
-40
For a given climate zone, the amount of space heating and cooling energy demand is largely determined by the overall effective U-value of the enclosure and its airtightness.
The overall U-value is strongly influenced by the window-to-wall ratio.

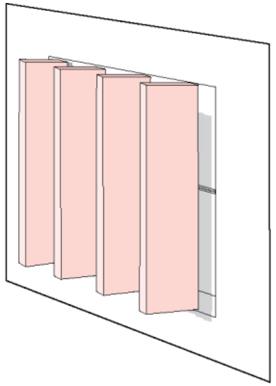
Shading Devices



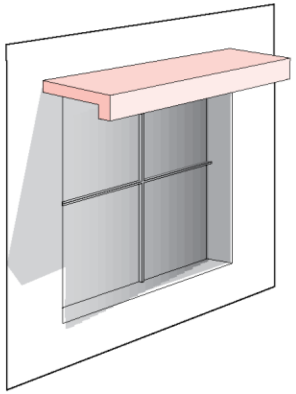




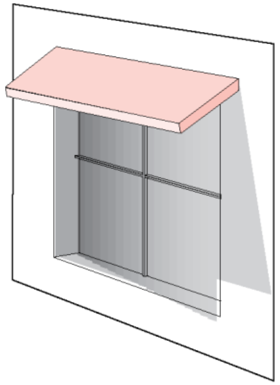
Standard horizontal overhang.



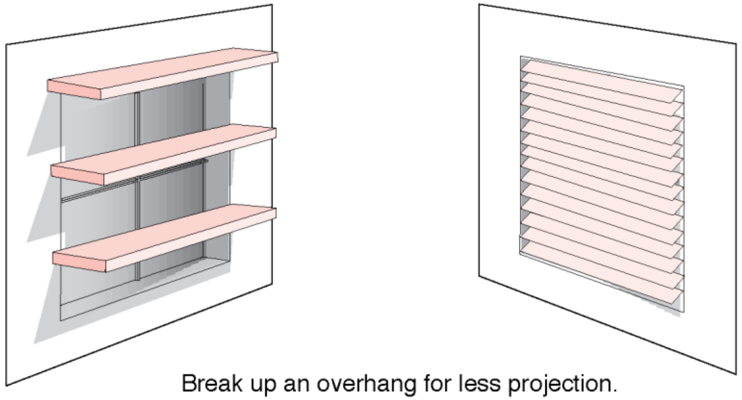
Vertical louvers or fins for east and especially west facades.



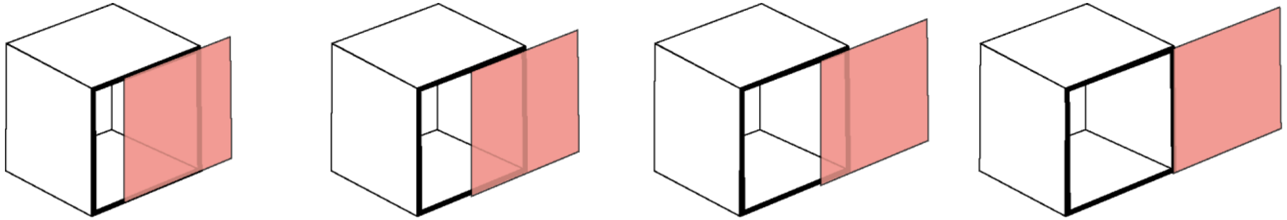
Drop the edge for less projection.



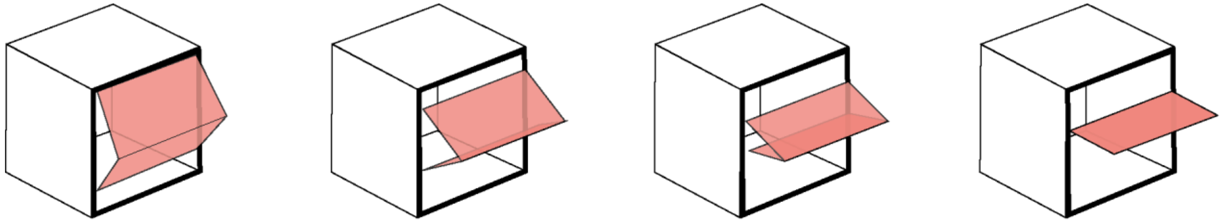
Slope it down for less projection.



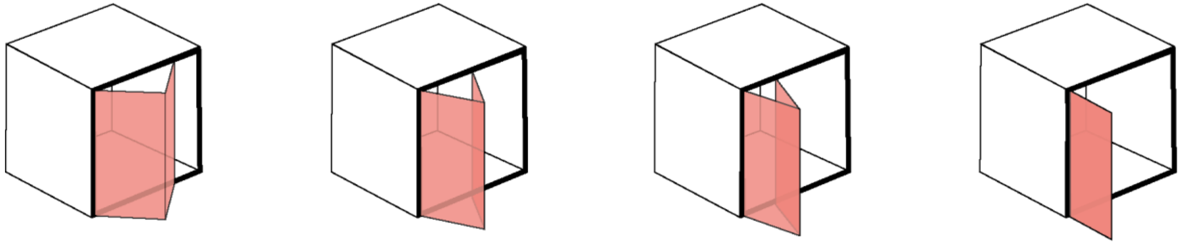
Break up an overhang for less projection.



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

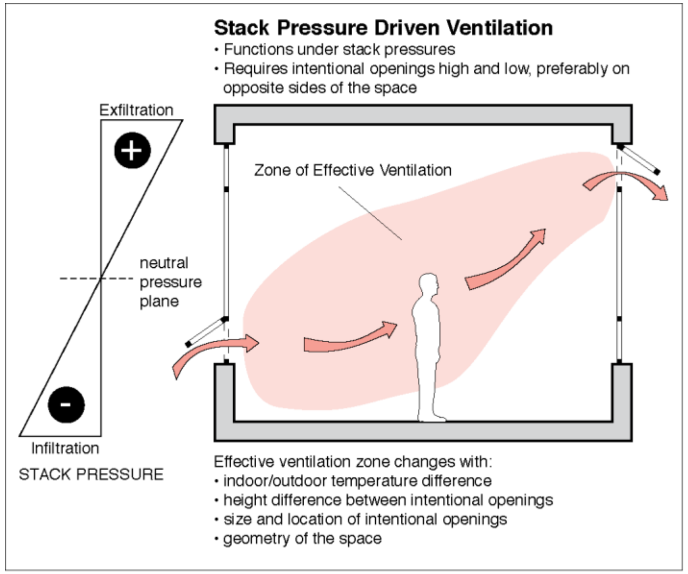


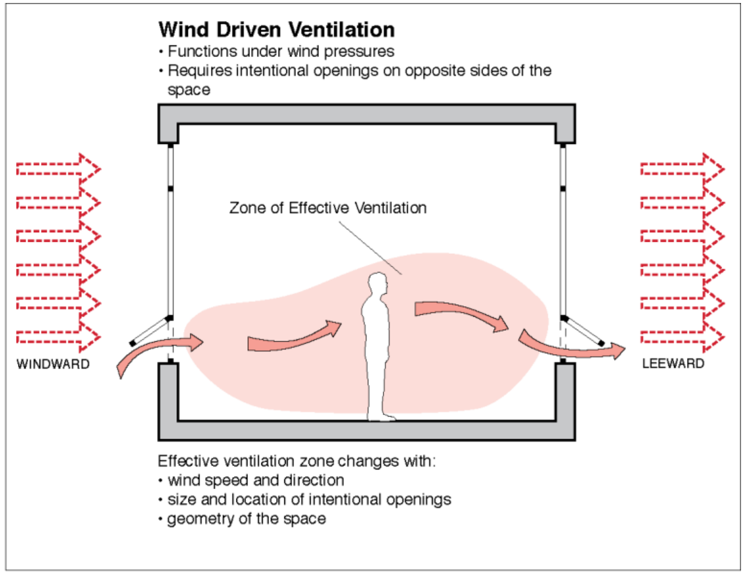
Horizontal folding panels perform better than sliding panels, but are prone to developing snow and ice accumulations.

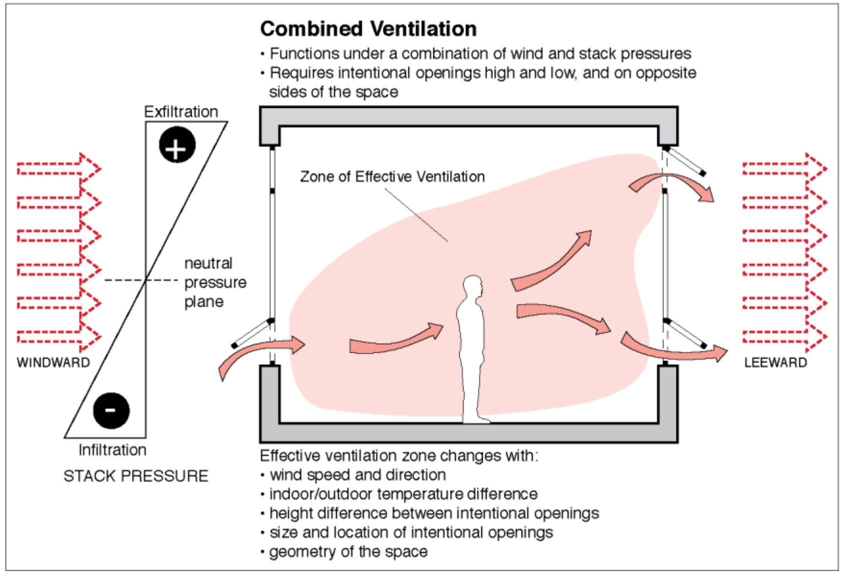


Vertical folding panels provide the best overall performance and flexibility, especially when panels are mounted on each side of the fenestration opening.

Natural Ventilation



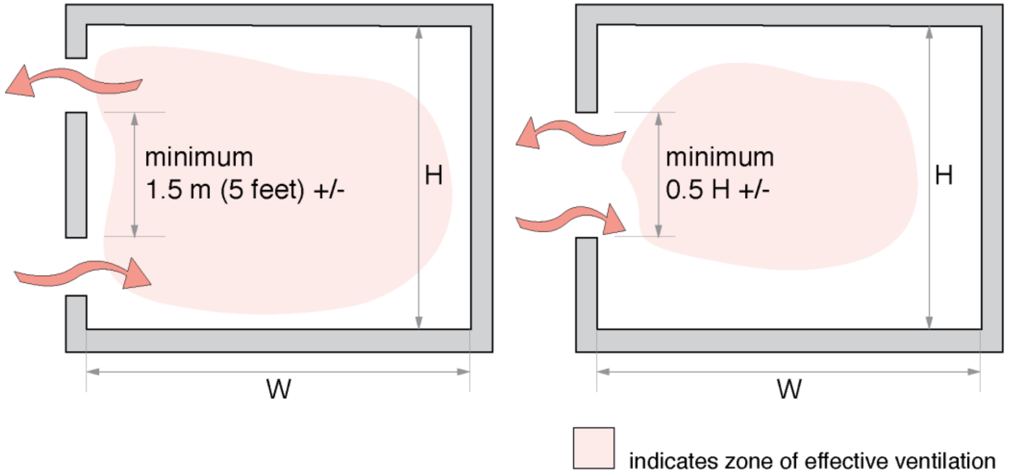




Rules of Thumb - Natural Ventilation Design Parameters

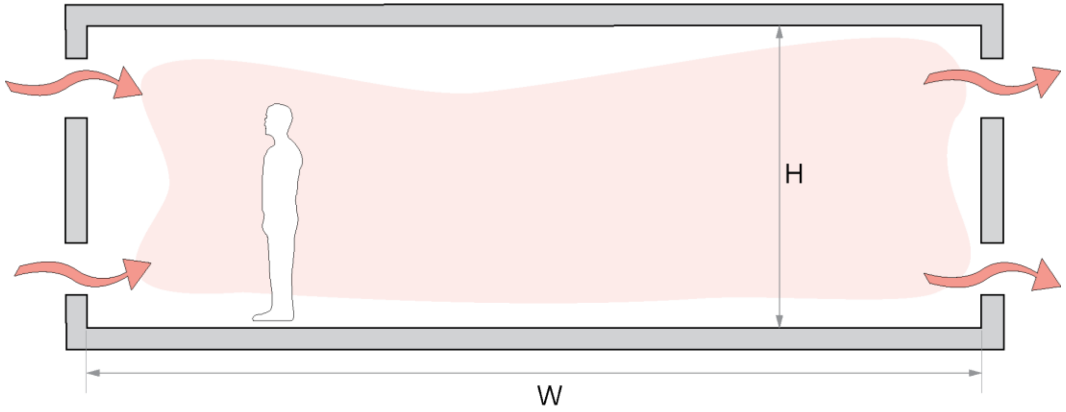
Single-Sided Ventilation

- 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)

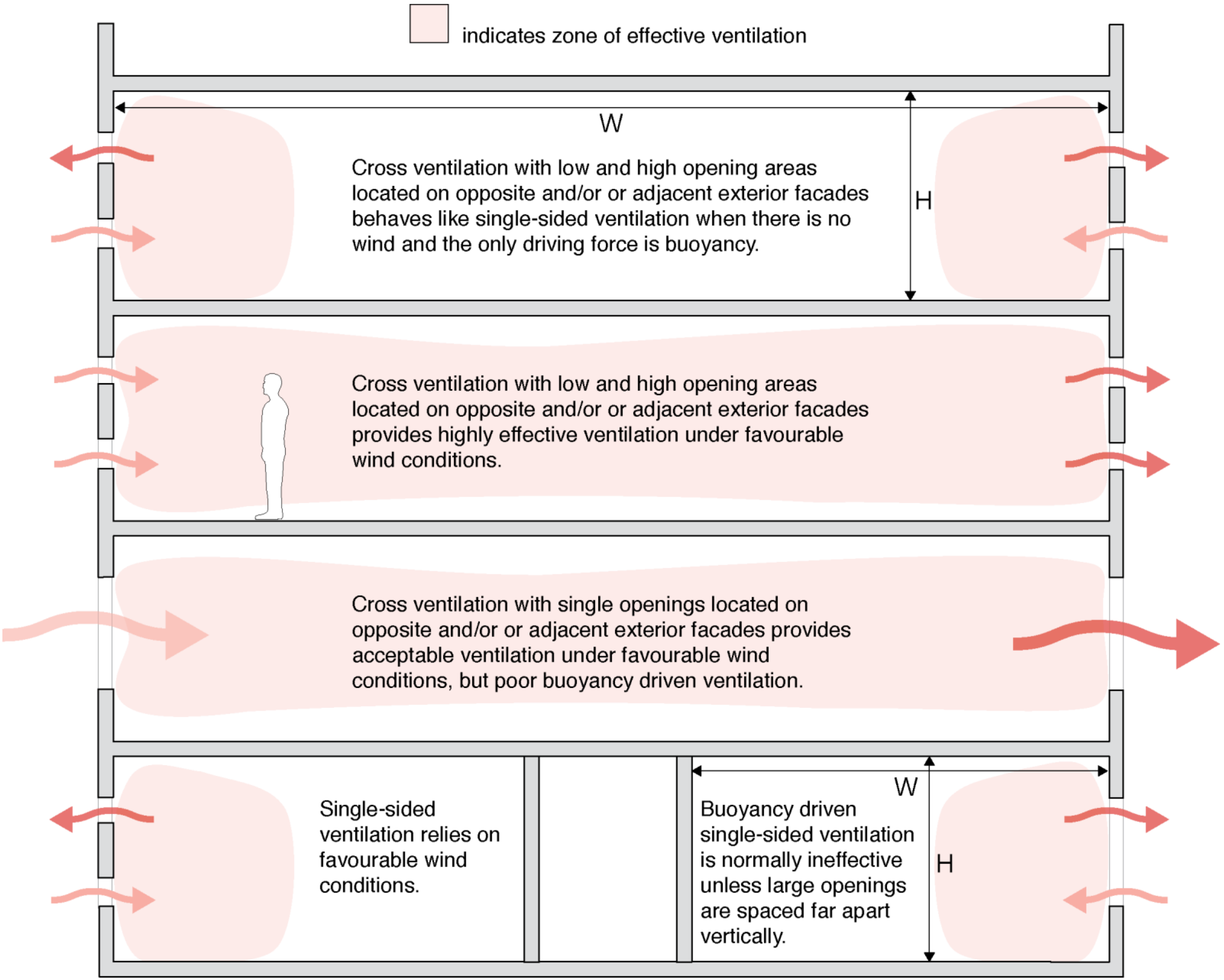


Cross Ventilation

- 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)



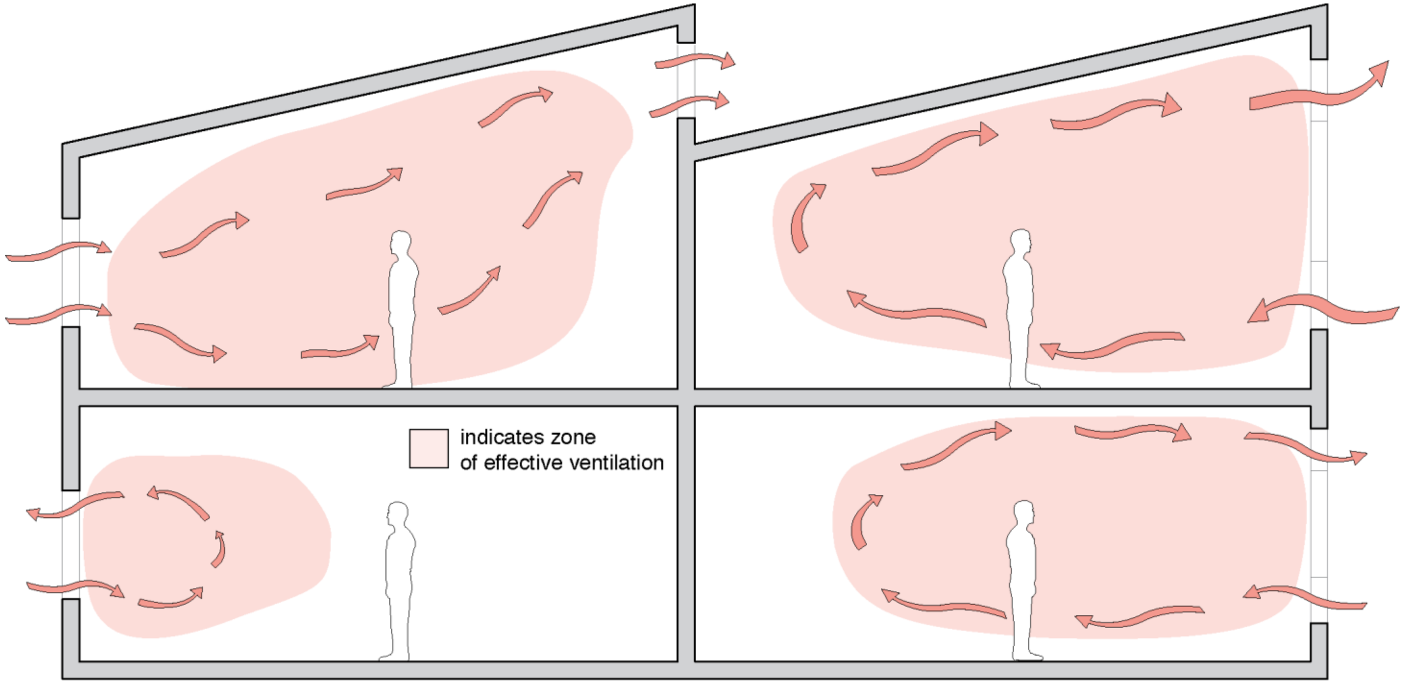
Single-sided ventilation is less effective than cross ventilation.



The effective natural ventilation of all compartmentalized spaces is challenging.

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

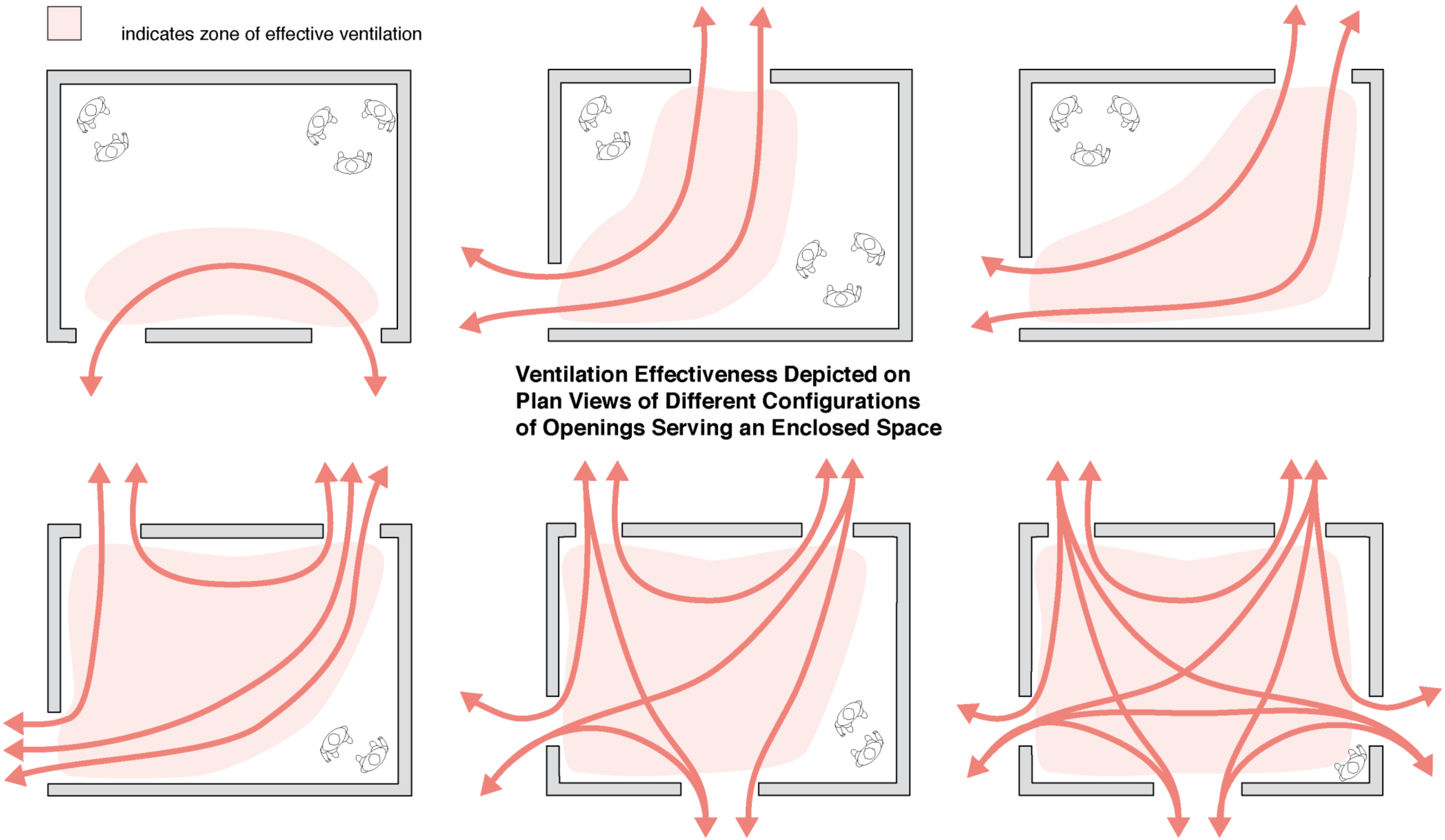
Single sided ventilation with large, well spaced low and high opening areas combined with dynamic room geometry delivers acceptable ventilation effectiveness.



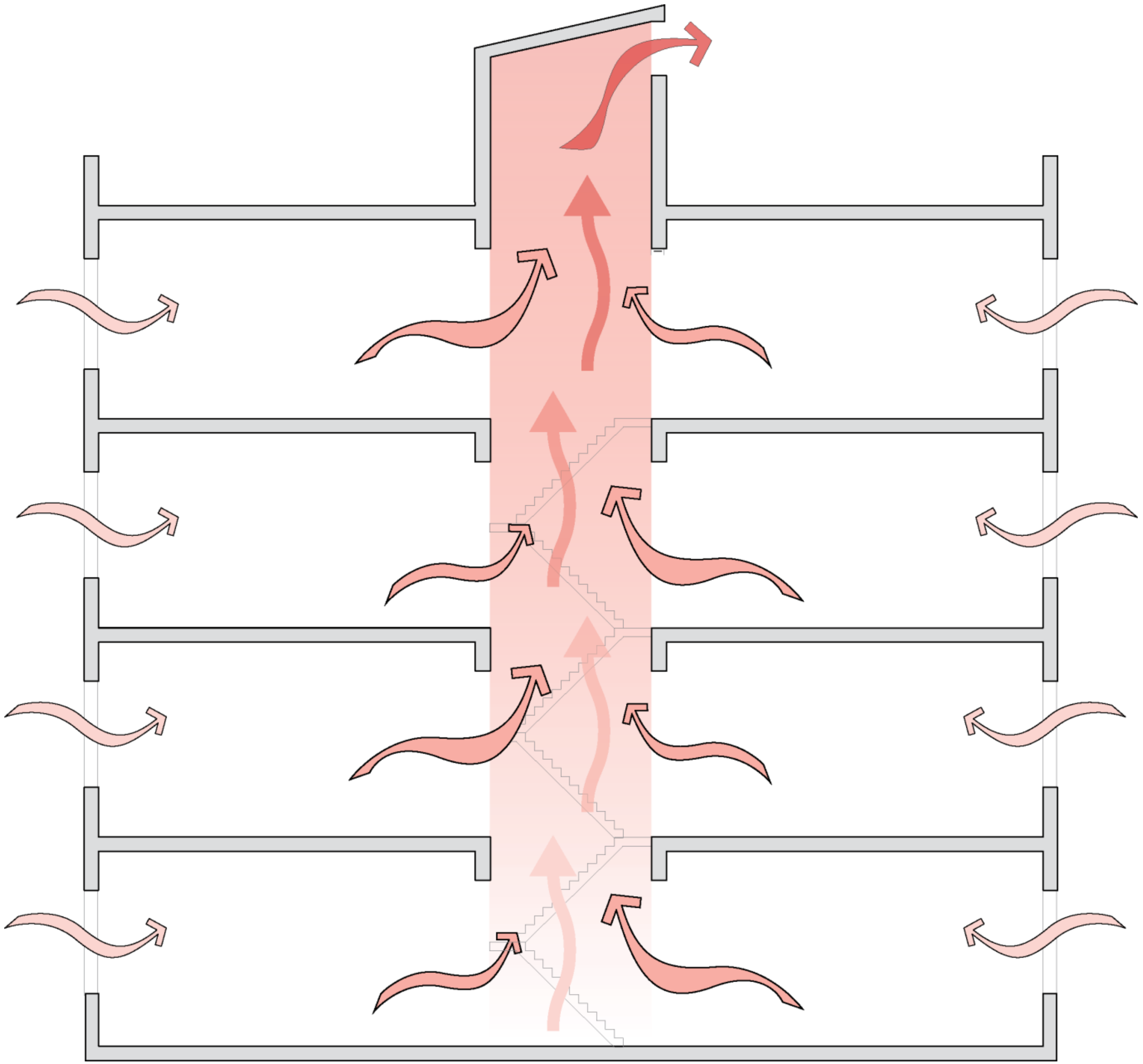
Single sided ventilation with small opening areas provides marginal ventilation effectiveness.

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

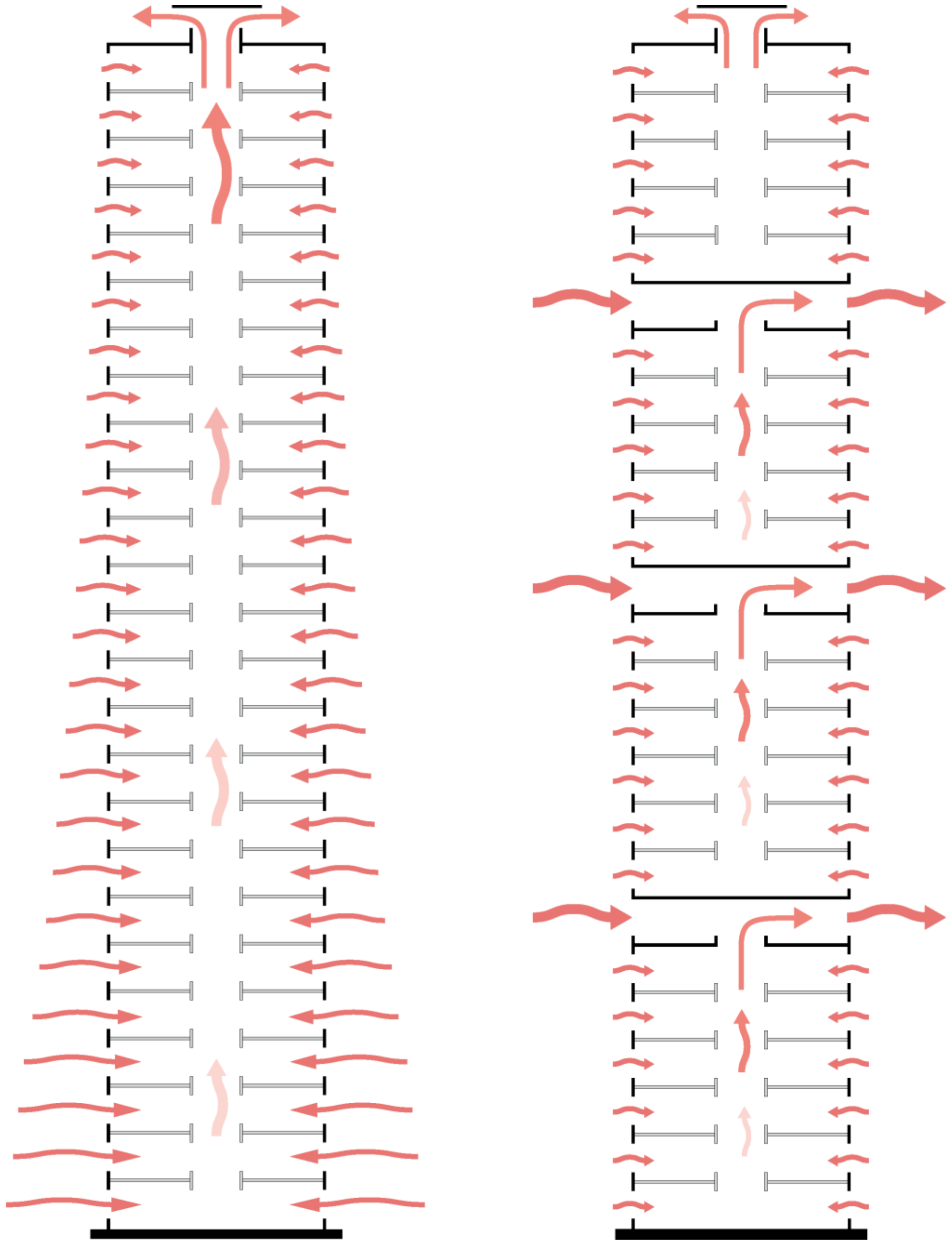
Natural ventilation techniques range in degrees of effectiveness.



The configuration of ventilation openings is among the most critical factors affecting natural ventilation effectiveness.

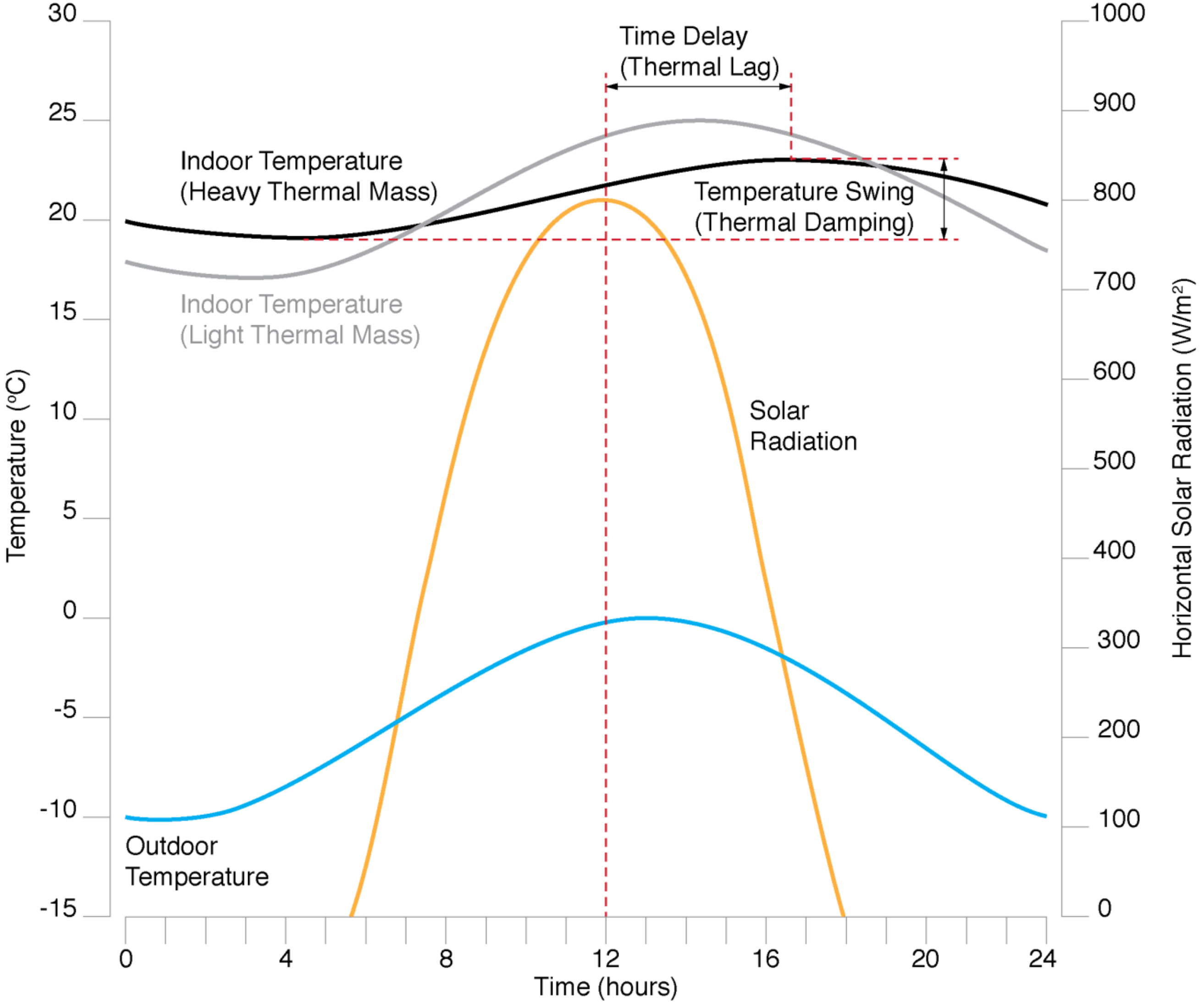


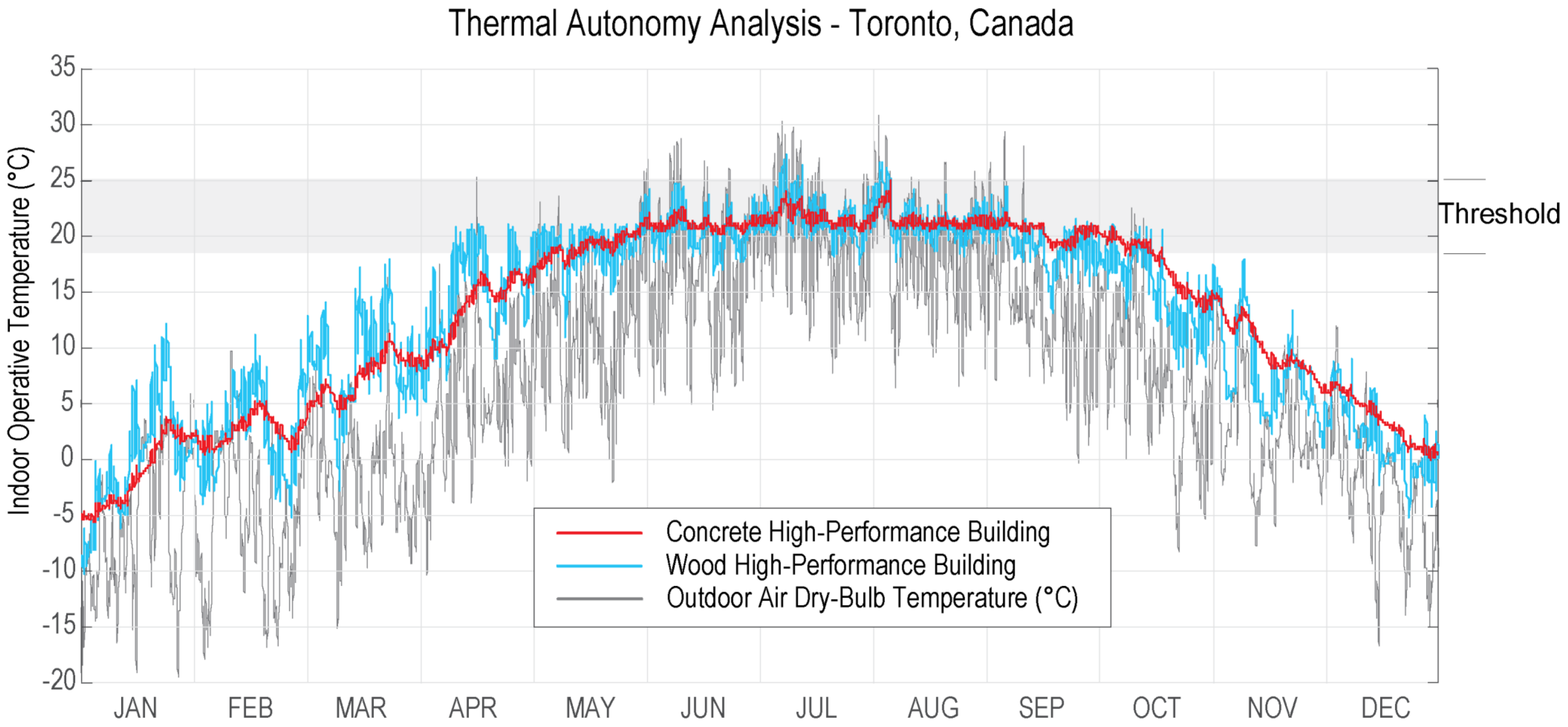
Vernacular architecture provides successful precedents for enhanced natural ventilation.



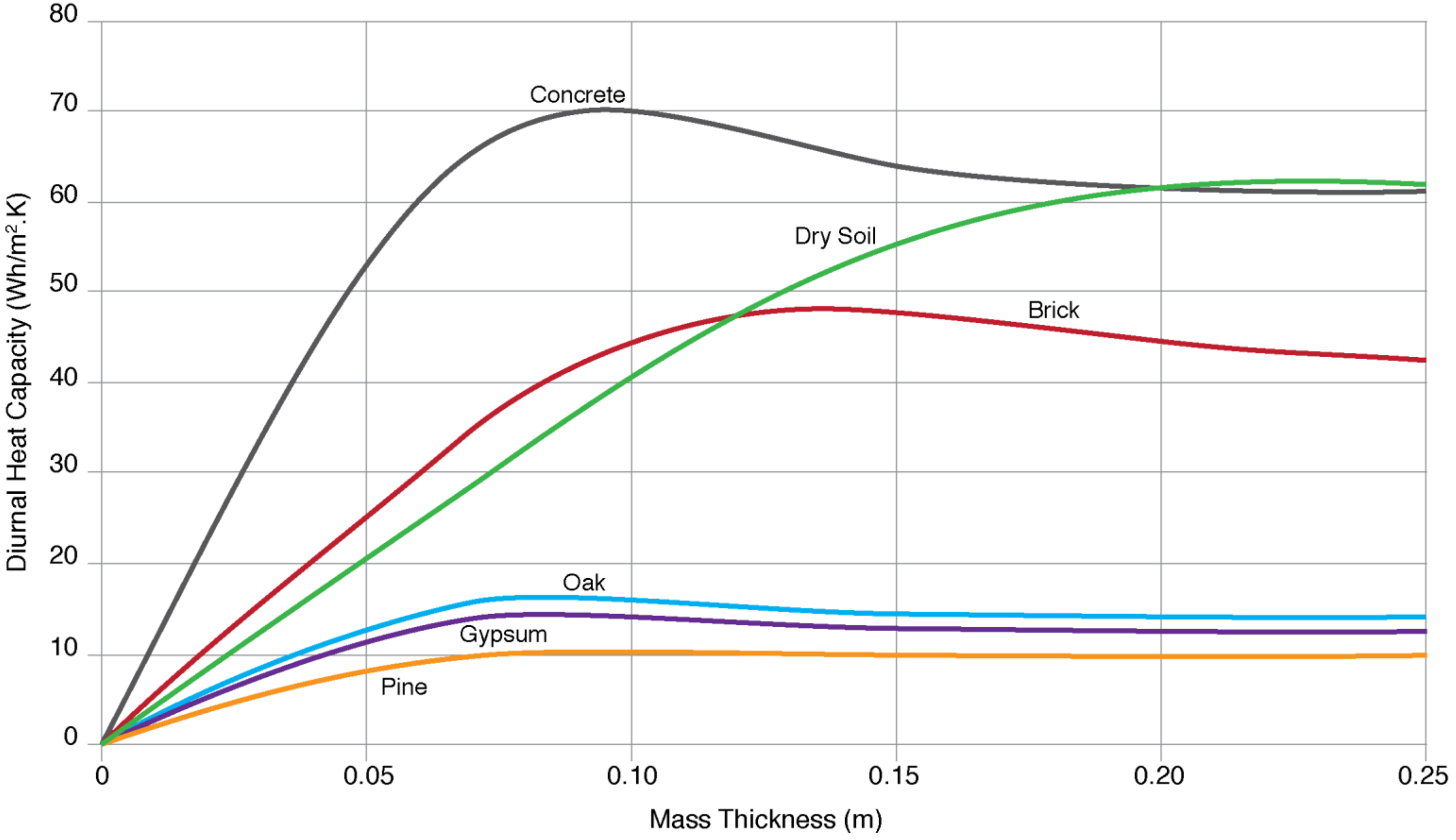
Natural ventilation in tall buildings must be specially engineered.

Thermal Mass

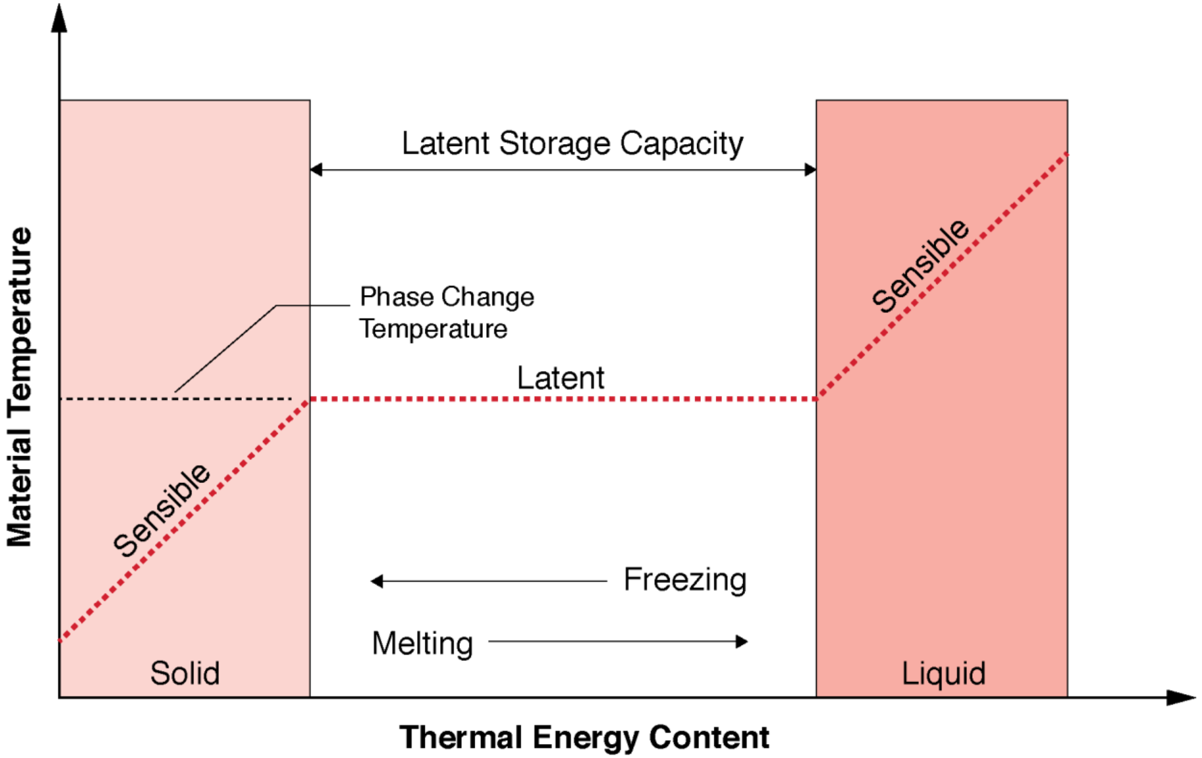




Thermal mass enhances thermal resilience.



More is not always better when it comes to thermal mass in buildings.



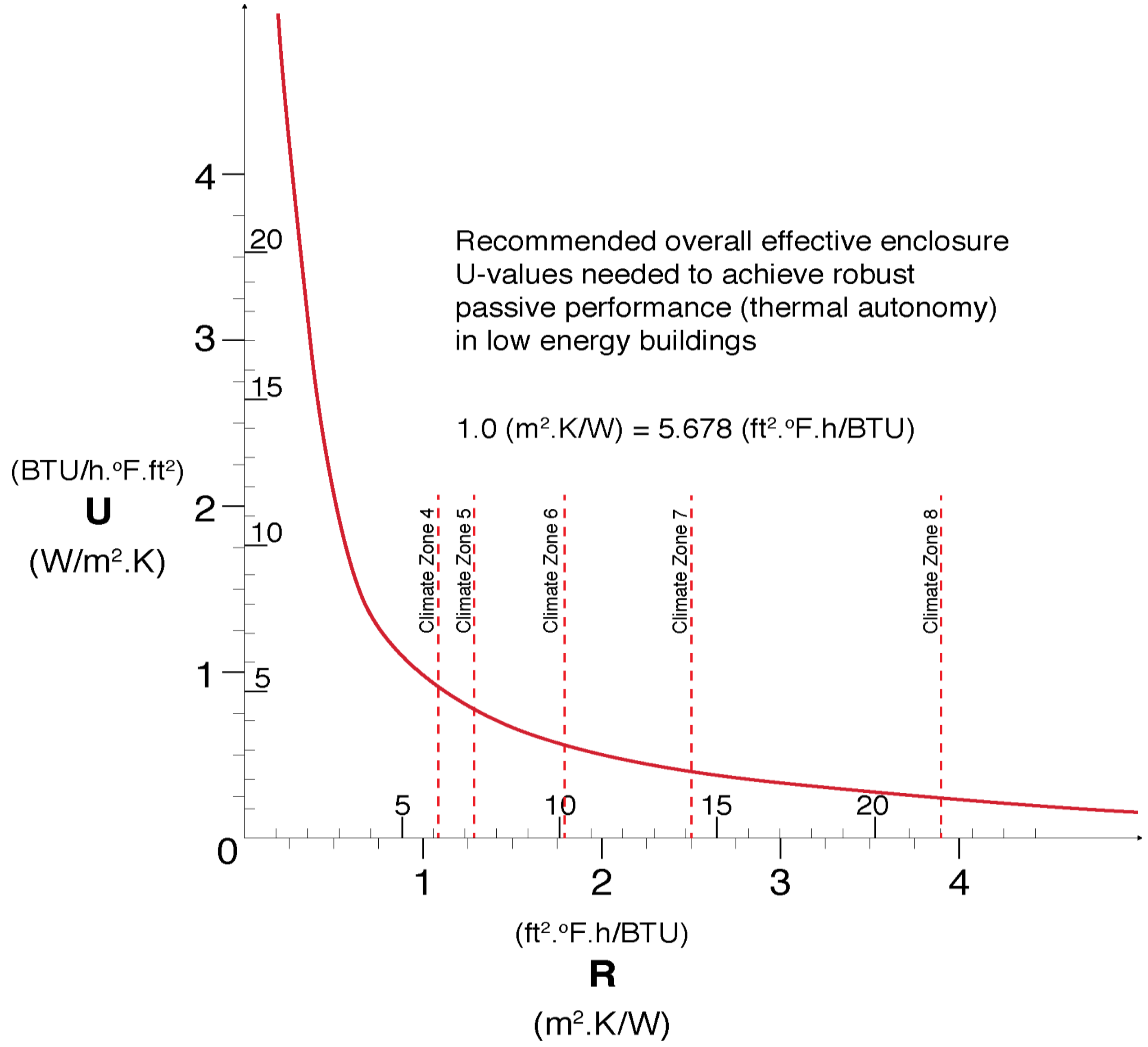
Phase change materials (PCMs) have a high heat of fusion and absorb thermal energy when they transform from solid to liquid phase, and conversely release thermal energy when they transform back to solid phase.

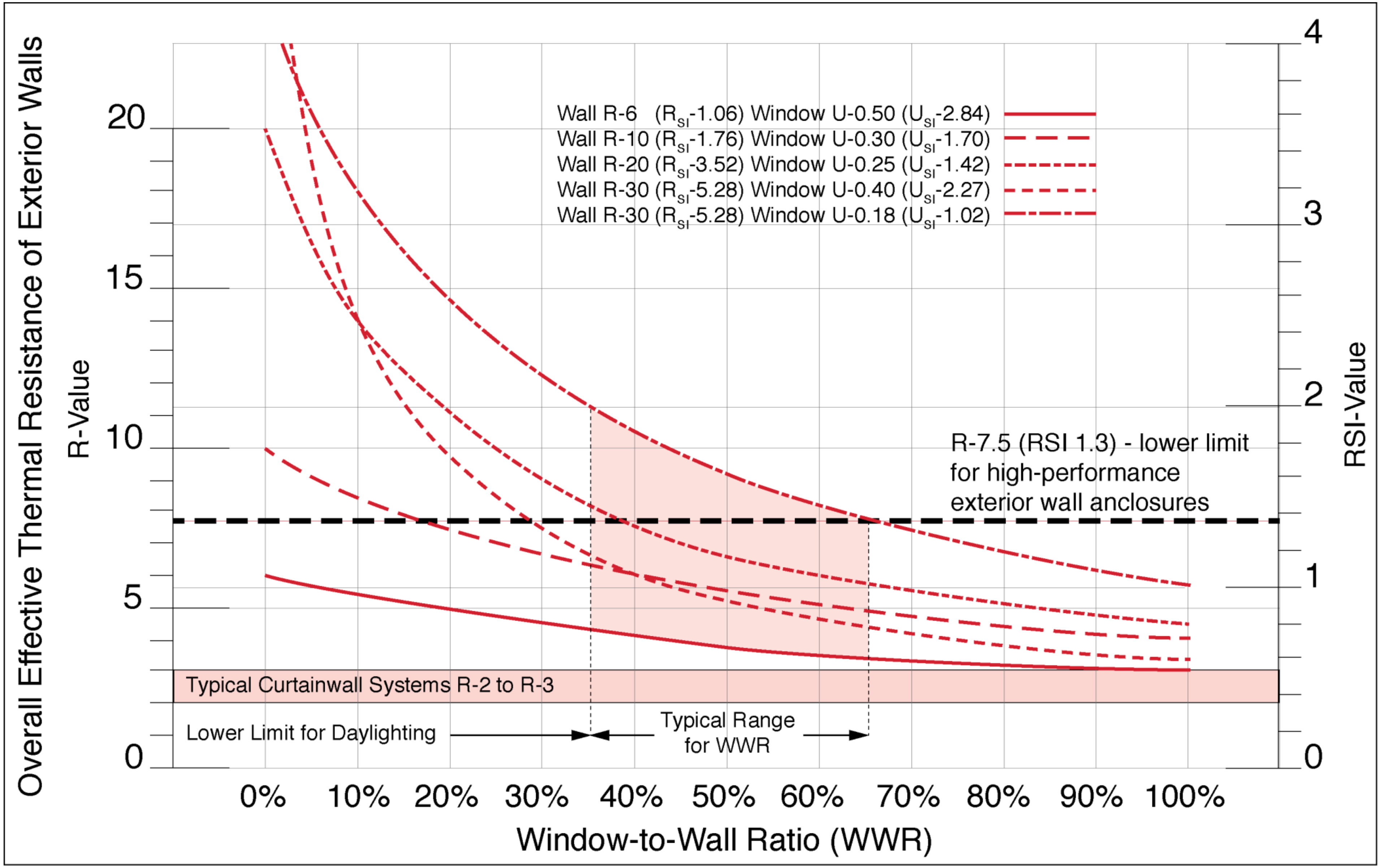
Typical phase change storage media consist of salts or organic compounds embedded in building materials, usually located inboard of the thermal control layer(s) of a building enclosure, preferably located in contact with the interior conditioned space.

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.

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.

Enclosure Thermal Efficiency by Climate Zone





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.

Enclosure Thermal Efficiency Chart

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.

Recommended Minimum Enclosure Thermal Efficiency 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	0.91	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**	**6.7**	**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	1.32	1.32	1.32	1.32	1.32
Windows (RSI)	0.5	0.5	0.5	0.6	0.6	0.7	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	1.40	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	0.7	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	1.75	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

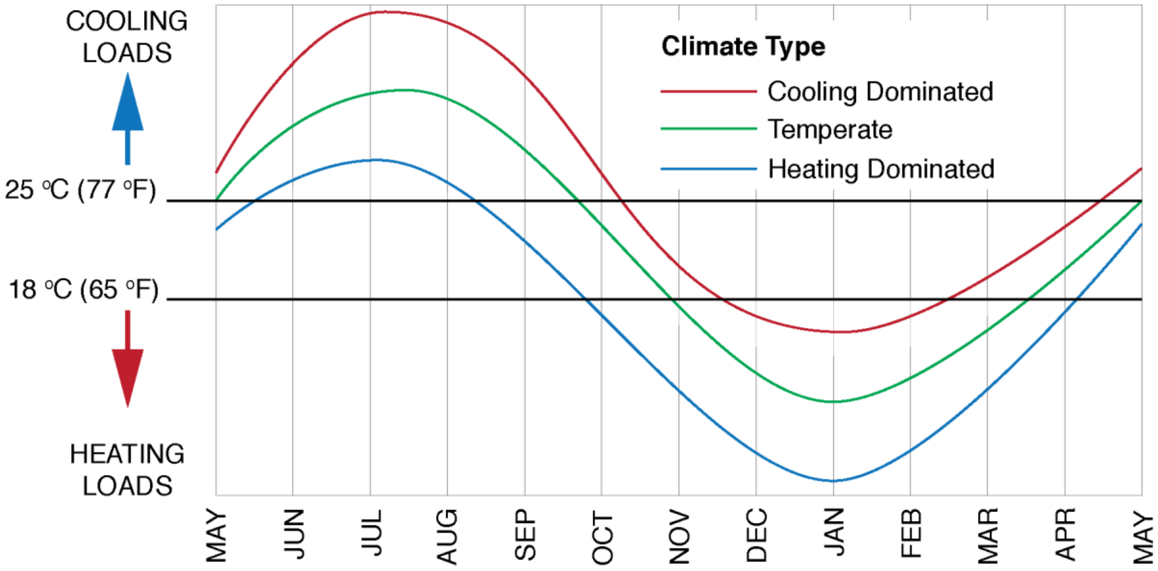
Window-to-Wall Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%
Roof (RSI)	7.04	7.04	7.04	7.04	8.81	8.81	8.81	8.81	10.56
Walls (RSI)	4.4	4.93	4.93	4.93	5.64	5.64	5.64	5.64	7.04
Slab-On-Grade (RSI)	1.76	2.64	2.64	2.64	2.64	2.64	2.64	2.64	3.52
Windows (RSI)	0.5	0.6	0.8	1	1	1.2	1.5	1.5	1.5
Overall USI-value	0.38	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**

Recommended Passive Measures By Climate Type

- High levels of thermal insulation
- Appropriate window-to-wall ratio
- Efficient glazing with suitable SHGC
- Continuous air barrier system
- Shading devices
- Natural ventilation

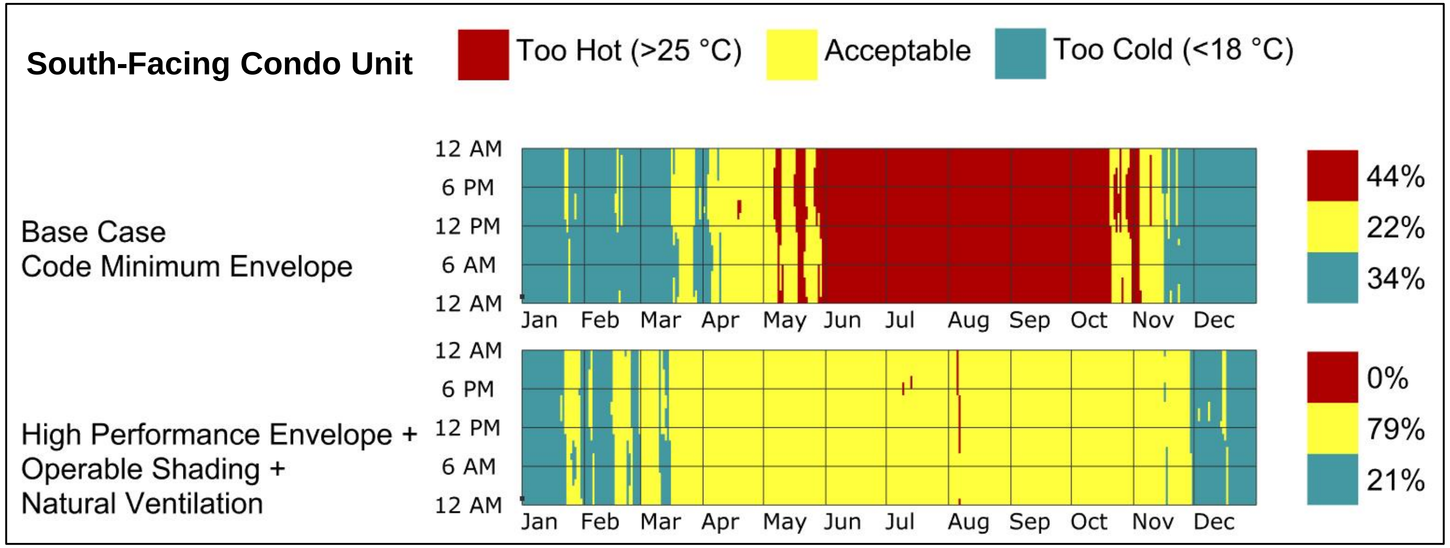


Thermal Resilience Passive Measures

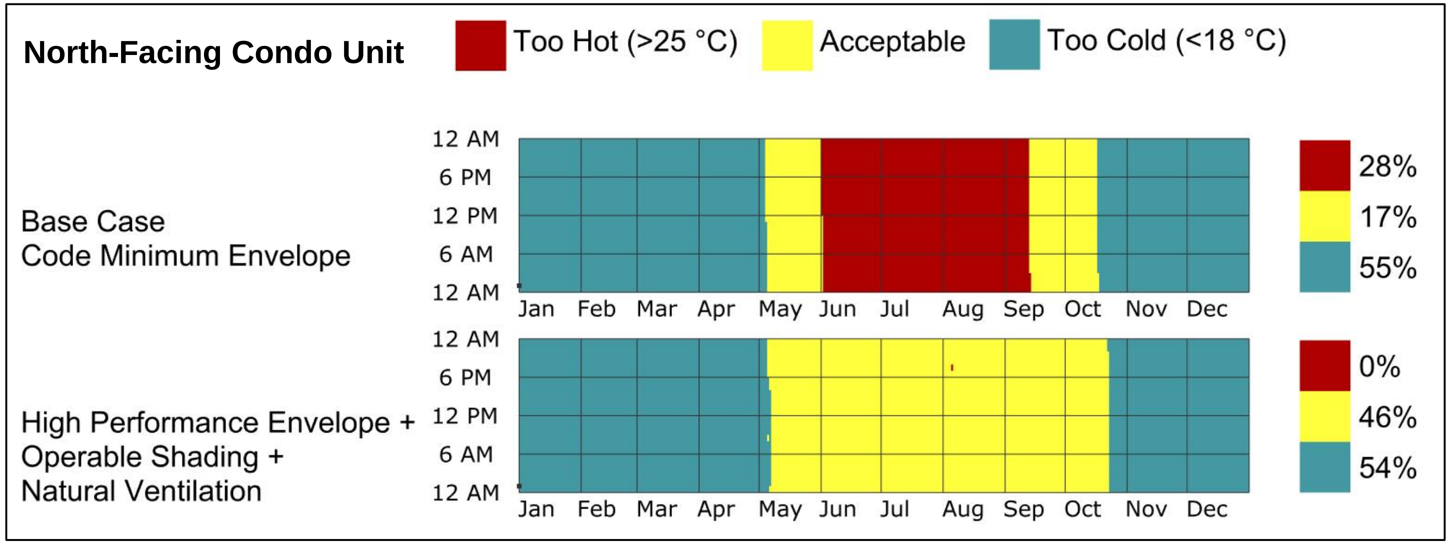
● Critical ◐ Recommended ○ Optional

	High Thermal Insulation	40% < WWR > 60%	Low SHGC Glazing	Continuous Air Barrier	Thermal Breaks for Balconies	Shading Devices	Natural Ventilation
Cooling Dominated	Recommended	Recommended	Critical	Critical	Optional	Critical	Critical
Temperate	Recommended	Optional	Recommended	Critical	Recommended	Critical	Critical
Heating Dominated	Critical	Critical	Optional	Critical	Critical	Recommended	Recommended

Solar Orientation Affects Thermal Resilience in Cold Climates



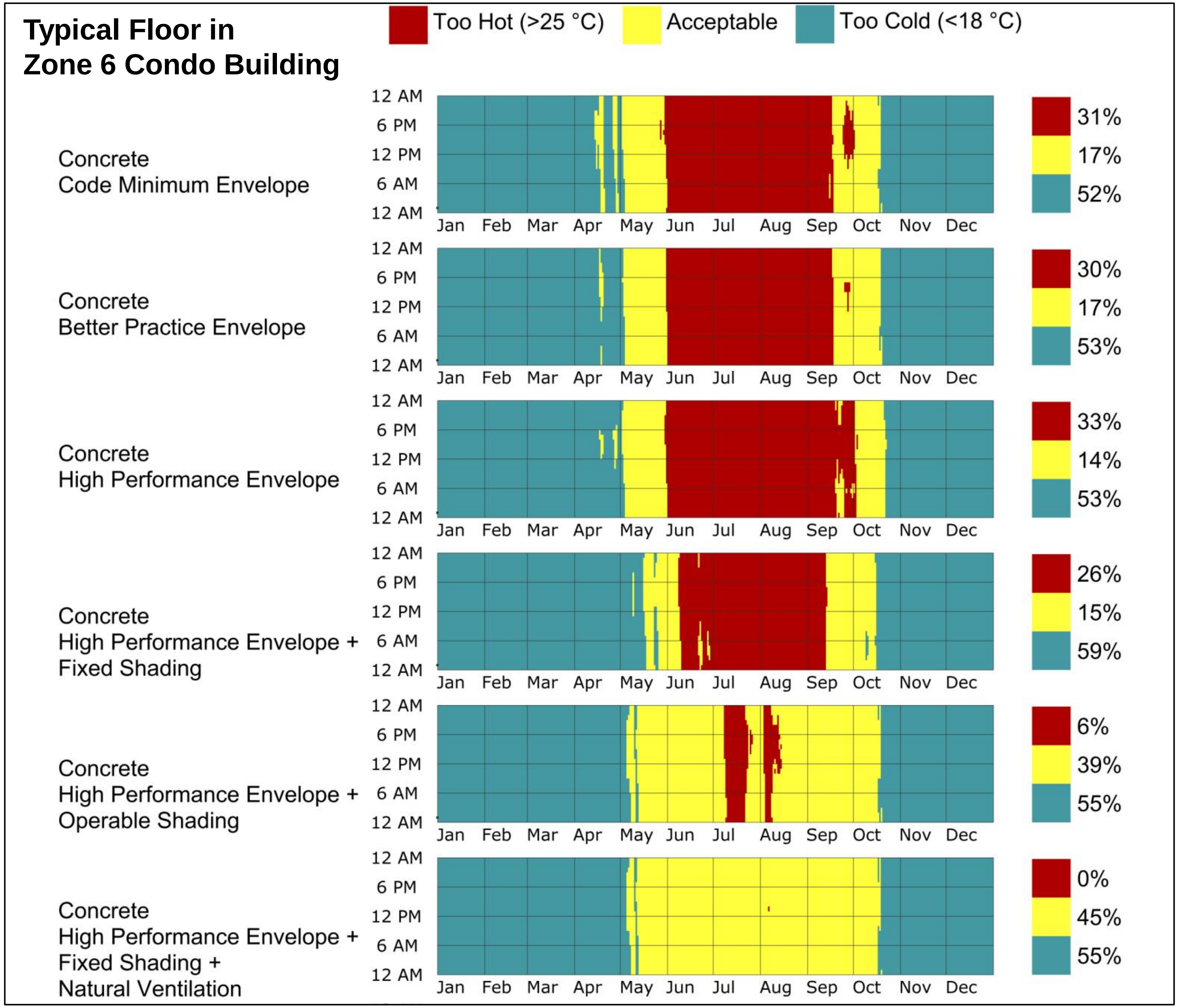
In Climate Zone 6, a high performance enclosure with a balcony (shading from solar gains) and active inhabitants (able to respond with appropriate clothing levels and operate windows and/or shading devices) resulted in about 79% thermal autonomy.



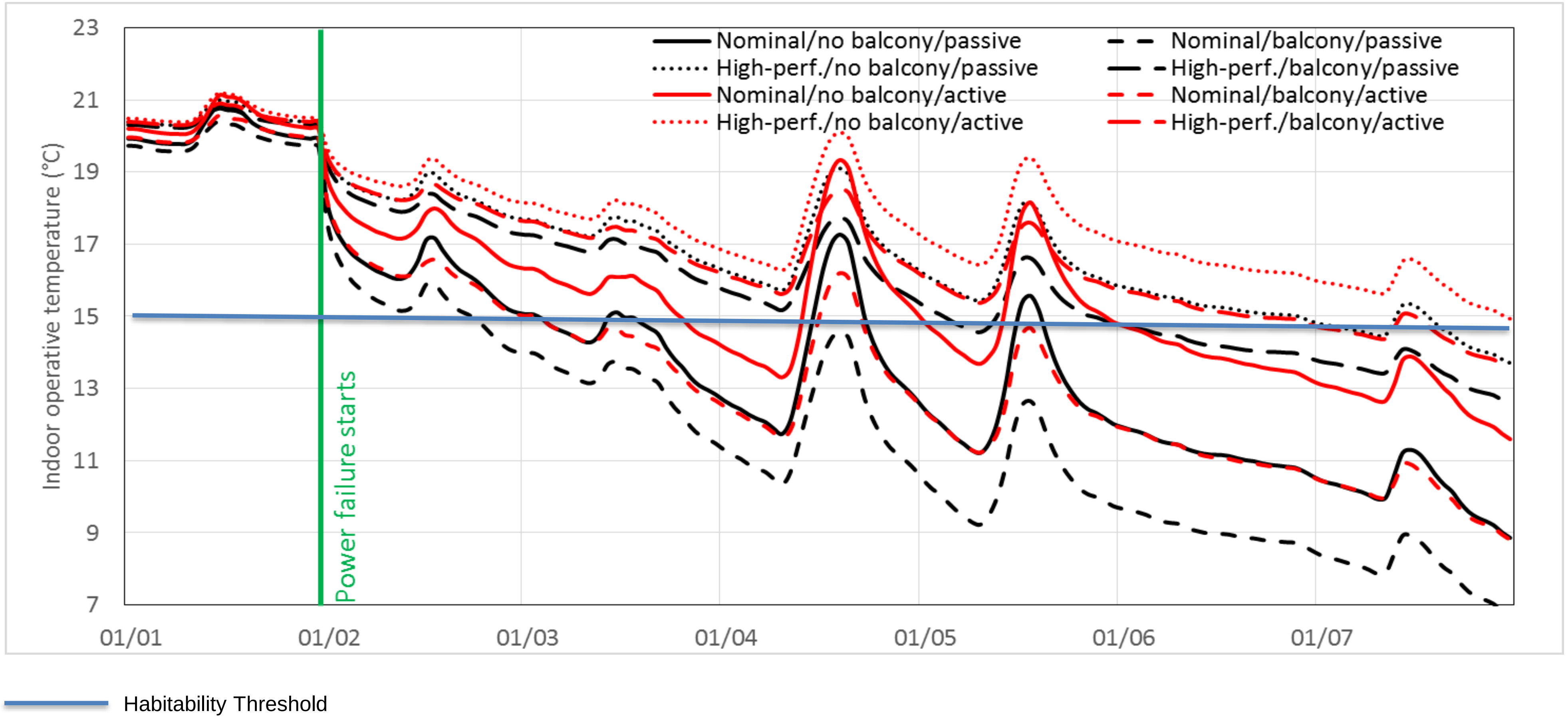
But a north-facing suite can only achieve about 46% thermal autonomy and supplemental heating demands dominate.

When the whole building is modelled, and an open floor plate is assumed, the thermal autonomy approaches that of a north-facing suite.

This suggests that for non-residential buildings, such as offices, a means of isolating a south-facing zone is necessary to create a place of habitable refuge.

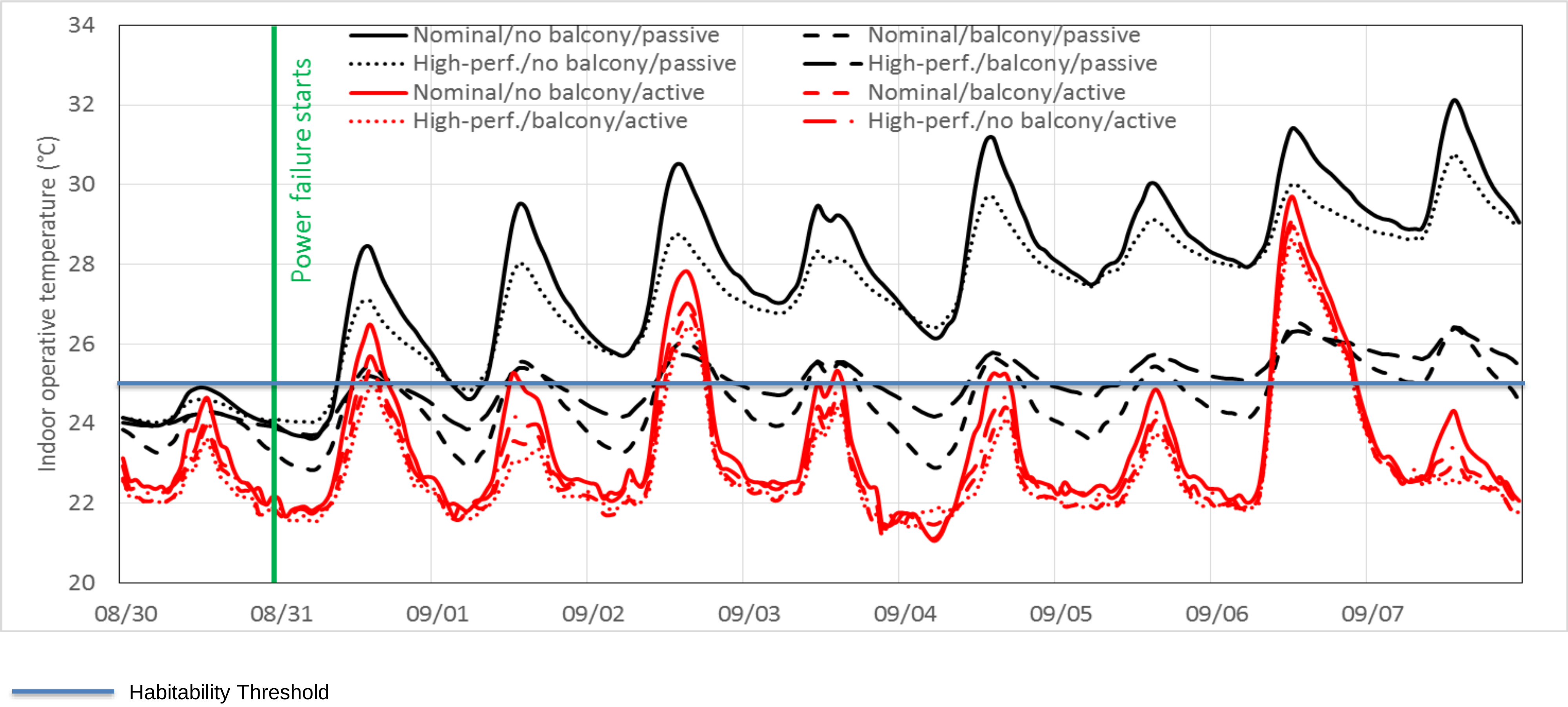


Passive Habitability South-facing condo: Winter



In Climate Zone 6, a high performance enclosure with no balcony (no shading from solar gains) and active inhabitants (able to respond with appropriate clothing levels and operate windows and/or shading devices) resulted in the best cold weather passive habitability response.

Passive Habitability South-facing condo: Summer



In Climate Zone 6, a high performance enclosure with a balcony (shading from solar gains) and active inhabitants (able to respond with appropriate clothing levels and operate windows and/or shading devices) resulted in the best hot weather passive habitability response.

Beyond Thermal Resilience

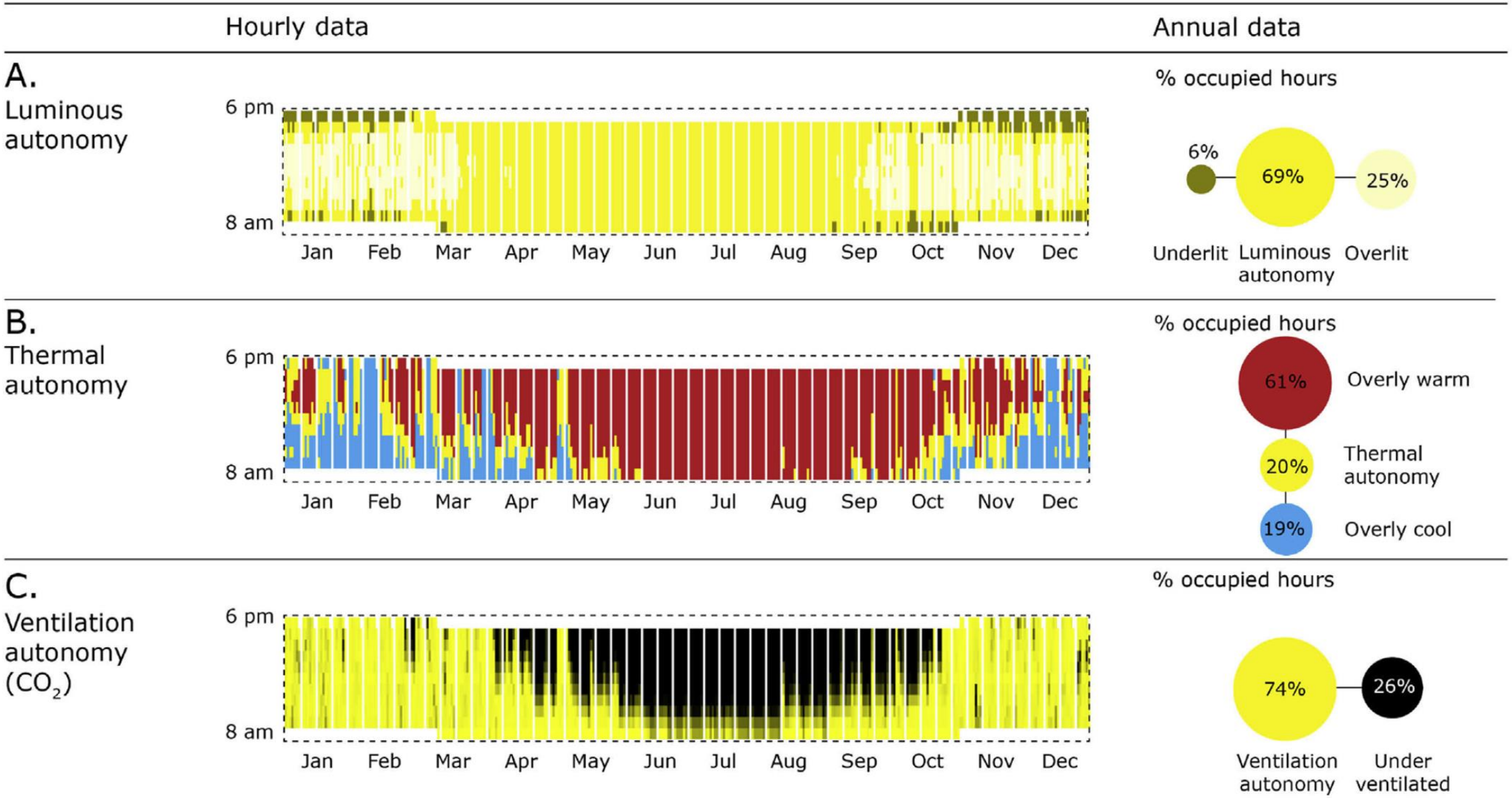
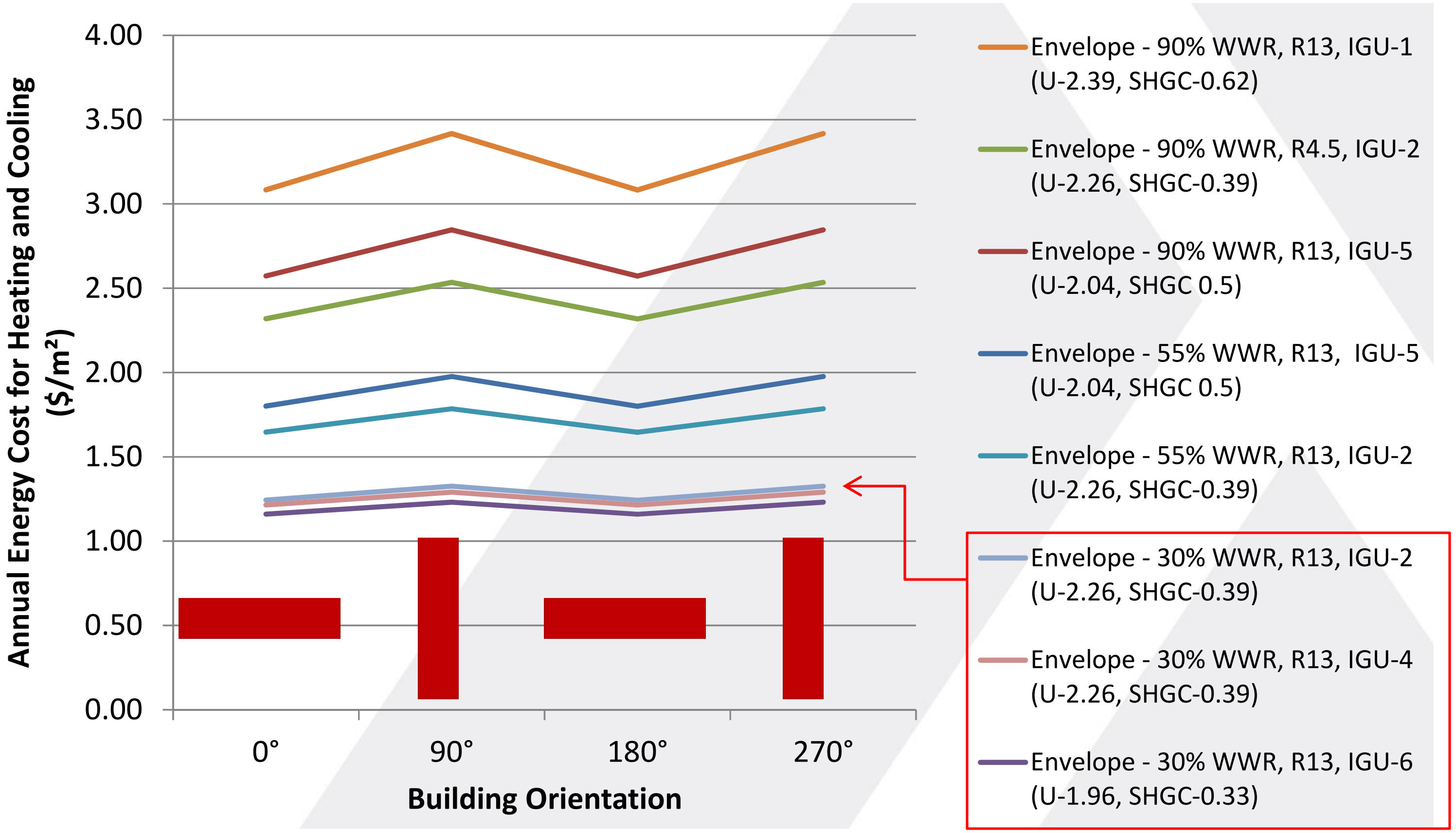


Fig. 6. Hourly autonomy map and annual summary – Phoenix, AZ; A. Luminous autonomy (based on the UDI-a, 300–3,000-lux model); B. Thermal autonomy (based on the adaptive-comfort model); and C. Ventilation autonomy (based on CO2 concentration; ASHRAE 62.1).

Ventilation, thermal and luminous autonomy metrics for an integrated design process.
Won Hee Ko, Stefano Schiavon, Gail Brager, Brendon Levitt (2018). Building and Environment 145 (2018) 153-165.

Enclosures Rule



Source: *The Relative Impact of Building Form on Energy Consumption*. Steve Kemp, MMM Group, 2014.

High performance enclosures permit a greater degree of design freedom for building form and orientation.

Building Stock Rehab 101

Strategies for Sustaining Where We Live, Work and Play

Dr. Ted Kesik, P.Eng.

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

Daniels

The Deep Retrofit Challenge

- **Design Dumb**
- **Build Cheap**
- **Maintain Expensive**

The focus of cities should be on renewal more so than on new development.

Tower Renewal Guidelines

For the Comprehensive Retrofit of Multi-Unit Residential Buildings in Cold Climates

Ted Kesik and Ivan Saleff
Daniels Faculty of Architecture, Landscape, and Design
University of Toronto

Toronto
Mayor's Tower Renewal
CMHC SCHL
Toronto Atmospheric Fund
Daniels

DANIELS

Resilience Planning Guide

November 2017, Version 1.0

Sponsored by: ROCKWOOL

UofT

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

Enhancing the Liveability and Resilience of Multi-Unit Residential Buildings (MURBs)

MURB DESIGN GUIDE

VERSION 2.0, FEBRUARY 2019

BY:

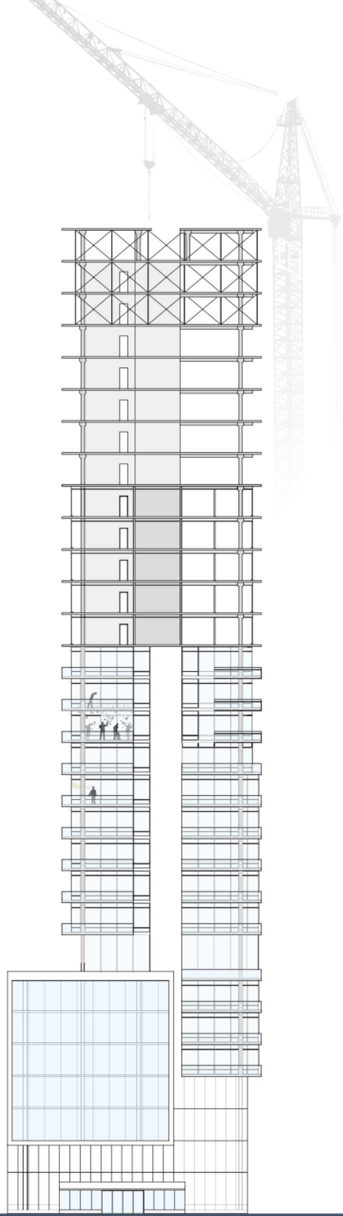
TED KESIK, UNIVERSITY OF TORONTO
LIAM O'BRIEN, CARLETON UNIVERSITY
TERRI PETERS, RYERSON UNIVERSITY

CONTRIBUTIONS BY:

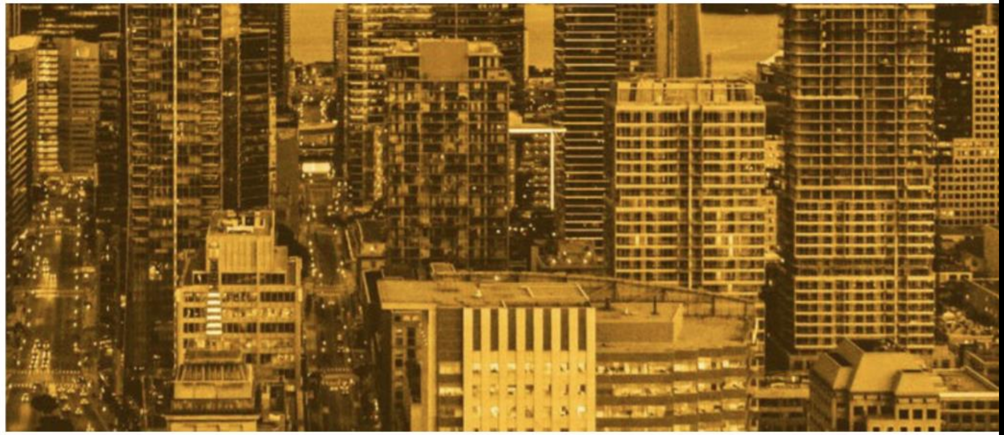
AYLIN OZKAN
CRAIG BROWN
AMANDA CHONG
ANAMARIJA KOROLJ
NADIA PULEZ

SPONSORS:

BC HOUSING
Ontario MINISTRY OF RESEARCH AND INNOVATION
DANIELS U OF T
Hbi Human-Building Interaction Laboratory
Carleton UNIVERSITY
Ryerson University



Thermal Resilience Design Guide



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

ROCKWOOL

POPULAR BUILDING SCIENCE

ABOUT PBS RESEARCH PUBLICATIONS RESOURCES COMMENTARY CONTACT

DANIELS

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

U OF T

https://pbs.daniels.utoronto.ca

Thank you.

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

ROCKWOOL™