Dynamic thermal effects

- Level I: static (steady state): heat flow is primarily a function of temperature difference (the driving force) and thermal resistance (the resisting force)
  - Expressed in algebraic equations

- Level II: quasi steady-state
  - ASHRAE RTS cooling load calculation method

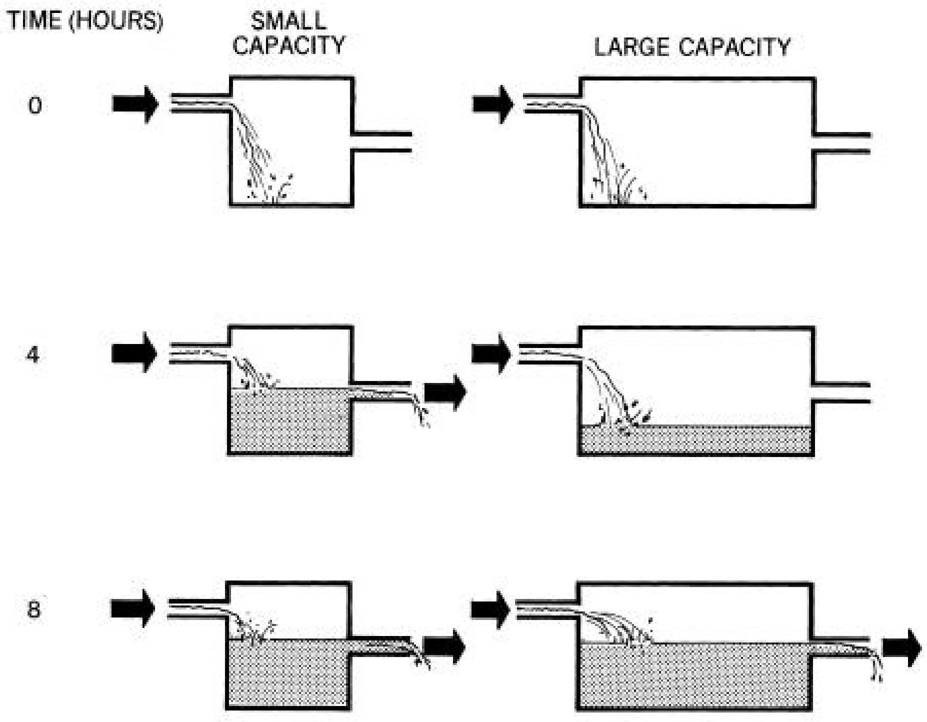
- Level III: dynamic (transient, unsteady): the aforementioned two factors + heat capacity (storage)
  - Expressed in differential equations

Heat capacity

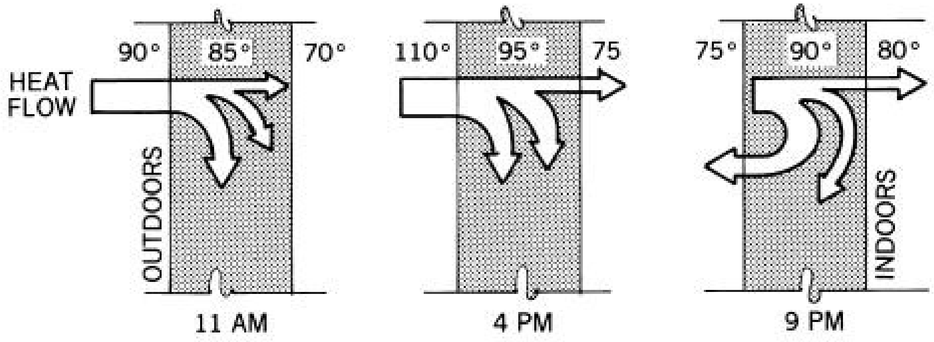
- Density: kg/m^3, lb/ft^3
  - The greater density, the greater heat capacity
- Specific heat: a measure of the amount of heat required to raise the temperature of a given mass of material by 1^{o}C (J/kg^{o}K, Btu/lb^{o}F)
  - Table E.1: specific heat for common materials
- Heat capacity= density x specific heat x volumes
  - The greater heat capacity, the more heat it can store in a given volume per degree of temperature increase.
    - Concrete: 2240 kg/m^3 x (1.0 x 10^3 J/kg^{o}K) x 1m^3 = 2240 kJ/K
    - Water: 992 kg/m^3 x (4.18 x 10^3 J/kg^{o}K) x 1m^3 = 4147 kJ/K
    - Plywood: 800 kg/m^3 x (1.21 x 10^3 J/kg^{o}K) x 1m^3 = 968 kJ/K
    - Glass fiber:100 kg/m^3 x (0.96 x 10^3 J/kg^{o}K) x 1m^3 = 96 kJ/K
    - Air: 1.2 kg/m^3 x (1.0 x 10^3 J/kg^{o}K) x 1m^3 = 1.2 kJ/K

Time lag

A measure of the delay in the flow of a pulse of heat through a material that results from thermal capacity. Units are hours



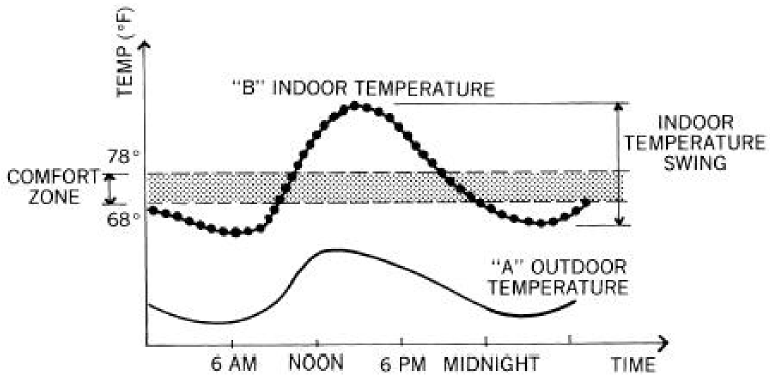
High capacity delays the passage of water



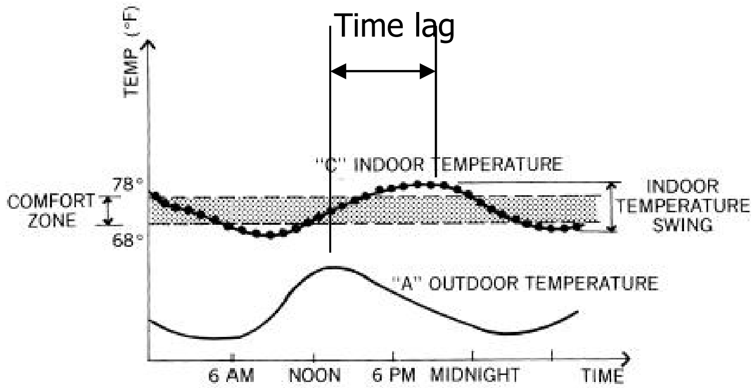
High heat capacity delays the transmission of heat

< Benefits >
- Peak load reduction
- Reduction in equipment sizing

Time lag

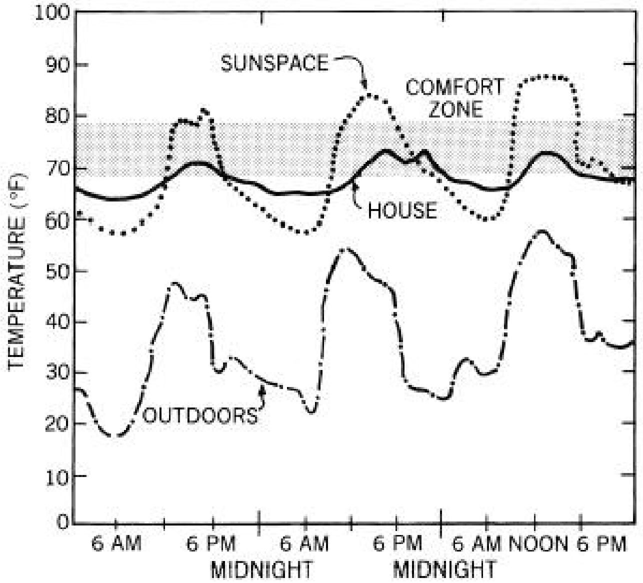


Low-mass passive solar

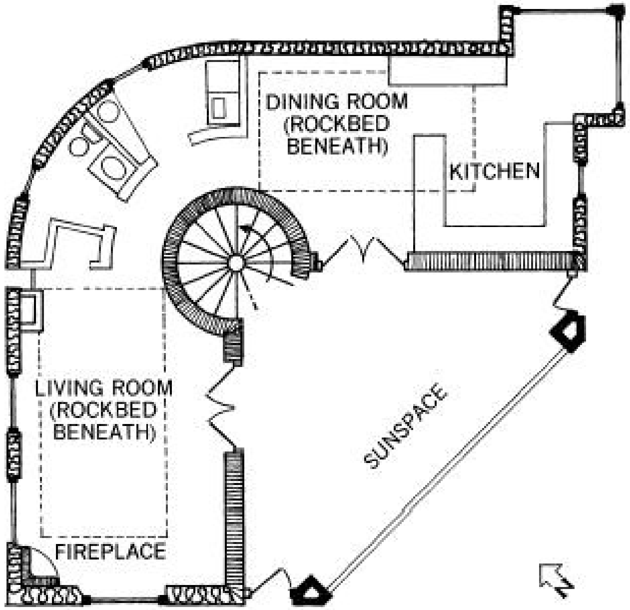


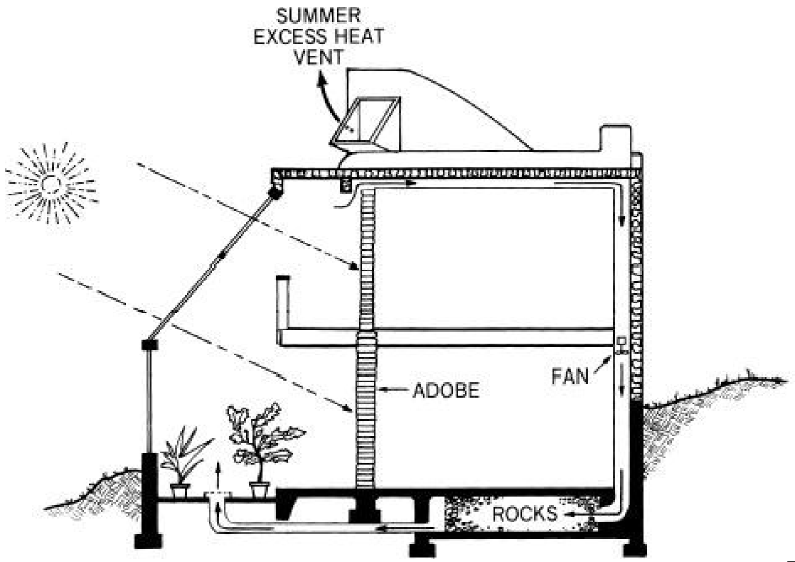
high-mass passive solar

Balcomb house, New Mexico



Three winter days





9.4 Latent heat flow through the opaque envelope

- Water also moves through the building envelop assemblies in vapor or liquid states.
- Vapor pressure difference is to latent heat flow as temperature difference is to sensible heat flow.
- Permeance equivalent to conductance, permeability equivalent to conductivity
- The less permeable a material is, the greater the resistance to water vapor flow.
- SI unit of permeance: $ng/(s.m^2.Pa)$
- Vapor retarder: materials with low permeance

Cold climate moisture control

- Most common building materials (gypsum board, concrete, brick, wood glass fiber insulation) are easily permeable.
- In cold climates,
  - Outside air: less moisture (low humidity ratio), higher RH
  - Inside air: more moisture (high humidity ratio), lower RH
  - The resulting differential vapor pressure becomes a driving force of the flow of the water vapor (from high to low vapor pressure, typically from warm to cold)

Cold climate moisture control

- Problems:
  - Insulation can become wet and thereby less effective.
  - Dry rot in wood structure members
- Two usual remedies
  - (1) Vapor retarder installed within the building envelope assembly. → install as close to the warm side as possible: typically just behind the interior surface, e.g., gypsum board, wood flooring, etc.
  - (2) Vinyl wallpaper or vapor retarder paints on the interior surfaces

Hot humid climate moisture control

- Problem: mold grows on damp surfaces
- Objective: to keep the moisture in the warmer outside air from penetrating to the cooler (and usually less humid) interior
- Usual remedy
  - drainage plane: simple tar paper (building felt) installed just inside the exterior surface material.

Vapor barrier

Vapor Barrier Placement By Geographical Location

In most cold climates, vapor barriers should be placed on the interior(warm-in-winter) side of walls. However, the map shows that in some southern climates, the vapor barrier should be omitted, while in hot and humid climates, such as along the Gulf coast and in Florida, the vapor barrier should be placed on the exterior of the wall.

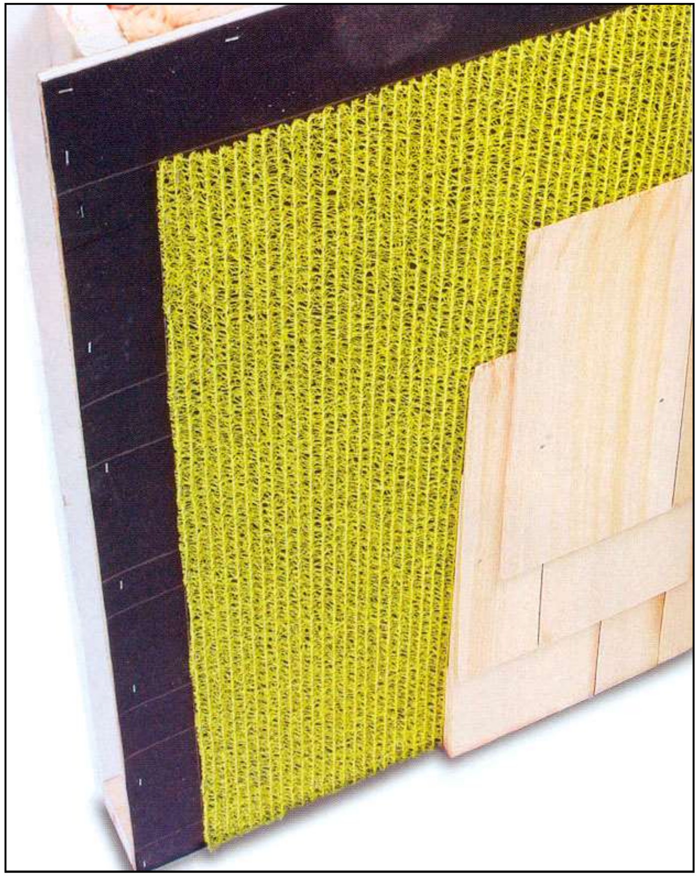
Perm Ratings of Different Materials

(Rating of 1 or less qualifies as a vapor barrier)

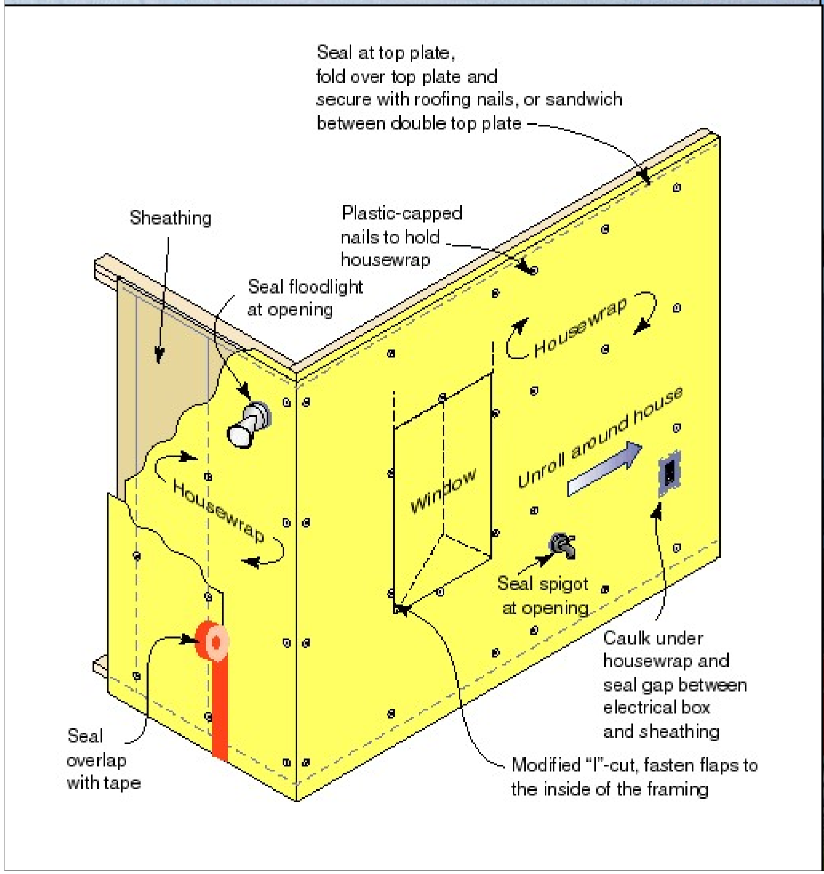
Asphalt-coated paper backing on insulation	0.40
Polyethylene plastic (6 mil)	0.06
Plywood with exterior glue	0.70
Plastic-coated insulated foam sheathing	0.4 to 1.2
Aluminum foil (.35 mil)	0.05
Vapor barrier paint or primer	0.45
Drywall (unpainted)	5 0
Drywall (painted - latex paint)	2 -3

https://www.nachi.org/vapor-barriers.htm

Rain screen / vapor retarder / drainage plane



Housewrap as a weather barrier



Heat flow through transparent/translucent elements

- Transparent: permits a undistorted view (clear glass, low-e glass)
- Translucent: like milky plastic or glass blocks
- Special attention should be paid to windows and skylights
  - Low R (high U value)
  - Major contributors to infiltration (heating and cooling load)
  - Admitting solar heat (winter and summer)
  - Admitting daylight and providing ventilation

https://inhabitat.com/lsarcs-randall-house-bridges-indoors-and-outdoors/randall-house-translucent-windows-at-bath/

NFRC

- National Fenestration Rating Council
- A sample NFRC label →
- Characteristics of some residential windows: Table E.15

Fig. 9.12 Certifying window thermal performance; a sample NFRC window label. (© National Fenestration Rating Council; used with permission.)

Table E.14 U-Factors of Representative Window Assemblies

Glazing System Description	Aluminum without Thermal Break I-P: Btu/h ft² °F (SI: W/m² K)	Aluminum with Thermal Break I-P: Btu/h ft² °F (SI: W/m² K)	Insulated Wood/ Vinyl I-P: Btu/h ft² °F (SI: W/m² K)	Fiberglass/Vinyl I-P: Btu/h ft² °F (SI: W/m² K)
Single glazing with uncoated ⅛ in. [3.2 mm] clear pane	1.23 (7.01)	1.07 (6.08)	0.91 (5.20)	0.85 (4.83)
Single glazing with uncoated ¼ in. [6.4 mm] acrylic/polycarbonate pane	1.10 (6.23)	0.94 (5.35)	0.80 (4.52)	0.74 (4.18)
Double glazing with ⅛ in. [3.2 mm] panes: uncoated clear | clear with ¼ in. [6.4 mm] air space	0.81 (4.62)	0.64 (3.61)	0.55 (3.14)	0.50 (2.84)
Double glazing with ⅛ in. [3.2 mm] panes: uncoated clear | clear with ½ in. [13 mm] air space	0.76 (4.30)	0.58 (3.31)	0.50 (2.86)	0.45 (2.58)
Double glazing with ⅛ in. [3.2 mm] panes: uncoated clear | low-ε (0.2) on surface 3 with ½ in. [13 mm] air space	0.65 (3.70)	0.48 (2.75)	0.41 (2.34)	0.37 (2.07)
Triple glazing with ⅛ in. [3.2 mm] panes: uncoated clear | clear with ½ in. [13 mm] air spaces	0.61 (3.46)	0.44 (2.47)	0.38 (2.14)	0.34 (1.90)
Triple glazing with ⅛ in. [3.2 mm] panes: uncoated clear | low-ε (0.2) on surfaces 3 and 5 with ½ in. [13 mm] air spaces	0.52 (2.95)	0.35 (1.99)	0.30 (1.69)	0.26 (1.48)
Quadruple glazing with ⅛ in. [3.2 mm] panes: uncoated clear | low-ε (0.1) on surfaces 3 and 5 with ½ in. [13 mm] air spaces	0.48 (2.71)	0.31 (1.77)	0.26 (1.49)	0.23 (1.28)

Source: Reprinted with permission; ©ASHRAE, www.ashrae.org. 2017 *ASHRAE Handbook—Fundamentals*.

Based upon an operable 3-ft × 5-ft (0.9-m × 1.5-m) aluminum-framed window.

Glazing surfaces are numbered starting with the surface closest to the sun; thus, surface 2 would be the inner surface of an exterior pane of glass.

Table E.15 Representative Window Characteristics[a]

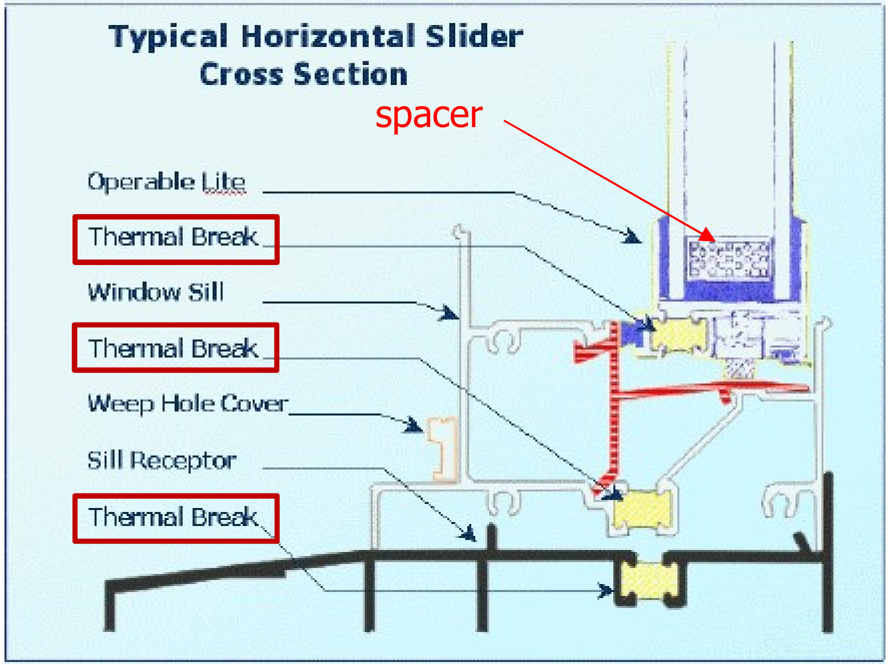
Glazing Description and Reference Number	Layers of Glazing and Spaces (outside to inside)	Frame (and spacer)	Total Window U-Factor Btu/ h ft² °F	Total Window U-Factor W/m²K	Total Window SHGC[b]	VT[c]	LSG[d]	FHR[e]	FCR[e]	Air Leakage cfm/ lin ft	L/s m	cfm/ ft²	L/s m²
1. Single-glazed clear	⅛ in. (3 mm) clear	Aluminum, no thermal break	1.30	7.38	0.79	0.69	0.87	0	0	0.65	1.01	0.98	4.98
2. Single-glazed bronze	⅛ in. (3 mm) bronze	Aluminum, no thermal break	1.30	7.38	0.69	0.52	0.75	−2	8	0.65	1.01	0.98	4.98
3. Double-glazed clear	⅛ in. (3 mm) clear ½ in. (13 mm) air ⅛ in. (3 mm) clear	Aluminum, thermal break (aluminum)	0.64	3.63	0.65	0.62	0.95	19	12	0.37	0.57	0.56	2.85
4. Double-glazed bronze	⅛ in. (3 mm) bronze ½ in. (13 mm) air ⅛ in. (3 mm) clear	Aluminum, thermal break (aluminum)	0.64	3.63	0.55	0.47	0.85	17	20	0.37	0.57	0.56	2.85
5. Double-glazed clear	⅛ in. (3 mm) clear ½ in. (13 mm) air ⅛ in. (3 mm) clear	Wood or vinyl (aluminum)	0.49	2.78	0.58	0.57	0.98	24	18	0.37	0.57	0.56	2.85
6. Double-glazed bronze	⅛ in. (3 mm) bronze ½ in. (13 mm) air ⅛ in. (3 mm) clear	Wood or vinyl (aluminum)	0.49	2.78	0.48	0.43	0.90	22	25	0.37	0.57	0.56	2.85
7. Double-glazed low-ε[f]	⅛ in. (3 mm) clear ½ in. (13 mm) argon ⅛ in. (3 mm) low-ε 0.20	Wood or vinyl (stainless)	0.33	1.87	0.55	0.52	0.95	32	19	0.10	0.16	0.15	0.76
8. Double-glazed low-ε[f]	⅛ in. (3 mm) low-ε 0.08 ½ in. (13 mm) argon ⅛ in. (3 mm) clear	Wood or vinyl (stainless)	0.30	1.70	0.44	0.56	1.27	32	27	0.10	0.16	0.15	0.76
9. Double-glazed spectrally selective[f]	⅛ in. (3 mm) low-ε 0.04 ½ in. (13 mm) argon ⅛ in. (3 mm) clear	Wood or vinyl (stainless)	0.29	1.65	0.31	0.51	1.65	30	36	0.10	0.16	0.15	0.76

FHR (Fenestration Heating Rating) and FCR (Fenestration Cooling Rating) are heating season and cooling season (respectively) estimates of the percentage of energy saved in a typical residential application compared to using Window 1.

ASHRAE Handbook Fundamentals (Ch.15, 2017)

Table 4 U-Factors for Various Fenestration Products in $W/(m^2 \cdot K)^i$

Product Type		Glass Only		Vertical Installation									
				Operable (including sliding and swinging glass doors)					Fixed				
Frame Type		Center of Glass	Edge of Glass	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
ID	Glazing Type												
	Single Glazing												
1	3.2 mm glass	*5.91*	*5.91*	7.01	6.08	5.27	5.20	4.83	6.38	6.06	5.58	5.58	5.40
2	6 mm acrylic/polycarb	*5.00*	*5.00*	6.23	5.35	4.59	4.52	4.18	5.55	5.23	4.77	4.77	4.61
3	3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.62	5.72	4.93	4.86	4.51	5.96	5.64	5.18	5.18	5.01
	Double Glazing												
4	6 mm airspace	*3.12*	*3.63*	4.62	3.61	3.24	3.14	2.84	3.88	3.52	3.18	3.16	3.04
5	13 mm airspace	*2.73*	*3.36*	4.30	3.31	2.96	2.86	2.58	3.54	3.18	2.85	2.83	2.72
6	6 mm argon space	*2.90*	*3.48*	4.43	3.44	3.08	2.98	2.69	3.68	3.33	3.00	2.98	2.86
7	13 mm argon space	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
	Double Glazing, e = 0.60 on surface 2 or 3												
8	6 mm airspace	*2.95*	*3.52*	4.48	3.48	3.12	3.02	2.73	3.73	3.38	3.04	3.02	2.90
9	13 mm airspace	*2.50*	*3.20*	4.11	3.14	2.80	2.70	2.42	3.34	2.99	2.67	2.65	2.53
10	6 mm argon space	*2.67*	*3.32*	4.25	3.27	2.92	2.82	2.54	3.49	3.13	2.81	2.79	2.67
11	13 mm argon space	*2.33*	*3.08*	3.98	3.01	2.68	2.58	2.31	3.20	2.84	2.52	2.50	2.39
	Double Glazing, e = 0.40 on surface 2 or 3												
12	6 mm airspace	*2.78*	*3.40*	4.34	3.35	3.00	2.90	2.61	3.59	3.23	2.90	2.88	2.77
13	13 mm airspace	*2.27*	*3.04*	3.93	2.96	2.64	2.54	2.27	3.15	2.79	2.48	2.46	2.35
14	6 mm argon space	*2.44*	*3.16*	4.07	3.09	2.76	2.66	2.38	3.30	2.94	2.62	2.60	2.49
15	13 mm argon space	*2.04*	*2.88*	3.75	2.79	2.48	2.38	2.11	2.95	2.60	2.29	2.27	2.16
	Double Glazing, e = 0.20 on surface 2 or 3												
16	6 mm airspace	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
17	13 mm airspace	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
18	6 mm argon space	*2.16*	*2.96*	3.84	2.88	2.56	2.46	2.19	3.05	2.70	2.38	2.36	2.26
19	13 mm argon space	*1.70*	*2.62*	3.47	2.53	2.24	2.14	1.88	2.66	2.30	2.00	1.98	1.88
	Double Glazing, e = 0.10 on surface 2 or 3												
20	6 mm airspace	*2.39*	*3.12*	4.02	3.05	2.72	2.62	2.34	3.25	2.89	2.57	2.55	2.44
21	13 mm airspace	*1.82*	*2.71*	3.56	2.62	2.32	2.22	1.96	2.76	2.40	2.10	2.08	1.98
22	6 mm argon space	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
23	13 mm argon space	*1.53*	*2.49*	3.33	2.40	2.12	2.02	1.76	2.51	2.16	1.86	1.84	1.74
	Double Glazing, e = 0.05 on surface 2 or 3												
24	6 mm airspace	*2.33*	*3.08*	3.98	3.01	2.68	2.58	2.31	3.20	2.84	2.52	2.50	2.39
25	13 mm airspace	*1.70*	*2.62*	3.47	2.53	2.24	2.14	1.88	2.66	2.30	2.00	1.98	1.88
26	6 mm argon space	*1.87*	*2.75*	3.61	2.66	2.36	2.26	2.00	2.81	2.45	2.15	2.12	2.02
27	13 mm argon space	*1.42*	*2.41*	3.24	2.31	2.04	1.94	1.69	2.42	2.06	1.76	1.74	1.65
	Triple Glazing												
28	6 mm airspace	*2.16*	*2.96*	3.78	2.78	2.46	2.42	2.17	3.02	2.68	2.36	2.36	2.25
29	13 mm airspace	*1.76*	*2.67*	3.46	2.47	2.18	2.14	1.90	2.68	2.34	2.03	2.03	1.92
30	6 mm argon space	*1.93*	*2.79*	3.60	2.60	2.30	2.26	2.02	2.82	2.49	2.17	2.17	2.06
31	13 mm argon space	*1.65*	*2.58*	3.36	2.39	2.10	2.06	1.83	2.58	2.24	1.93	1.93	1.83
	Triple Glazing, e = 0.20 on surface 2, 3, 4, or 5												
32	6 mm airspace	*1.87*	*2.75*	3.55	2.56	2.26	2.22	1.98	2.78	2.44	2.12	2.12	2.01
33	13 mm airspace	*1.42*	*2.41*	3.18	2.21	1.94	1.90	1.67	2.38	2.05	1.74	1.74	1.64
34	6 mm argon space	*1.59*	*2.54*	3.32	2.34	2.06	2.02	1.79	2.53	2.20	1.89	1.89	1.78
35	13 mm argon space	*1.25*	*2.28*	3.04	2.08	1.82	1.78	1.55	2.24	1.90	1.60	1.60	1.50
	Triple Glazing, e = 0.20 on surfaces 2 or 3 and 4 or 5												



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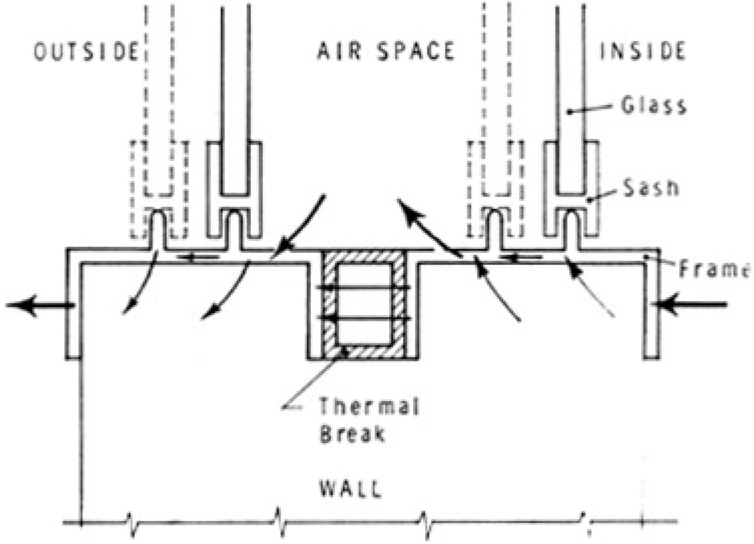

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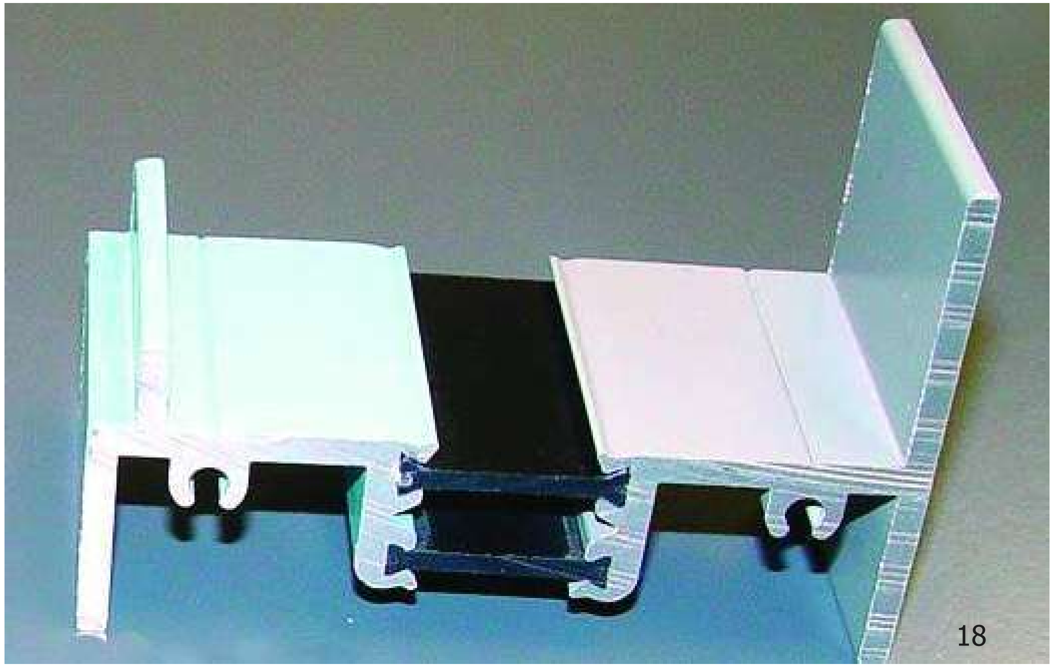
Thermal Break



U factor

- The NFRC U factor melds significant differences in heat flow rates between the center-of-glass, the edge-of-glass (2 ½" band around the perimeter of glazing), and frame portions of a unit into a single representative value for an entire window or skylight unit.
- The air gap between glazings, the gas fill between glazings, the coatings on the glazings, frame construction all influence the U factor
- Tables E.14, E.15, E.16 (textbook pp.1723-1726)

SHGC, g-value

- SHGC = the fraction of incident irradiance that enters the glazing and becomes heat gain typically ranging from 0.2 to 0.9
- A high SHGC is desirable for solar heating applications, whereas a lower SHGC is better for windows where cooling is the dominant thermal issue.
- SC= the ratio of the radiant gain through a given type of glass relative to 1/8" (3mm) thick single glass.
- Textbook Tables E.17—E.24 or ASHRAE F.2017 Ch.15 (fenestration)