Surface air films

- At the exposed surfaces of solids, heat transfer takes place both by convection and by radiation.
- When air motion along a surface is minimal, an insulating layer of air "attaches" itself to the surface. The resistance of this layer of 'still air' along a vertical surface is equivalent to that of a thickness of ½-in (12.7mm) plywood.
- When this air is disturbed, its resistance drops quickly. See Table E.3
- The surface conductance (the reciprocal of resistance) are as shown in Table E.3 (h_i, h_o)

TABLE E.3 Thermal Properties of Surface Air Films and Air Spaces

Part A. Surface Conductances[a] and Resistances[b] for Surface Air Films

		Surface Emittance, ε											
		I-P Units[c]						*SI Units*[d]					
		Nonreflective		Reflective				Nonreflective		Reflective			
		ε = 0.90		ε = 0.20		ε = 0.05		ε = 0.90		ε = 0.20		ε = 0.05	
Position of Surface	**Direction of Heat Flow**	h_i	R	h_i	R	h_i	R	h_i	R	h_i	R	h_i	R
Still Air													
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32	9.26	0.11	5.17	0.19	4.32	0.23
Sloping–45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37	9.09	0.11	5.00	0.20	4.15	0.24
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70	8.29	0.12	4.20	0.24	3.35	0.30
Sloping–45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22	7.50	0.13	3.41	0.29	2.56	0.39
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55	6.13	0.16	2.10	0.48	1.25	0.80
Moving Air (any position)		h_o	R					h_o	R				
Winter Wind													
15 mph (6.7 m/s)	Any	6.00	0.17					34.0	0.030				
Summer Wind													
7.5 mph (3.4 m/s)	Any	4.00	0.25					22.7	0.044				

Air spaces

- A planar volume of air contained on two sides by some elements (drywall, brick, insulation, etc.) of an envelope assembly.
- The resistance provided by an air space depends on its width, position (vertical, horizontal, tilted), and surrounding emittances. (Table E.5)

For other values in Table E.5, interpolation and extrapolation are permissible!!

TABLE E.5 Thermal Resistances of Plane[a] Air Spaces (SI Units)

All resistance values are expressed in K m²/W. Values apply only to air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no leakage of air to or from the space. These conditions are not normally present in standard building construction. Thermal resistance values for multiple air spaces must be based on careful estimates of mean temperature differences for each air space.

Position of Air Space	Direction of Heat Flow		Air Space: Mean Temp,[b] °C	Air Space: Temp Diff,[b] C°	13-mm Air Space[d], Value of E[b,c]: 0.03	0.05	0.2	0.5	0.82	20-mm Air Space[d], Value of E[b,c]: 0.03	0.05	0.2	0.5	0.82
Horizontal	Up	↑	32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
			10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
			10.0	5.6	0.37	0.36	0.28	0.30	0.15	0.40	0.39	0.30	0.20	0.15
			−17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
			−17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
			−45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
			−45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
45° Slope	Up	↗	32.2	5.6	0.43	0.41	0.29	0.19	0.13	0.52	0.49	0.33	0.20	0.14
			10.0	16.7	0.36	0.35	0.27	0.19	0.15	0.35	0.34	0.27	0.19	0.14
			10.0	5.6	0.45	0.43	0.32	0.21	0.16	0.51	0.48	0.35	0.23	0.17
			−17.8	11.1	0.39	0.38	0.31	0.23	0.18	0.37	0.36	0.30	0.23	0.18
			−17.8	5.6	0.46	0.45	0.36	0.25	0.19	0.48	0.46	0.37	0.26	0.20
			−45.6	11.1	0.37	0.36	0.31	0.25	0.21	0.36	0.35	0.31	0.25	0.20
			−45.6	5.6	0.46	0.45	0.38	0.29	0.23	0.45	0.43	0.37	0.29	0.23
Vertical	Horizontal	→	32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
			10	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
			10	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
			−17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
			−17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
			−45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
			−45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27
45° Slope	Down	↘	32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15
			10.0	16.7	0.46	0.44	0.33	0.22	0.16	0.60	0.57	0.39	0.24	0.17
			10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.67	0.63	0.42	0.26	0.18
			−17.8	11.1	0.51	0.49	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
			−17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.73	0.69	0.49	0.32	0.23
			−45.6	11.1	0.56	0.54	0.44	0.33	0.25	0.67	0.64	0.51	0.36	0.28
			−45.6	5.6	0.57	0.56	0.45	0.33	0.26	0.77	0.74	0.57	0.39	0.29

Effective emittance

- ε_1 and ε_2: emittances of the surfaces of the air space.

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$q_{rad} = \varepsilon_{eff}\sigma(T_1^4 - T_2^4)$$

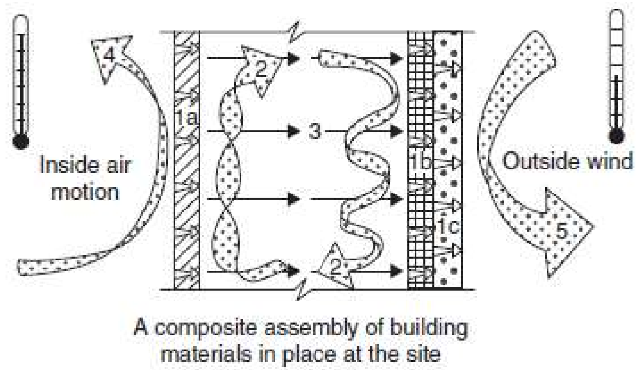


Fig. 9.6 Heat flow through materials, across air spaces, and through convection, and radiation.

Aluminum foil, bright

ε_1	ε_2	$\frac{1}{\varepsilon_1}$	$\frac{1}{\varepsilon_2}$	$\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$
0.1	0.1	10.0	10.0	19.0	0.05
0.1	0.9	10.0	1.11	10.11	0.10
0.2	0.9	5.0	1.11	5.11	0.20
0.9	0.9	1.11	1.11	1.22	**0.82**

wood, paper, masonry, nonmetallic paints

Example

e_eff	0.82	
e_eff	0.10	
Stefan-Boltzmann constant (W/m^2K^4)	5.67E-08	
T1	15	288.15
T2	3	276.15
q"	50.0	(W/m^2)
q"	6.0	(W/m^2)

Thermal properties

- Table E.3: surface heat transfer coefficient (resistance of surface air films) (h_i, h_o)
- Table E.5: resistance of air spaces

U factor

- One overall property that expresses the steady-state rate at which heat flows through composite envelope assemblies.
- Overall coefficient of thermal transmittance, W/m^2K
- Many codes and standards specify maximum U-factors (for insulation alone, minimum R)
- Tables E.6-E.16: U factors for doors, walls, windows are presented
  - Typically based on 15 mph (6.7m/s), except for summer conditions

Table E.6 U-Factors for Common Wall, Roof, and Floor Assemblies

Assembly	Basic Construction	Other Thermal Components	*I-P* Insulation R-value °F ft² h/Btu	*SI* Insulation R-value K m²/W	*I-P* Assembly U-factor Btu/°F ft² h	*SI* Assembly U-factor W/K m²
Wall	Wood studs, nominal 2 in. × 4 in., 16 in. o.c. (50 mm × 100 mm, 400 mm o.c.)	Exterior air film, stucco, exterior gypsum board, interior gypsum board, interior air film	11	1.94	0.096	0.55
	As above	Above plus R-4 (SI: R-0.7) continuous insulation	15	2.64	0.068	0.39
	Wood studs, nominal 2 in. × 6 in., 24 in. o.c. (50 mm × 150 mm, 400 mm o.c.)		18	3.17	0.065	0.37
	Steel studs, nominal 2 in. × 4 in., 16 in. o.c. (50 mm × 100 mm, 400 mm o.c.)		11	1.94	0.132	0.75
	As above	Above plus R-4 (SI: R-0.7) continuous insulation	15	2.64	0.087	0.49
	6-in. concrete masonry unit at 115 lb/ft³ (150 mm, at 1840 kg/m³)	Partly grouted, cells insulated	N/A	N/A	0.41	2.33
	As above	Above with R-4 (SI: R-0.7) continuous insulation with 1-in. (25-mm) framing and interior gypsum board	4	0.70	0.17	0.97
Roof	Standard wood joists	Semiexterior air film, gypsum board, interior air film	30	5.28	0.034	0.19
	Steel joists	Exterior air film, metal deck, interior air film	30	5.28	0.041	0.23
	System with insulation entirely above roof deck	Exterior air film, metal deck, interior air film	30	5.28	0.032	0.18
Floor	Nominal 6-in. wood joists (150 mm)	Semiexterior air film, wood subfloor, carpet and pad, interior film air	11	1.94	0.074	0.42
	Steel floor joists	Semiexterior air film, metal deck, concrete slab, carpet and pad, interior air film	11	1.94	0.078	0.44

Source: Extracted and used with permission; ©ASHRAE, www.ashrae.org. ANSI/ASHRAE/IESNA Standard 90.1-2016: *Energy Standard for Buildings Except Low-Rise Residential Buildings*

Note: The SI units for resistance and U-factor were appended to the ASHRAE I-P data by the authors.

$$R = R_1 + R_2 + R_3 + R_4 + \cdots + R_n$$

where

$R_1, R_2, \ldots, R_n$ = resistances of individual layers, $(m^2 \cdot K)/W$

R = resistance of building assembly surface to surface, $(m^2 \cdot K)/W$

Total Thermal Resistance of a Flat Building Component

Total thermal resistance to heat flow through a flat building component composed of parallel layers between the environments at both sides is given by

$$R_T = R_i + R + R_o \tag{5}$$

where

R_i = thermal resistance of indoor air film, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$
R_o = thermal resistance of outdoor air film, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$

For a wall that includes an air space of conductance C, the overall resistance is

$$R_T = R_i + R_1 + \frac{1}{C} + R_2 + R_o \tag{6}$$

where

R_1 = thermal resistance of layer at one side of air space, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$
R_2 = thermal resistance of layer at other side of air space, $(\mathrm{m}^2 \cdot \mathrm{K})/\mathrm{W}$

Thermal Transmittance of a Flat Building Component

The thermal transmittance or U-factor of a flat building component is the reciprocal of R_T:

$$U = \frac{1}{R_T} \tag{7}$$

Calculation of U-Factor

EXAMPLE 9.1 What is the winter U-factor for the wall assembly shown in Fig. 9.8?

SOLUTION

Component	R (I-P)	R (SI)	Data Source
Inside air film	0.68	0.12	Table E.3
Gypsum board (0.375 in. [10 mm])	0.32	0.056	Table E.1
Plastic film vapor retarder	nil	nil	Table E.1
Glass fiber batt insulation (nominal 6 in. [150 mm])	19.00	3.35	Table E.1
Plywood (0.5 in. [12 mm])	0.62	0.11	Table E.1
Wood siding (1 in. [25 mm])	0.79	0.14	Table E.1
Outside air film	0.17	0.03	Table E.3
Total resistance (R)	21.58	3.81	

$$U\ (\text{I-P}) = 1/\Sigma R = 1/21.58 = 0.046$$

$$U\ (\text{SI}) = 1/\Sigma R = 1/3.81 = 0.262$$

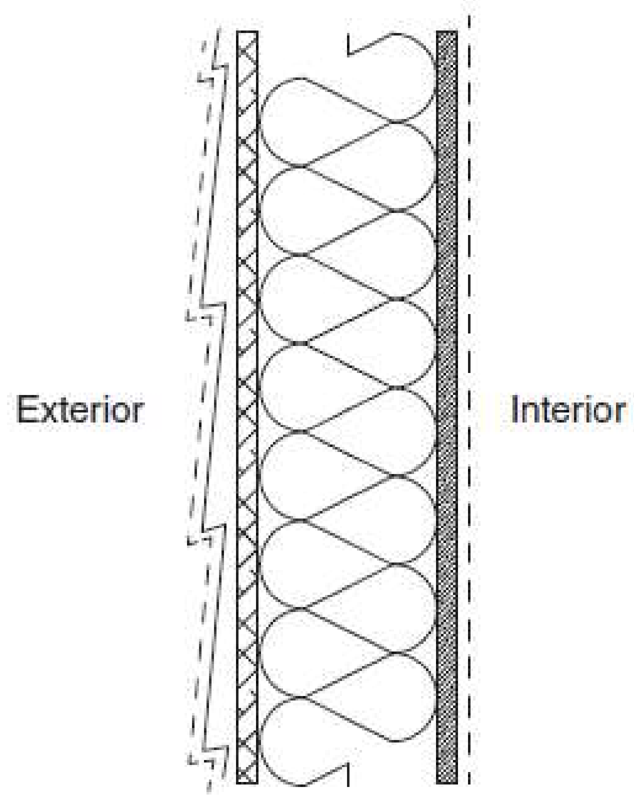
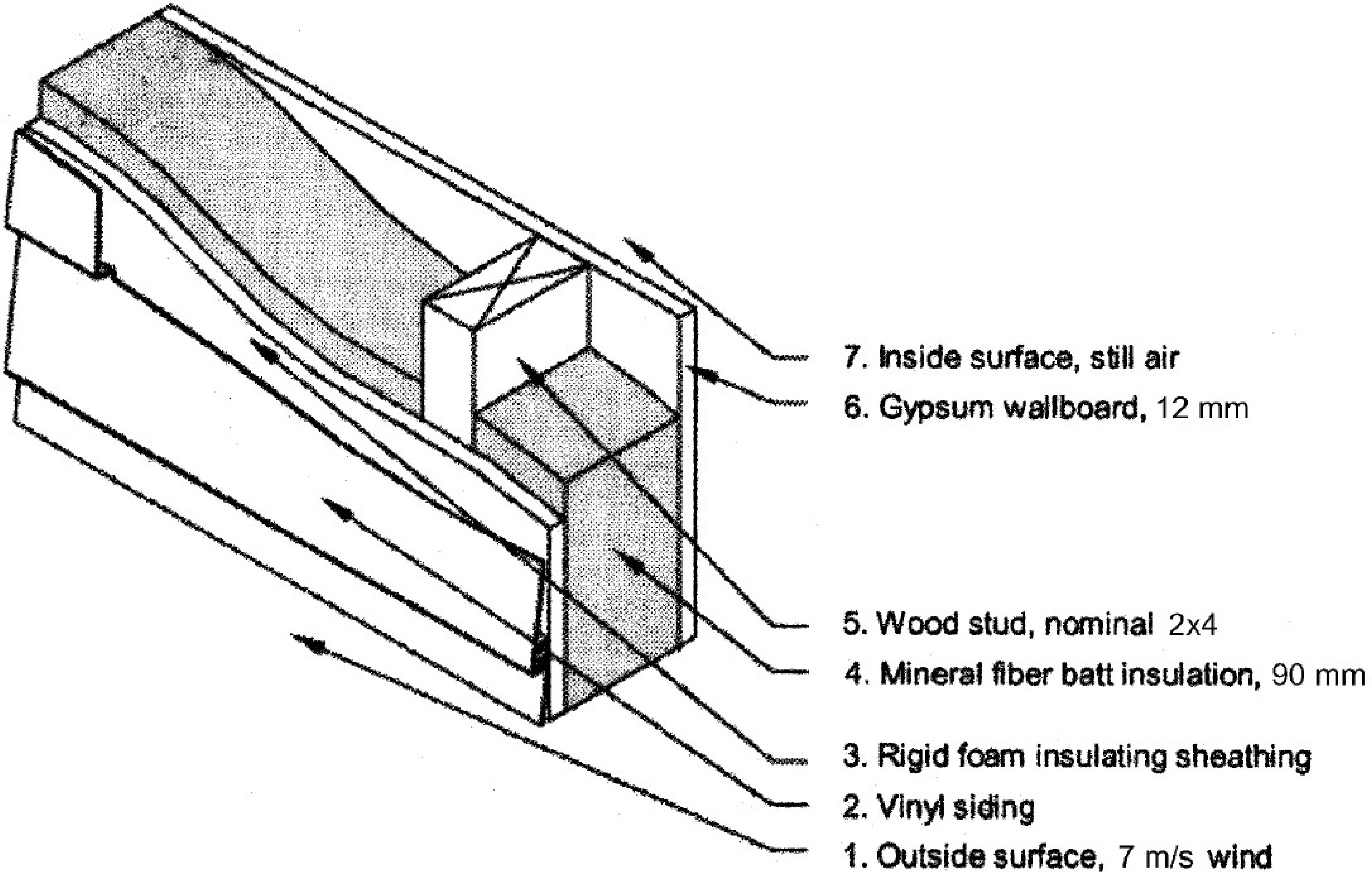


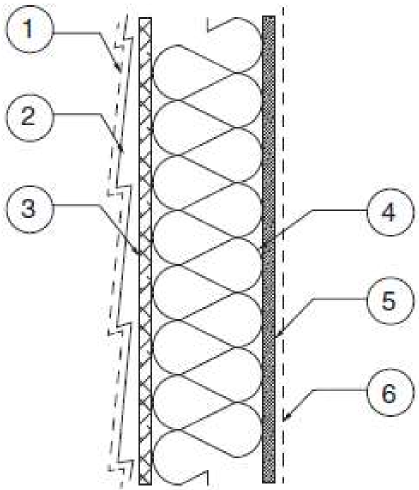
Fig. 9.8 Wall section used in Example 9.1 to illustrate the process for determining a U-factor (overall thermal transmittance). (Drawn by Sharon Alitema.)

Note: The U-factor addresses only sensible hear flow resulting from a temperature difference, not addressing latent (moisture-related) heat flow.

Stud wall (example)



EXAMPLE 9.2 Considering thermal bridging, what is the winter U-factor for the wall assembly shown in Fig. 9.9?



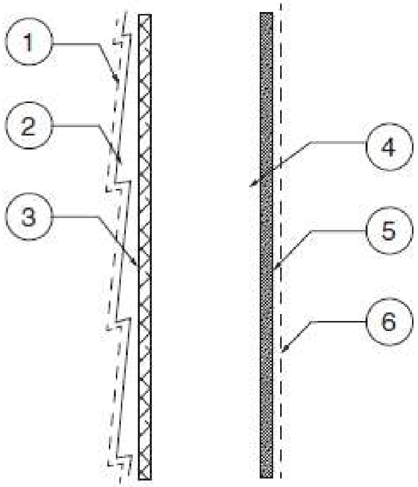


Fig. 9.9 *Wall sections used in Example 9.2 to illustrate the process for determining a weighted-average U-factor to account for thermal*

SOLUTION

For those portions of the wall where insulation is encountered:

Component	*R (I-P)*	*R (SI)*
(6) Inside air film (still)	0.68	0.12
(5) Gypsum board (0.5 in. [12 mm])	0.45	0.079
Plastic film vapor retarder	nil	nil
(4) Glass fiber batt insulation (6 in. [150 mm])	19.0	3.32
(3) Vegetable fiber board (0.5 in. [12 mm])	1.32	0.23
(2) Lapped wood siding (0.5 in. [12 mm])	0.81	0.14
(1) Outside air film (15 mph [24 km/h])	0.17	0.03
Total resistance through insulation	22.43	3.92

U=0.255 W/m²K

For those portions of the wall where framing is encountered:

Component	*R (I-P)*	*R (SI)*
(6) Inside air film (still)	0.68	0.12
(5) Gypsum board (0.5 in. [12 mm])	0.45	0.079
Plastic film vapor retarder	nil	nil
(7) Wood studs (nominal 6 in. [150 mm])	6.82	1.20
(3) Vegetable fiber board (0.5 in. [12 mm])	1.32	0.23
(2) Lapped wood siding (0.5 in. [12 mm])	0.81	0.14
(1) Outside air film (15 mph [24 km/h])	0.17	0.03
Total resistance through framing	10.25	1.80

U=0.556 W/m²K

Assuming that 12% of the surface area of the wall consists of framing (studs, sills, and plates), the area-weighted U-factor of the overall wall is as follows:

$$R_{insulated} = 22.43;\ \text{while } R_{frame} = 10.25$$

$$U_{insulated} = (1/22.43) = 0.045;\ \text{while } U_{frame} = (1/10.25) = 0.98$$

$$U_{weighted} = (0.88)(0.045) + (0.12)(0.98) = 0.158$$

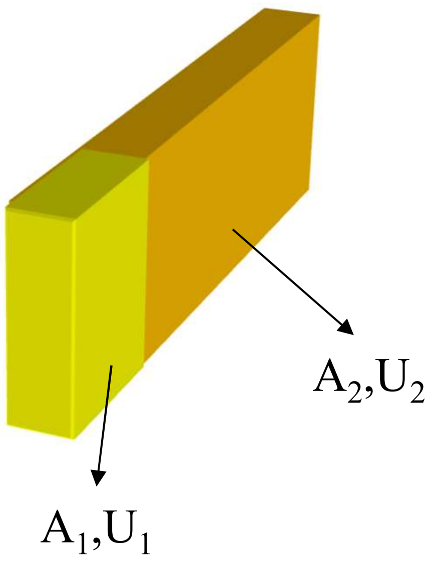
The predicted U-factor for the actual wall assembly is thus 0.158 (compared to 1/22.43 = 0.045 if framing is ignored).

$$SI: R_{insulated} = 3.92;\ \text{while } R_{frame} = 1.80$$

$$SI: U_{insulated} = (1/3.92) = 0.255;\ \text{while } U_{frame} = (1/1.80) = 0.556$$

$$SI: U_{weighted} = (0.88)(0.255) + (0.12)(0.556) = 0.291$$

■



$$U = \frac{U_1 A_1}{\sum A} + \frac{U_2 A_2}{\sum A} \dots + \frac{U_n A_n}{\sum A}$$

$$U = 0.255 \times 0.88 + 0.556 \times 0.12 = 0.291$$

The effect of framing

- Wood or metal stud
- Stud spacing

o.c. = on-center spacing

Metal building wall, nominal 4 in. U = 0.14
(SI: 100 mm; U = 0.79)
Steel frame wall, 3.5 in. at 16-in. o.c. U = 0.134
(SI: 90 mm at 400-mm o.c.; U = 0.76)
Steel frame wall, 3.5 in. at 24-in. o.c. U = 0.115
(SI: 90 mm at 600-mm o.c.; U = 0.65)
Wood frame wall, 3.5 in. at 16-in. o.c. U = 0.094
(SI: 90 mm at 400-mm o.c.; U = 0.53)
Wood frame wall, 3.5 in. at 24-in. o.c. U = 0.091
(SI: 90 mm at 600-mm o.c.; U = 0.52)

Roofs

- The U factor of roofs is calculated as for walls.
- The effect of thermal bridging (as shown in the stud wall example in the prev. slide) must be included.
- Un-insulated attic: treat it as at outdoor temperature
  - A more complex calculation method presented in ASHRAE F. Ch.28

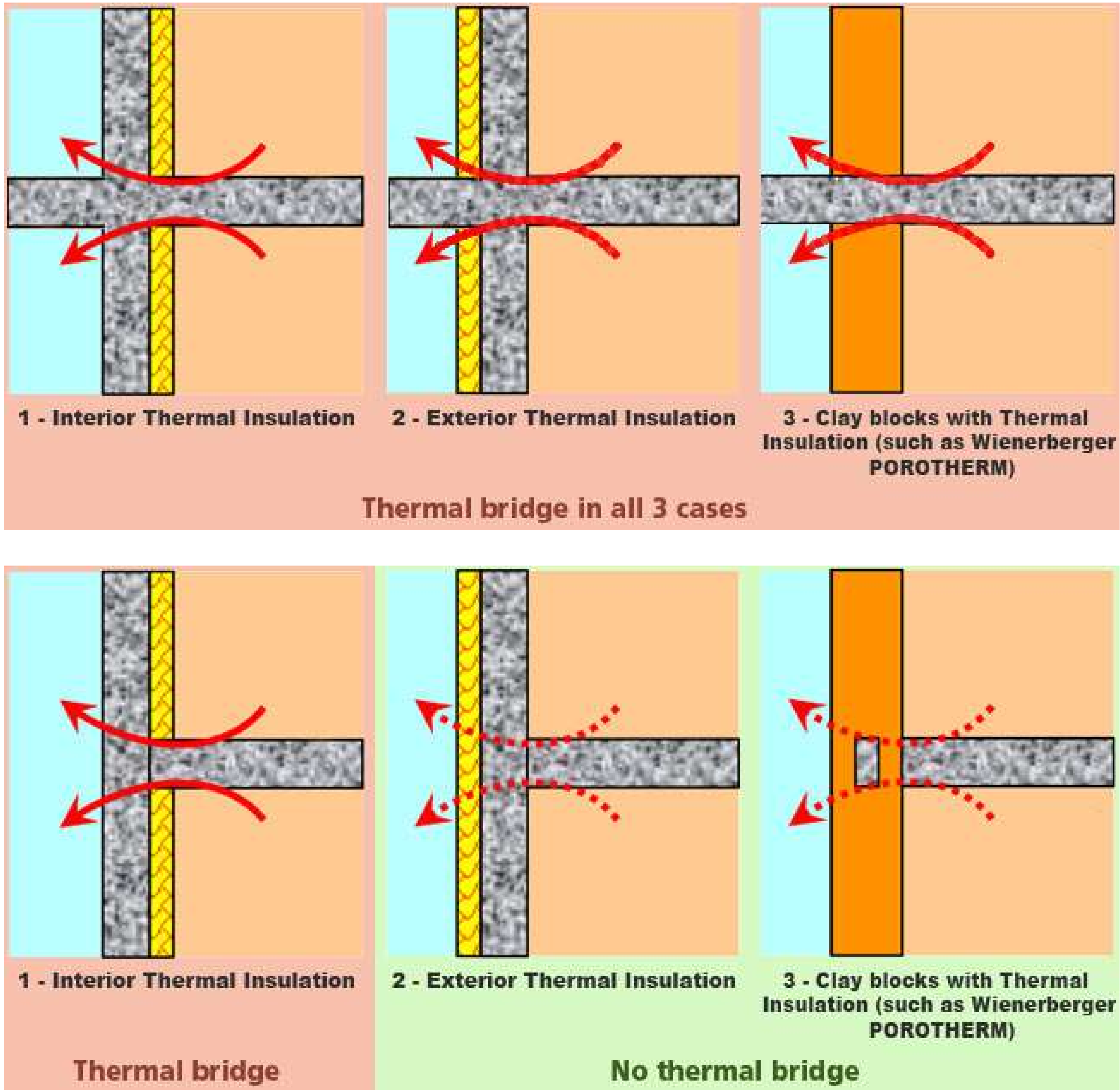


Image source: http://beodom.com/en/education/entries/fighting-thermal-bridges-or-how-to-make-better-buildings

Floors

- When a floor is exposed to outdoor air (as with a cantilever or crawl space), the U-factor is calculated as for walls and roofs.
- The effect of thermal bridging must be included.
- Vented crawl space: treat it as at outdoor temperature
  - A more complex calculation method presented in ASHRAE F. Ch.29