LECTURE 3

HEAT TRANSMISSION IN BUILDING STRUCTURES

Chapter 5

Building envelope

- In HVAC work the term *building envelope* refers to the walls, roof, floors, and any fenestrations that enclose the building
- It is through these components of a building that energy may enter or leave by heat transfer
- Good estimates of the corresponding heat transfer rates are necessary to design an acceptable air-conditioning system

Building envelope contd..

- Walls and roofs are rather complex assemblies of materials

- Windows are often made of two or more layers of glass with air spaces between them and usually have drapes or curtains

- In basements, floors and walls are in contact with the ground

- Because of these conditions, precise calculation of heat transfer rates is difficult, but experience and experimental data make reliable estimates possible

Modes of heat transfer

- Conduction – predominantly in solids
- Convection – predominantly in fluids
- Radiation – predominantly in vacuum

Thermal conduction

- Mechanism of heat transfer between parts of a continuum due to the transfer of energy between particles or groups of particles at the atomic level

- Fourier equation: $\dot{q} = -kA\frac{dT}{dx}$

  $\dot{q}$ = heat transfer rate, Btu/hr or W

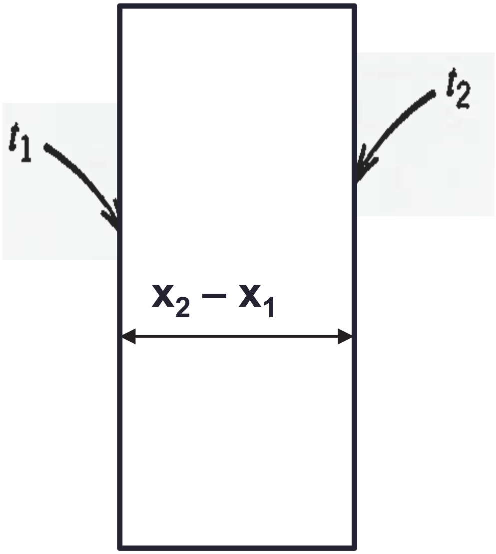
  k = thermal conductivity, Btu/(hr-ft-F) or W/(m-C)

  A = area normal to heat flow, ft^2 or m^2

  $\frac{dT}{dx}$ = temperature gradient, F/ft or C/m

- Negative sign indicates that $\dot{q}$ flows in the positive direction of *x* when $\frac{dT}{dx}$ is negative

Thermal Resistance



$$\dot{q} = -\frac{kA(t_2 - t_1)}{x_2 - x_1}$$

$$= -\frac{(t_2 - t_1)}{R'}$$

R' is defined as the thermal resistance such that:

$$R' = \frac{x_2 - x_1}{kA}$$

"*R* factor", is referred to as the *unit thermal resistance,* or simply the *unit resistance, R.* For a plane wall the unit resistance is

$$R = \frac{\Delta x}{k}$$

Unit thermal conductance C = $\frac{1}{R} = \frac{k}{\Delta x}$ in Btu/(hr-ft^2-F) or W/(m^2-K)

Electrical analogy

- Thermal resistance *R'* is analogous to *electrical resistance*

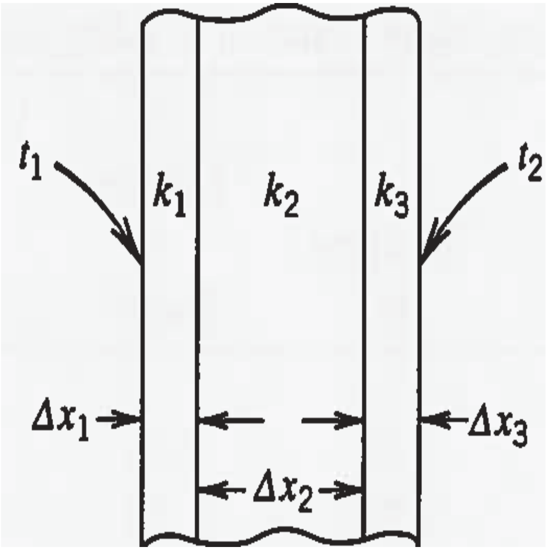
- $\dot{q}$ *is* analogous to *current*, and

- (t_2 - t_1) is analogous to *potential difference* in Ohm's law (V = IR)

- This analogy provides a very convenient method of analyzing a wall or slab made up of two or more layers of dissimilar materials

Resistances in series

Figure shows a wall constructed of three different materials.



The heat transferred by conduction is given as

$$\dot{q} = -\frac{(t_2 - t_1)}{R'}$$

where the resistances are in series

$$R' = R'_1 + R'_2 + R'_3$$

$$= \frac{\Delta x_1}{k_1 A} + \frac{\Delta x_2}{k_2 A} + \frac{\Delta x_3}{k_3 A}$$

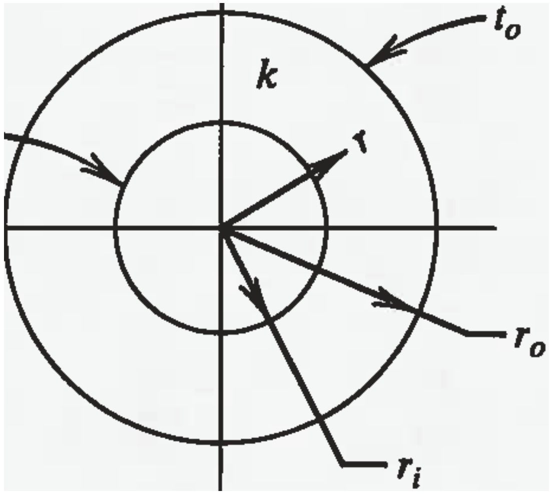
Radial heat flow in a hollow cylinder

- Surface temperatures t_i and t_0 are assumed to be uniform and steady over each surface
- Material is assumed to be homogeneous with a constant value of thermal conductivity

$$\dot{q} = \frac{2\pi kL}{\ln\left(\frac{r_o}{r_i}\right)}(t_i - t_o)$$

Here L = length of cylinder

$$Thermal\ resistance = R' = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi kL}$$



- Cylinders made up of several layers may be analyzed in a manner similar to the plane wall where resistances in series are summed

- The individual resistances are given by

$R' = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi kL}$, with r_o *and* r_i being the outer and inner radius of each layer.

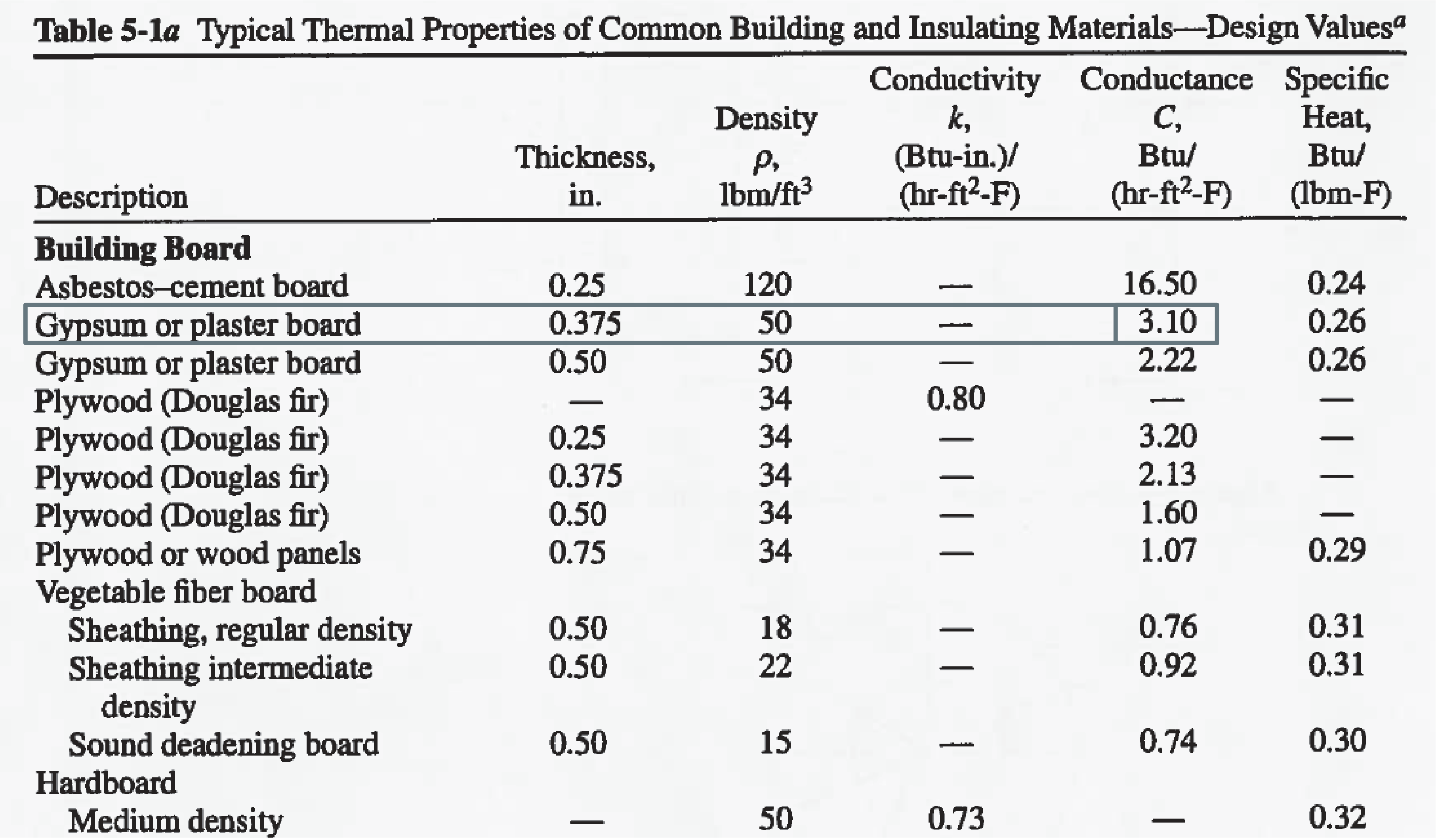


Table 5-1*a* Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a]

Description	Thickness, in.	Density ρ, lbm/ft^3	Conductivity k, (Btu-in.)/(hr-ft^2-F)	Conductance C, Btu/(hr-ft^2-F)	Specific Heat, Btu/(lbm-F)
Building Board					
Asbestos–cement board	0.25	120	—	16.50	0.24
Gypsum or plaster board	0.375	50	—	3.10	0.26
Gypsum or plaster board	0.50	50	—	2.22	0.26
Plywood (Douglas fir)	—	34	0.80	—	—
Plywood (Douglas fir)	0.25	34	—	3.20	—
Plywood (Douglas fir)	0.375	34	—	2.13	—
Plywood (Douglas fir)	0.50	34	—	1.60	—
Plywood or wood panels	0.75	34	—	1.07	0.29
Vegetable fiber board					
Sheathing, regular density	0.50	18	—	0.76	0.31
Sheathing intermediate density	0.50	22	—	0.92	0.31
Sound deadening board	0.50	15	—	0.74	0.30
Hardboard					
Medium density	—	50	0.73	—	0.32

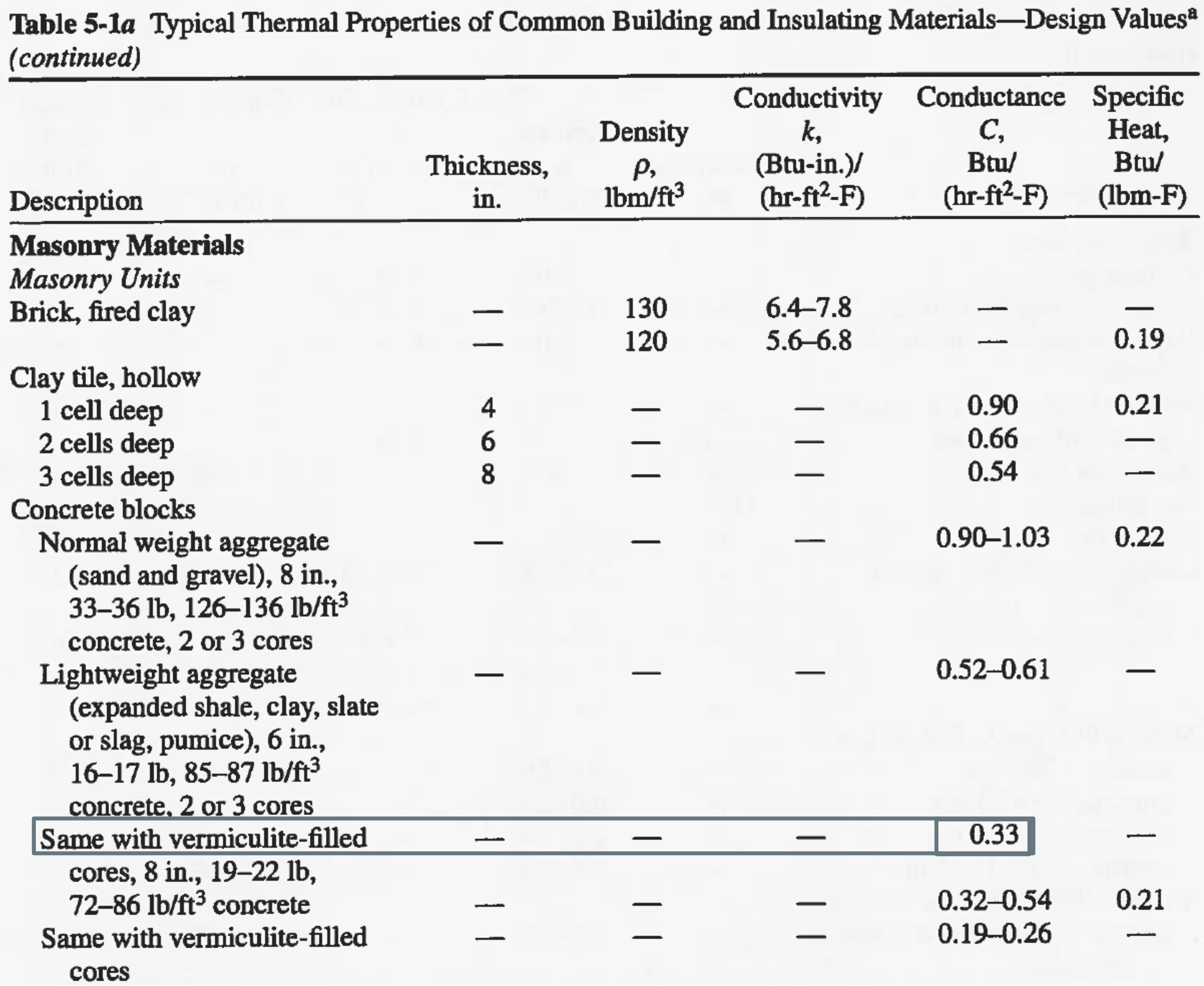


Table 5-1*a* Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] *(continued)*

Description	Thickness, in.	Density ρ, lbm/ft^3	Conductivity k, (Btu-in.)/(hr-ft^2-F)	Conductance C, Btu/(hr-ft^2-F)	Specific Heat, Btu/(lbm-F)
Masonry Materials					
Masonry Units					
Brick, fired clay	—	130	6.4–7.8	—	—
	—	120	5.6–6.8	—	0.19
Clay tile, hollow					
1 cell deep	4	—	—	0.90	0.21
2 cells deep	6	—	—	0.66	—
3 cells deep	8	—	—	0.54	—
Concrete blocks					
Normal weight aggregate (sand and gravel), 8 in., 33–36 lb, 126–136 lb/ft^3 concrete, 2 or 3 cores	—	—	—	0.90–1.03	0.22
Lightweight aggregate (expanded shale, clay, slate or slag, pumice), 6 in., 16–17 lb, 85–87 lb/ft^3 concrete, 2 or 3 cores	—	—	—	0.52–0.61	—
Same with vermiculite-filled	—	—	—	0.33	—
cores, 8 in., 19–22 lb, 72–86 lb/ft^3 concrete	—	—	—	0.32–0.54	0.21
Same with vermiculite-filled cores	—	—	—	0.19–0.26	—

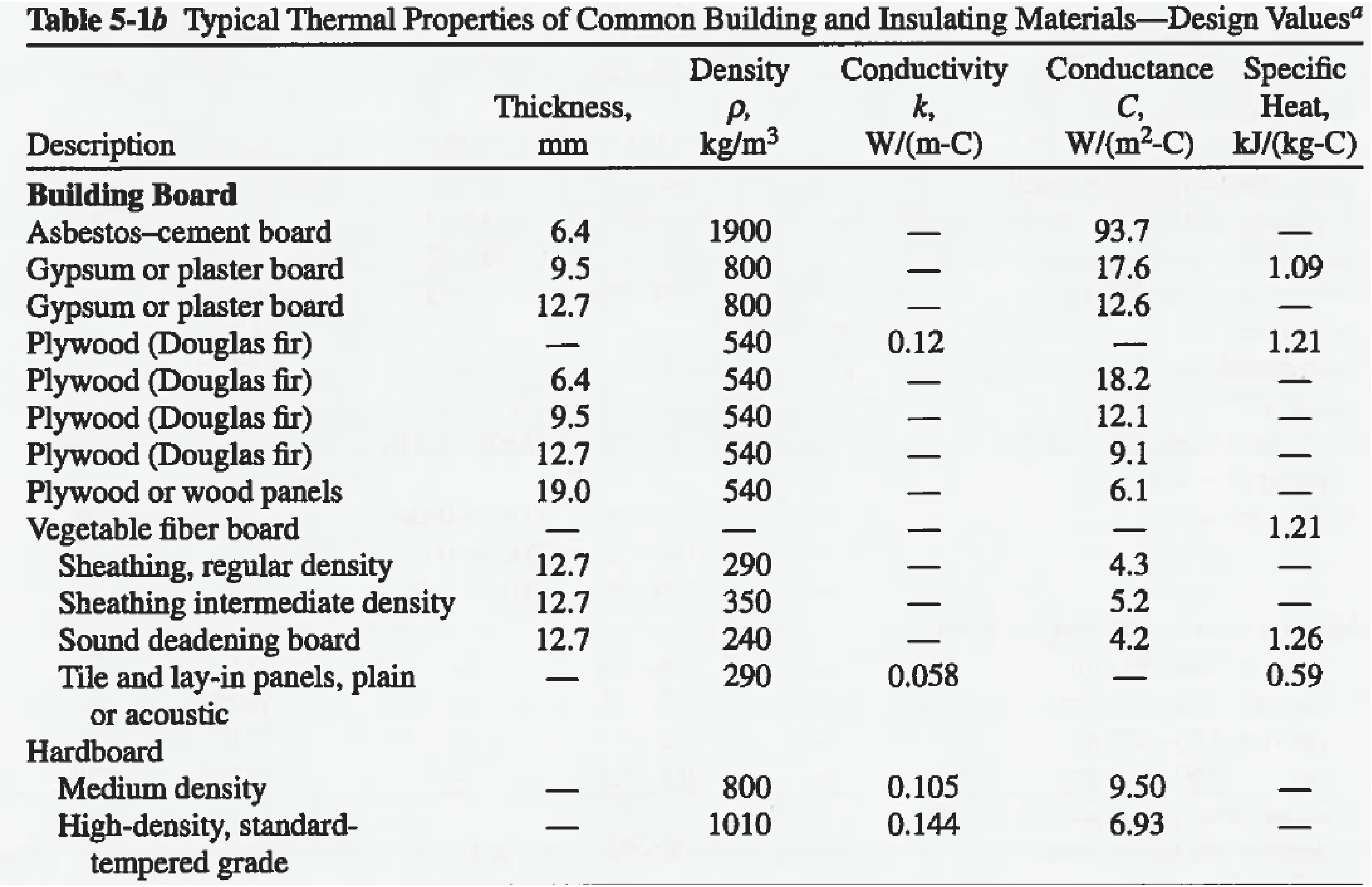


Table 5-1*b* Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a]

Description	Thickness, mm	Density ρ, kg/m^3	Conductivity k, W/(m-C)	Conductance C, W/(m^2-C)	Specific Heat, kJ/(kg-C)
Building Board					
Asbestos–cement board	6.4	1900	—	93.7	—
Gypsum or plaster board	9.5	800	—	17.6	1.09
Gypsum or plaster board	12.7	800	—	12.6	—
Plywood (Douglas fir)	—	540	0.12	—	1.21
Plywood (Douglas fir)	6.4	540	—	18.2	—
Plywood (Douglas fir)	9.5	540	—	12.1	—
Plywood (Douglas fir)	12.7	540	—	9.1	—
Plywood or wood panels	19.0	540	—	6.1	—
Vegetable fiber board	—	—	—	—	1.21
Sheathing, regular density	12.7	290	—	4.3	—
Sheathing intermediate density	12.7	350	—	5.2	—
Sound deadening board	12.7	240	—	4.2	1.26
Tile and lay-in panels, plain or acoustic	—	290	0.058	—	0.59
Hardboard					
Medium density	—	800	0.105	9.50	—
High-density, standard-tempered grade	—	1010	0.144	6.93	—

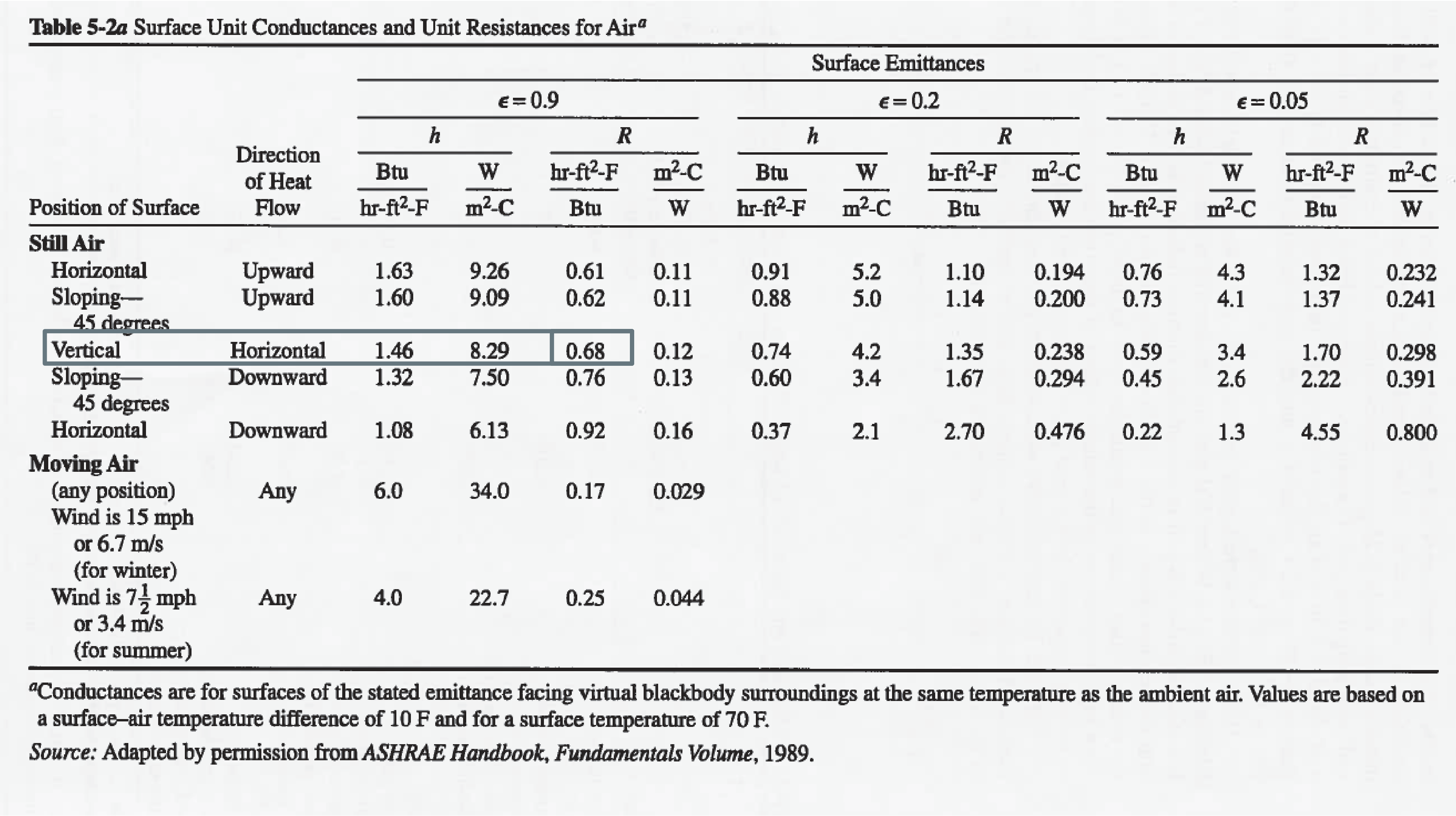


Table 5-2a Surface Unit Conductances and Unit Resistances for Air[a]

		Surface Emittances											
		$\epsilon = 0.9$				$\epsilon = 0.2$				$\epsilon = 0.05$			
		h		*R*		*h*		*R*		*h*		*R*	
Position of Surface	Direction of Heat Flow	Btu/hr-ft^2-F	W/m^2-C	hr-ft^2-F/Btu	m^2-C/W	Btu/hr-ft^2-F	W/m^2-C	hr-ft^2-F/Btu	m^2-C/W	Btu/hr-ft^2-F	W/m^2-C	hr-ft^2-F/Btu	m^2-C/W
Still Air													
Horizontal	Upward	1.63	9.26	0.61	0.11	0.91	5.2	1.10	0.194	0.76	4.3	1.32	0.232
Sloping—45 degrees	Upward	1.60	9.09	0.62	0.11	0.88	5.0	1.14	0.200	0.73	4.1	1.37	0.241
Vertical	Horizontal	1.46	8.29	0.68	0.12	0.74	4.2	1.35	0.238	0.59	3.4	1.70	0.298
Sloping—45 degrees	Downward	1.32	7.50	0.76	0.13	0.60	3.4	1.67	0.294	0.45	2.6	2.22	0.391
Horizontal	Downward	1.08	6.13	0.92	0.16	0.37	2.1	2.70	0.476	0.22	1.3	4.55	0.800
Moving Air													
(any position) Wind is 15 mph or 6.7 m/s (for winter)	Any	6.0	34.0	0.17	0.029								
Wind is $7\frac{1}{2}$ mph or 3.4 m/s (for summer)	Any	4.0	22.7	0.25	0.044								

[a]Conductances are for surfaces of the stated emittance facing virtual blackbody surroundings at the same temperature as the ambient air. Values are based on a surface–air temperature difference of 10 F and for a surface temperature of 70 F.

Source: Adapted by permission from *ASHRAE Handbook, Fundamentals Volume*, 1989.

Ex 5-4

What is the unit thermal resistance for an inside partition made up of 3/8 in. gypsum board on each side of 8 in. lightweight aggregate blocks with vermiculite-filled cores?

Ex 5-5

Compute the thermal resistance per unit length for a 4 in. schedule 40 steel pipe with 1½ in. of insulation. The insulation has a thermal conductivity of 0.2 Btu-in./(hr-ft^2-F).

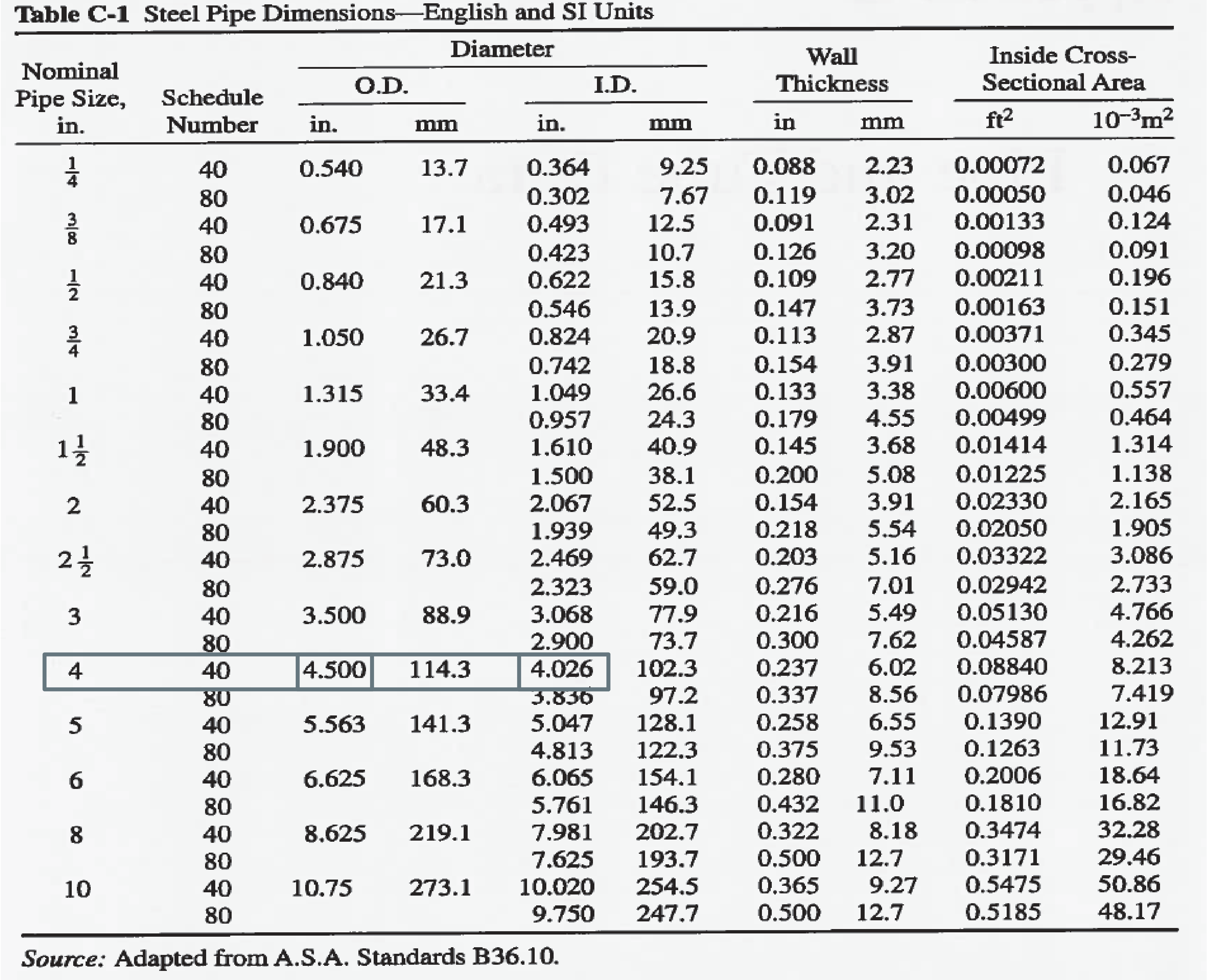


Table C-1 Steel Pipe Dimensions—English and SI Units

Nominal Pipe Size, in.	Schedule Number	Diameter				Wall Thickness		Inside Cross-Sectional Area	
		O.D.		I.D.					
		in.	mm	in.	mm	in	mm	ft^2	10^{-3}m^2
$\frac{1}{4}$	40	0.540	13.7	0.364	9.25	0.088	2.23	0.00072	0.067
	80			0.302	7.67	0.119	3.02	0.00050	0.046
$\frac{3}{8}$	40	0.675	17.1	0.493	12.5	0.091	2.31	0.00133	0.124
	80			0.423	10.7	0.126	3.20	0.00098	0.091
$\frac{1}{2}$	40	0.840	21.3	0.622	15.8	0.109	2.77	0.00211	0.196
	80			0.546	13.9	0.147	3.73	0.00163	0.151
$\frac{3}{4}$	40	1.050	26.7	0.824	20.9	0.113	2.87	0.00371	0.345
	80			0.742	18.8	0.154	3.91	0.00300	0.279
1	40	1.315	33.4	1.049	26.6	0.133	3.38	0.00600	0.557
	80			0.957	24.3	0.179	4.55	0.00499	0.464
$1\frac{1}{2}$	40	1.900	48.3	1.610	40.9	0.145	3.68	0.01414	1.314
	80			1.500	38.1	0.200	5.08	0.01225	1.138
2	40	2.375	60.3	2.067	52.5	0.154	3.91	0.02330	2.165
	80			1.939	49.3	0.218	5.54	0.02050	1.905
$2\frac{1}{2}$	40	2.875	73.0	2.469	62.7	0.203	5.16	0.03322	3.086
	80			2.323	59.0	0.276	7.01	0.02942	2.733
3	40	3.500	88.9	3.068	77.9	0.216	5.49	0.05130	4.766
	80			2.900	73.7	0.300	7.62	0.04587	4.262
4	40	4.500	114.3	4.026	102.3	0.237	6.02	0.08840	8.213
	80			3.836	97.2	0.337	8.56	0.07986	7.419
5	40	5.563	141.3	5.047	128.1	0.258	6.55	0.1390	12.91
	80			4.813	122.3	0.375	9.53	0.1263	11.73
6	40	6.625	168.3	6.065	154.1	0.280	7.11	0.2006	18.64
	80			5.761	146.3	0.432	11.0	0.1810	16.82
8	40	8.625	219.1	7.981	202.7	0.322	8.18	0.3474	32.28
	80			7.625	193.7	0.500	12.7	0.3171	29.46
10	40	10.75	273.1	10.020	254.5	0.365	9.27	0.5475	50.86
	80			9.750	247.7	0.500	12.7	0.5185	48.17

Source: Adapted from A.S.A. Standards B36.10.

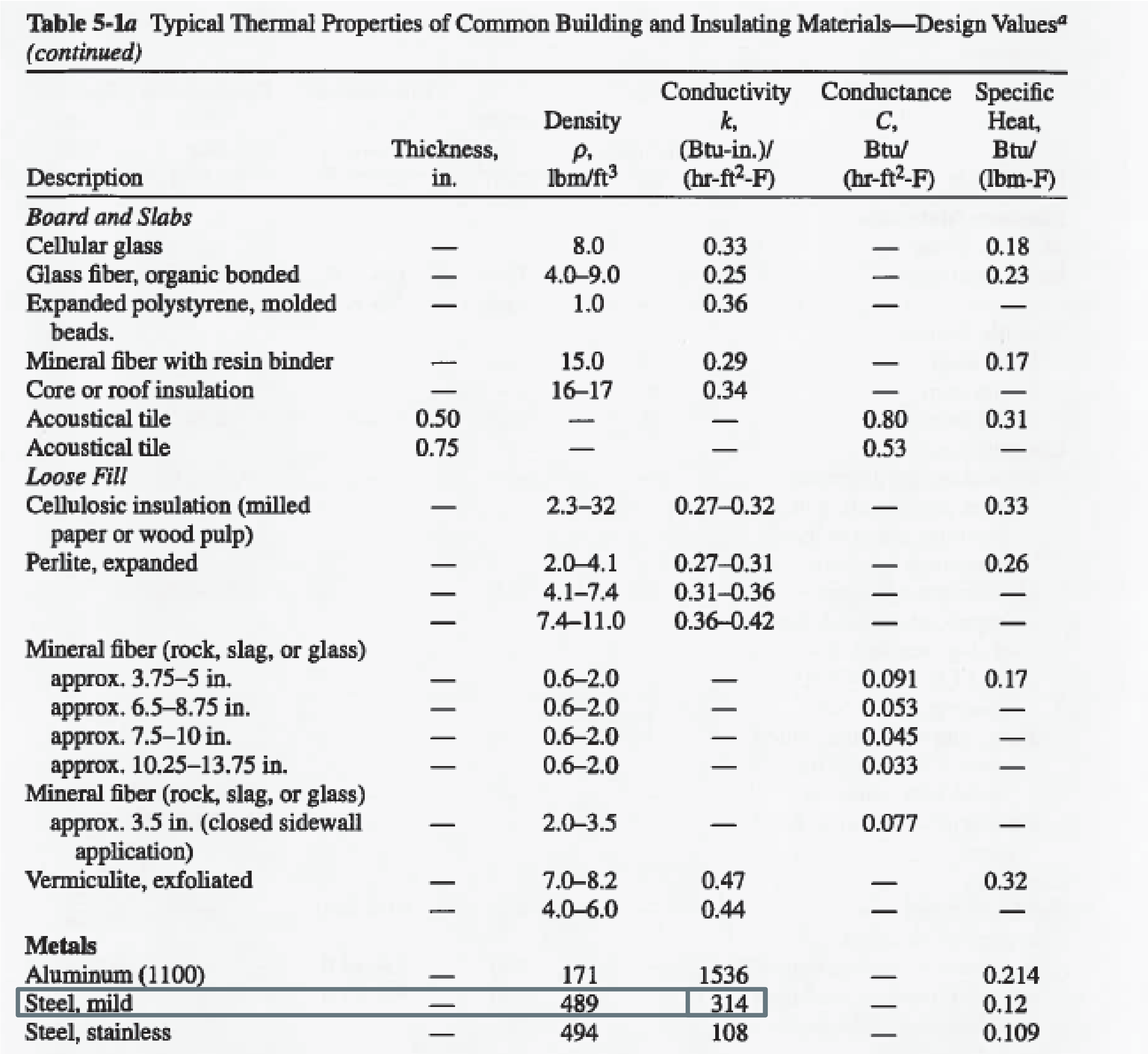


Table 5-1*a* Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] *(continued)*

Description	Thickness, in.	Density ρ, lbm/ft^3	Conductivity k, (Btu-in.)/(hr-ft^2-F)	Conductance C, Btu/(hr-ft^2-F)	Specific Heat, Btu/(lbm-F)
Board and Slabs					
Cellular glass	—	8.0	0.33	—	0.18
Glass fiber, organic bonded	—	4.0–9.0	0.25	—	0.23
Expanded polystyrene, molded beads.	—	1.0	0.36	—	—
Mineral fiber with resin binder	—	15.0	0.29	—	0.17
Core or roof insulation	—	16–17	0.34	—	—
Acoustical tile	0.50	—	—	0.80	0.31
Acoustical tile	0.75	—	—	0.53	—
Loose Fill					
Cellulosic insulation (milled paper or wood pulp)	—	2.3–32	0.27–0.32	—	0.33
Perlite, expanded	—	2.0–4.1	0.27–0.31	—	0.26
	—	4.1–7.4	0.31–0.36	—	—
	—	7.4–11.0	0.36–0.42	—	—
Mineral fiber (rock, slag, or glass)					
approx. 3.75–5 in.	—	0.6–2.0	—	0.091	0.17
approx. 6.5–8.75 in.	—	0.6–2.0	—	0.053	—
approx. 7.5–10 in.	—	0.6–2.0	—	0.045	—
approx. 10.25–13.75 in.	—	0.6–2.0	—	0.033	—
Mineral fiber (rock, slag, or glass)					
approx. 3.5 in. (closed sidewall application)	—	2.0–3.5	—	0.077	—
Vermiculite, exfoliated	—	7.0–8.2	0.47	—	0.32
	—	4.0–6.0	0.44	—	—
Metals					
Aluminum (1100)	—	171	1536	—	0.214
Steel, mild	—	489	314	—	0.12
Steel, stainless	—	494	108	—	0.109

Thermal convection

- Transport of energy by mixing in addition to conduction

- Convection is associated with fluids in motion, generally through a pipe or duct or along a surface

- The transfer mechanism is complex and highly dependent on the nature of the flow

Heat transfer rate

Simplified approach in convection is to express the heat transfer rate as

$$\dot{q} = hA(t - t_w)$$

where:

$\dot{q}$ = heat transfer rate from fluid to wall, Btu/hr or W

h = film coefficient, Btu/(hr-ft^2-F) or W/(m^2-s)

t = bulk temperature of the fluid, F or C

t_w = wall temperature, F or C

Convective heat transfer coefficient

$$\dot{q} = hA(t - t_w) = \frac{(t - t_w)}{(\frac{1}{hA})} = \frac{(t - t_w)}{R'}$$

$R' = \frac{1}{hA}$ in (hr-ft)/Btu or C/W

$R = \frac{1}{h} = \frac{1}{C}^{*}$ (hr-ft^2-F)/Btu or (m^2-C)/W

Film coefficient *h* is called the *unit surface conductance* or alternatively the *convective heat transfer coefficient*

h depends on

- the fluid,
- the fluid velocity,
- the flow channel or wall shape or orientation,
- the degree of development of the flow field (i.e., the distance from the entrance or wall edge and from the start of heating)

Forced and Free convection

- When the bulk of the fluid is moving relative to the heat transfer surface, the mechanism is called *forced convection,* because such motion is caused by a blower, fan, or pump that is forcing the flow.
- In forced convection buoyancy forces are negligible.
- In *free convection,* the motion of the fluid is due entirely to buoyancy forces, usually confined to a layer near the heated or cooled surface.
- The surrounding bulk of the fluid is stationary and exerts a viscous drag on the layer of moving fluid.
- As a result inertia forces in free convection are usually small.
- Free convection is often referred to as *natural convection.*

Convection in building structures

- Most building structures have forced convection due to wind along outer walls or roofs, and natural convection occurs inside narrow air spaces and on the inner walls.

- There is considerable variation in surface conditions, and both the direction and magnitude of the air motion (wind) on outdoor surfaces are very unpredictable.

- The film coefficient for these situations usually ranges from about 1.0 Btu/(hr-ft^2-F) [6 W/(m^2-C)] for free convection up to about 6 Btu/(hr-ft^2-F) [35 W/(m^2-C)] for forced convection with an air velocity of about 15 mph (20 ft/s or 6 m/s).

- Free convection film coefficients are low, and the amount of heat transferred by thermal radiation may be equal to or larger than that transferred by convection.

Thermal radiation

- Transfer of thermal energy by electromagnetic waves
- An entirely different phenomenon from conduction and convection
- Radiation can occur in a perfect vacuum
- Radiation is actually impeded by an intervening medium

Radiation heat transfer

$$\dot{q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}}$$

where:

σ = Boltzmann constant

= 0.1713 *x* 10^{-8} Btu/(hr-ft^2-R^4) = 5.673 *x* 10^{-8} W/ (m^2-K^4)

T = absolute temperature, R or K

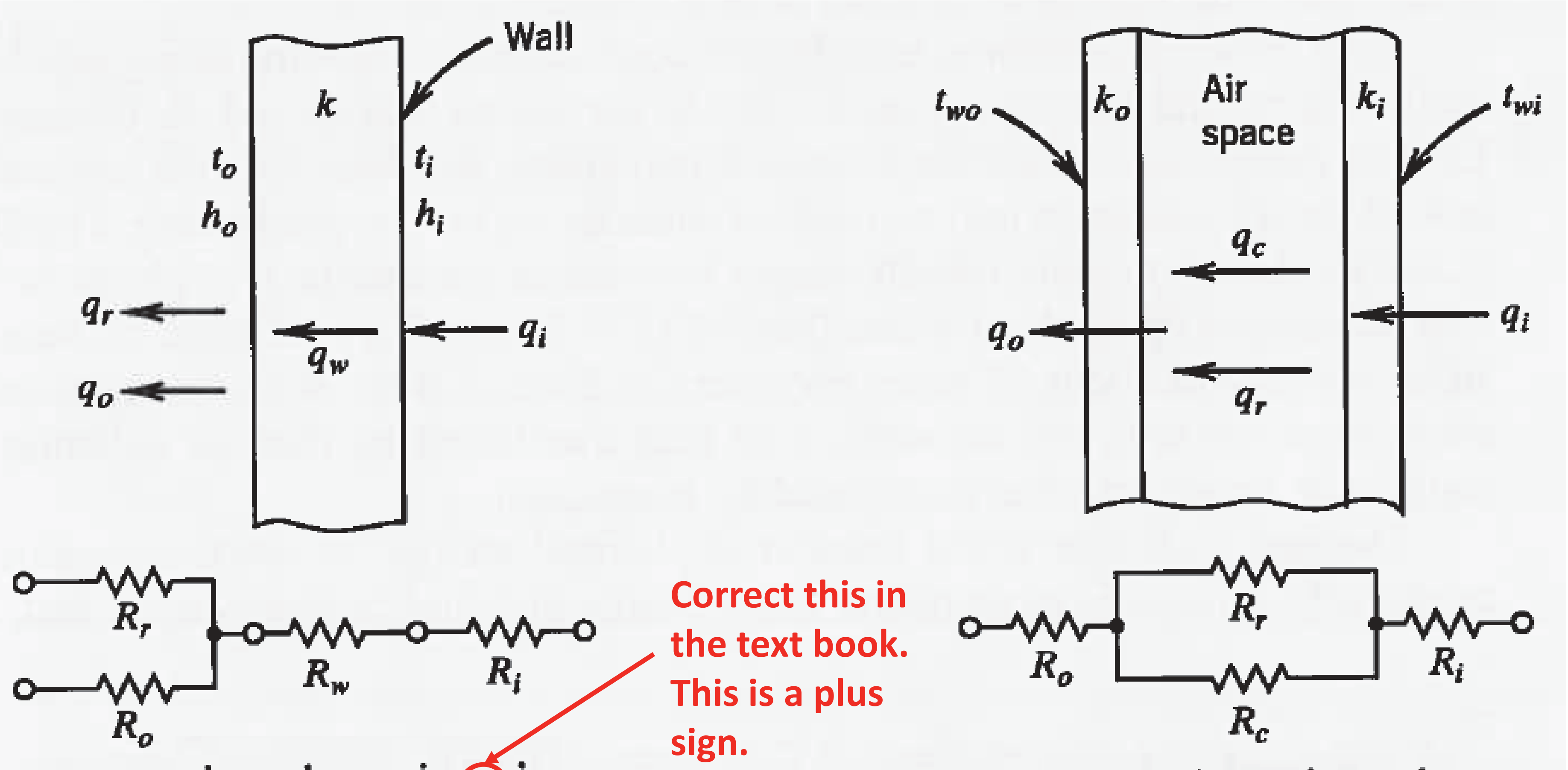
ε = emittance of surface 1 or surface 2

A = surface area, ft^2 or m^2

F = configuration factor, a function of geometry only

The **emissivity** is the relative ability of its surface to emit energy by radiation. A true black body would have an $\varepsilon = 1$ while any real object would have $\varepsilon < 1$.

It is assumed that both surfaces are "gray" (where the emittance ε = absorptance α)



Correct this in the text book. This is a plus sign.

$$\dot{q}_i = \dot{q}_w = \dot{q}_r + \dot{q}_o$$

$$\dot{q}_i = \dot{q}_r + \dot{q}_c = \dot{q}_o$$

Figure 5-3 Wall and air space, illustrating thermal radiation effects.

Thermal resistance of air spaces

- The thermal resistance for radiation is not easily computed because of the fourth power temperature relationship

- Theory and experiment have been combined to develop combined or effective unit thermal resistances and unit thermal conductances for many typical surfaces and air spaces.

- Tables on next slides show surface film coefficients and unit thermal resistances as a function of wall position, direction of heat flow, air velocity, and surface emittance for exposed surfaces such as outside walls.

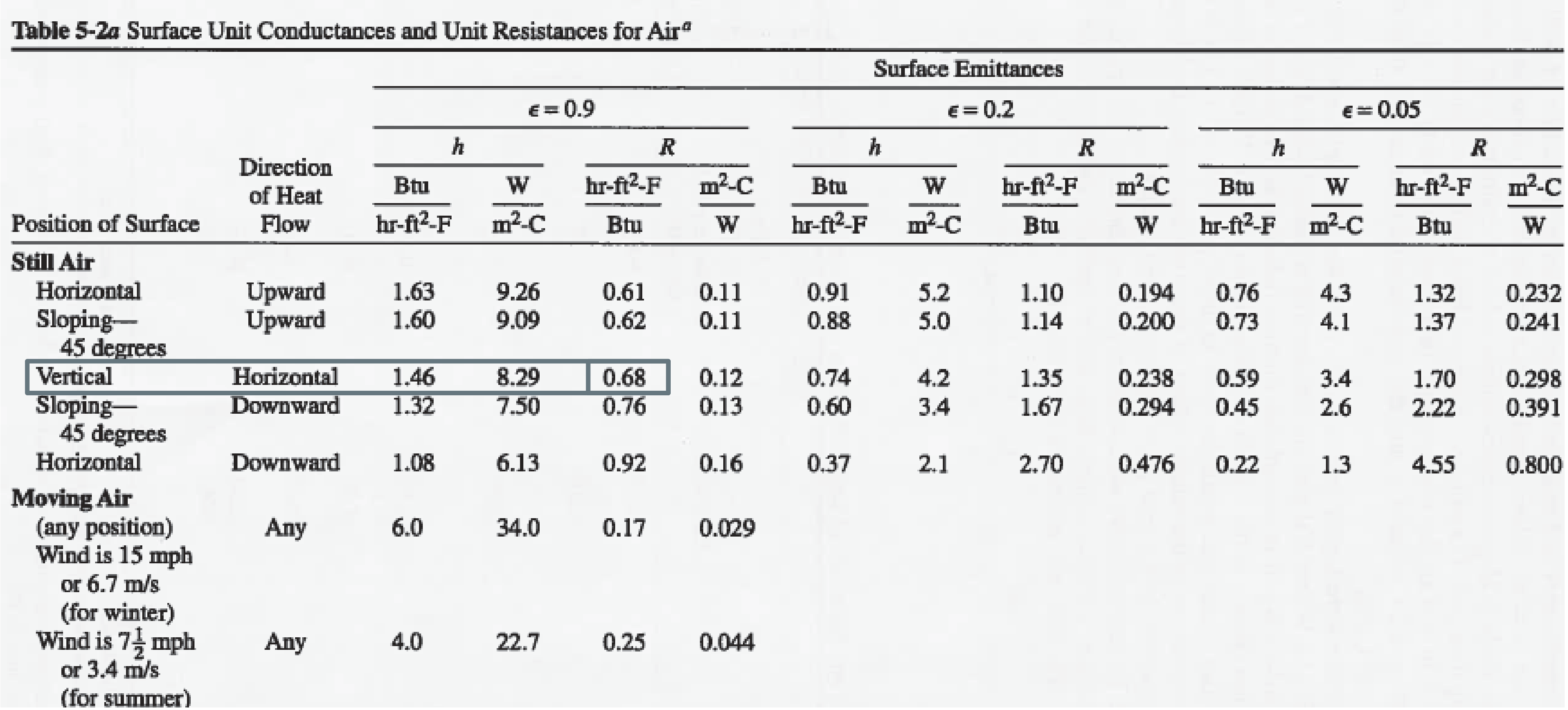


Table 5-2a Surface Unit Conductances and Unit Resistances for Air[a]

		Surface Emittances											
		$\epsilon = 0.9$				$\epsilon = 0.2$				$\epsilon = 0.05$			
		h		R		h		R		h		R	
Position of Surface	Direction of Heat Flow	$\frac{Btu}{hr\text{-}ft^2\text{-}F}$	$\frac{W}{m^2\text{-}C}$	$\frac{hr\text{-}ft^2\text{-}F}{Btu}$	$\frac{m^2\text{-}C}{W}$	$\frac{Btu}{hr\text{-}ft^2\text{-}F}$	$\frac{W}{m^2\text{-}C}$	$\frac{hr\text{-}ft^2\text{-}F}{Btu}$	$\frac{m^2\text{-}C}{W}$	$\frac{Btu}{hr\text{-}ft^2\text{-}F}$	$\frac{W}{m^2\text{-}C}$	$\frac{hr\text{-}ft^2\text{-}F}{Btu}$	$\frac{m^2\text{-}C}{W}$
Still Air													
Horizontal	Upward	1.63	9.26	0.61	0.11	0.91	5.2	1.10	0.194	0.76	4.3	1.32	0.232
Sloping—45 degrees	Upward	1.60	9.09	0.62	0.11	0.88	5.0	1.14	0.200	0.73	4.1	1.37	0.241
Vertical	Horizontal	1.46	8.29	0.68	0.12	0.74	4.2	1.35	0.238	0.59	3.4	1.70	0.298
Sloping—45 degrees	Downward	1.32	7.50	0.76	0.13	0.60	3.4	1.67	0.294	0.45	2.6	2.22	0.391
Horizontal	Downward	1.08	6.13	0.92	0.16	0.37	2.1	2.70	0.476	0.22	1.3	4.55	0.800
Moving Air													
(any position) Wind is 15 mph or 6.7 m/s (for winter)	Any	6.0	34.0	0.17	0.029								
Wind is 7½ mph or 3.4 m/s (for summer)	Any	4.0	22.7	0.25	0.044								

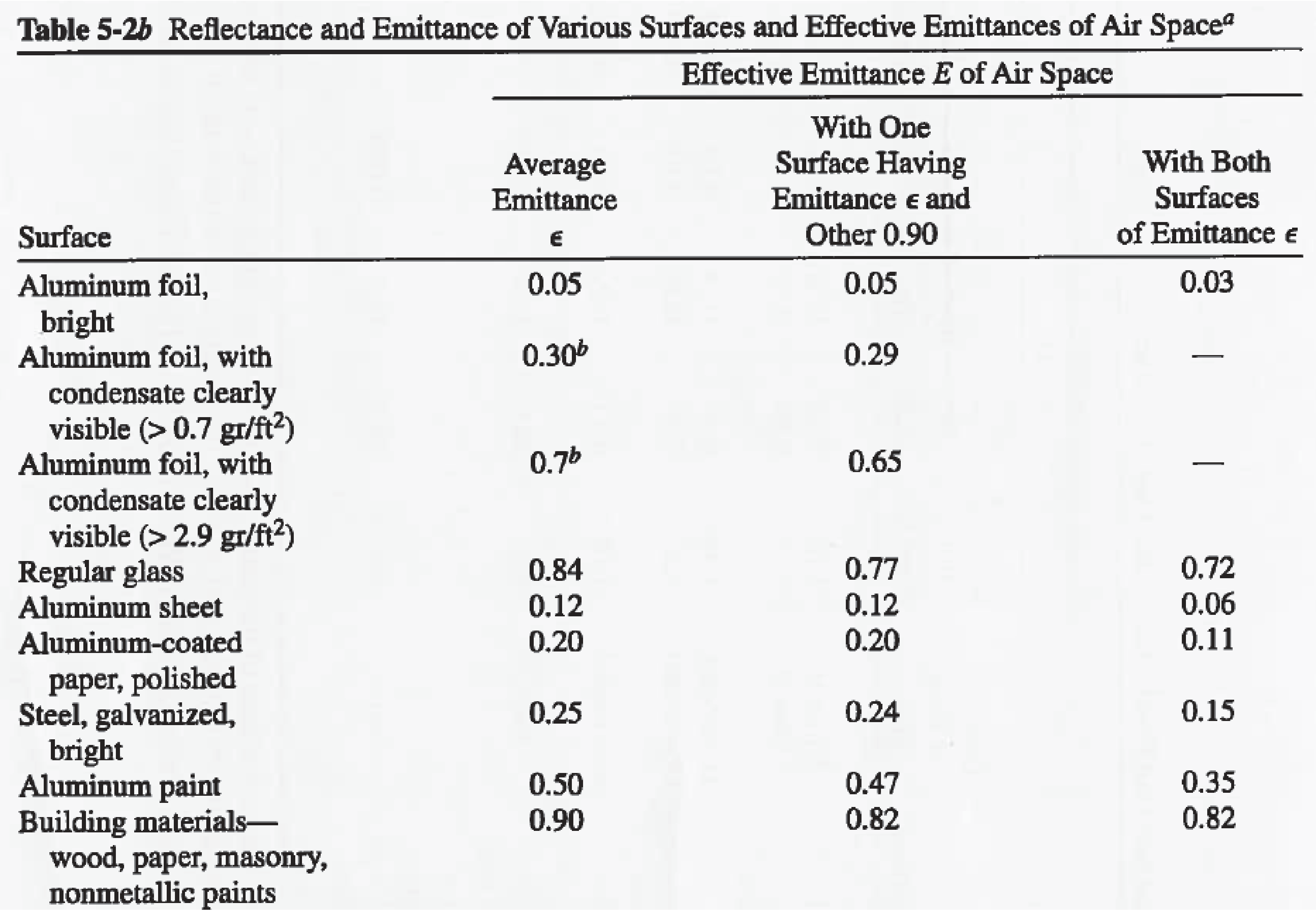


Table 5-2*b* Reflectance and Emittance of Various Surfaces and Effective Emittances of Air Space[a]

		Effective Emittance E of Air Space	
Surface	Average Emittance ϵ	With One Surface Having Emittance ϵ and Other 0.90	With Both Surfaces of Emittance ϵ
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil, with condensate clearly visible (> 0.7 gr/ft^2)	0.30[b]	0.29	—
Aluminum foil, with condensate clearly visible (> 2.9 gr/ft^2)	0.7[b]	0.65	—
Regular glass	0.84	0.77	0.72
Aluminum sheet	0.12	0.12	0.06
Aluminum-coated paper, polished	0.20	0.20	0.11
Steel, galvanized, bright	0.25	0.24	0.15
Aluminum paint	0.50	0.47	0.35
Building materials—wood, paper, masonry, nonmetallic paints	0.90	0.82	0.82

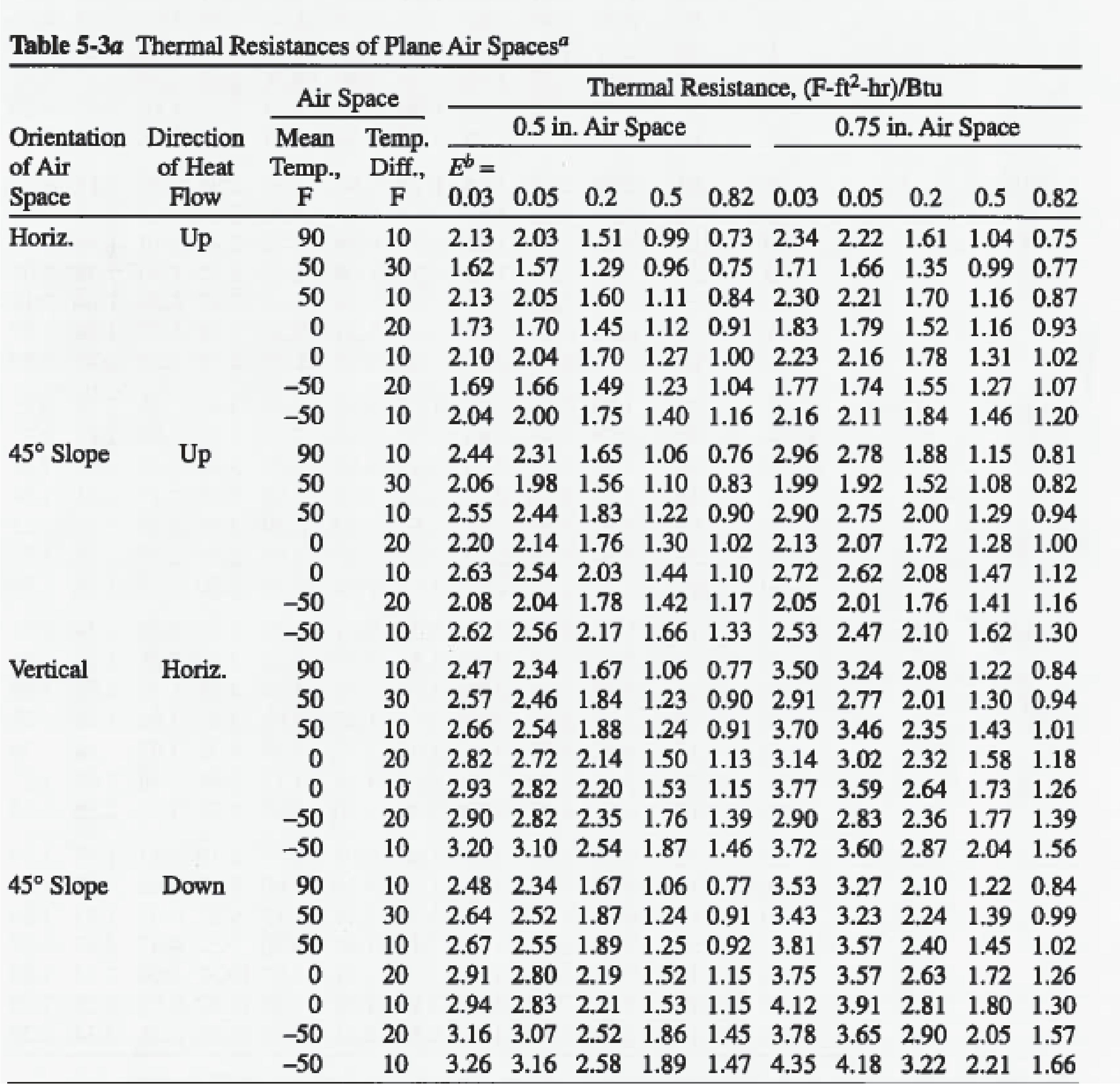
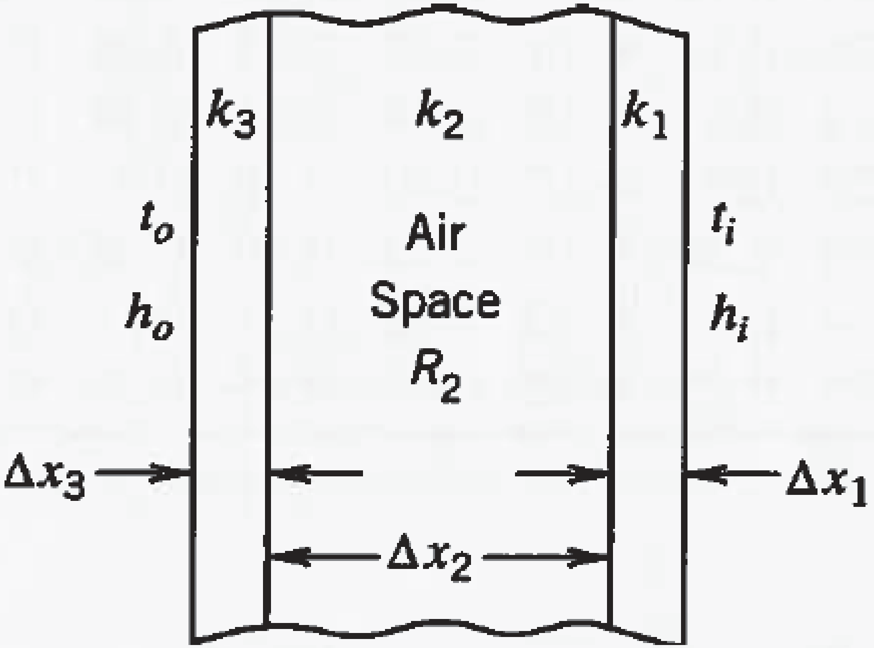


Table 5-3a Thermal Resistances of Plane Air Spaces[a]

Orientation of Air Space	Direction of Heat Flow	Air Space Mean Temp., F	Air Space Temp. Diff., F	0.5 in. Air Space E[b] = 0.03	0.5 in. 0.05	0.5 in. 0.2	0.5 in. 0.5	0.5 in. 0.82	0.75 in. Air Space 0.03	0.75 in. 0.05	0.75 in. 0.2	0.75 in. 0.5	0.75 in. 0.82
Horiz.	Up	90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
		0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		–50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		–50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
45° Slope	Up	90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
		0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		–50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		–50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
Vertical	Horiz.	90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
		0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		–50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		–50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
45° Slope	Down	90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
		0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		–50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		–50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66

Thermal Resistance, (F-ft^2-hr)/Btu

Wall with thermal resistances in series

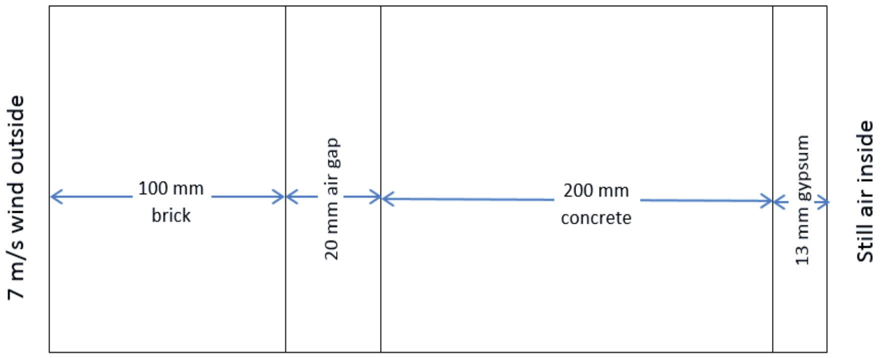


$$R_e' = \frac{1}{h_i A_i} + \frac{\Delta x_1}{k_1 A_1} + \frac{R_2}{A_2} + \frac{\Delta x_3}{k_3 A_3} + \frac{1}{h_0 A_0}$$

- The film coefficients may be read from Table *5-2a,* the thermal conductivities from Tables 5-1, and the thermal resistance for the air space from Tables *5-3.*
- For this case of a plane wall, the areas are all equal.

Ex 5-9

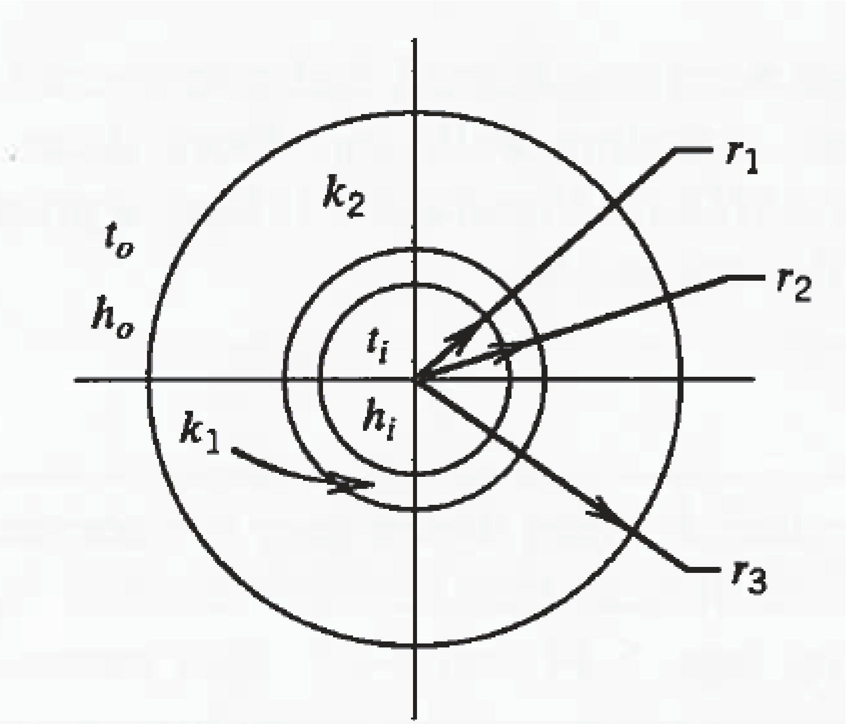
Compute the overall thermal resistance of a wall made up of 100 mm brick and 200 mm normal weight concrete block with a 20 mm air gap in between. There is 13 mm of gypsum plaster on the inside. Assume a 7 m/s wind velocity on the outside an still air inside.



Layer	R –– $(m^2 – C) / W$
Outside Surface (7 m/s)	0.029
Brick Venur (100 mm)	0.112
Air Space (20 mm)	0.180
Concrete Block (200 mm)	0.183
Gypsum Plaster (13 mm)	0.057
Inside Surface	0.120

Overall Thermal Resis. = 0.681 m^2C / W

Pipe with thermal insulation



$$R'_e = \frac{1}{h_o A_o} + \frac{In\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L} + \frac{In\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L} + \frac{1}{h_i A_i}$$

Resistances in parallel

- Thermal resistances may also occur in parallel
- Parallel thermal resistances can be combined together into an equivalent thermal resistances the same way as electrical resistances

$$\frac{1}{R'_e} = \frac{1}{R'_1} + \frac{1}{R'_2} + \frac{1}{R'_3} + \ldots + \frac{1}{R'_n}$$

Thermal bridge

- A large variation in the thermal resistance of parallel conduction paths is called a *thermal bridge*

- A *thermal bridge* is defined in the *ASHRAE Handbook* as an envelope area with a significantly higher rate of heat transfer than the contiguous enclosure

- A steel column in an insulated wall is an example of such a bridge, since the resistance for heat transfer through the part of the wall containing the column is much less than that of the wall containing only insulation

Two detrimental effects of thermal bridges

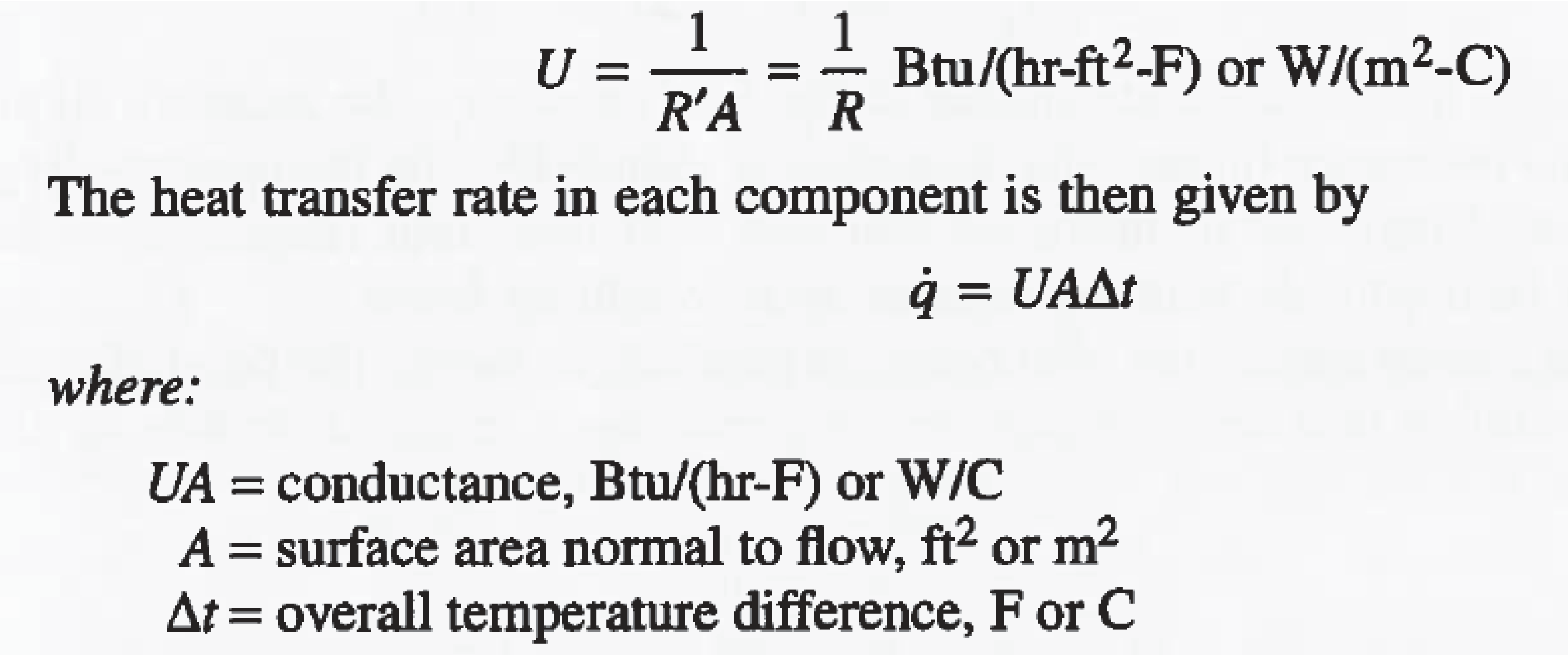
(i) They increase heat gain or loss, and
(ii) They can cause condensation inside or on the envelope surface

These effects can be significant in the building's energy cost or damage done to the building structure by moisture.

Methods to mitigate the effects of thermal bridging:

(i) Use of lower-thermal-conductivity bridging material,
(ii) Changing the geometry or construction system, and
(iii) Putting an insulating sheath around the bridge.

Overall heat transfer coefficient



$$U = \frac{1}{R'A} = \frac{1}{R} \text{ Btu/(hr-ft}^2\text{-F) or W/(m}^2\text{-C)}$$

The heat transfer rate in each component is then given by

$$\dot{q} = UA\Delta t$$

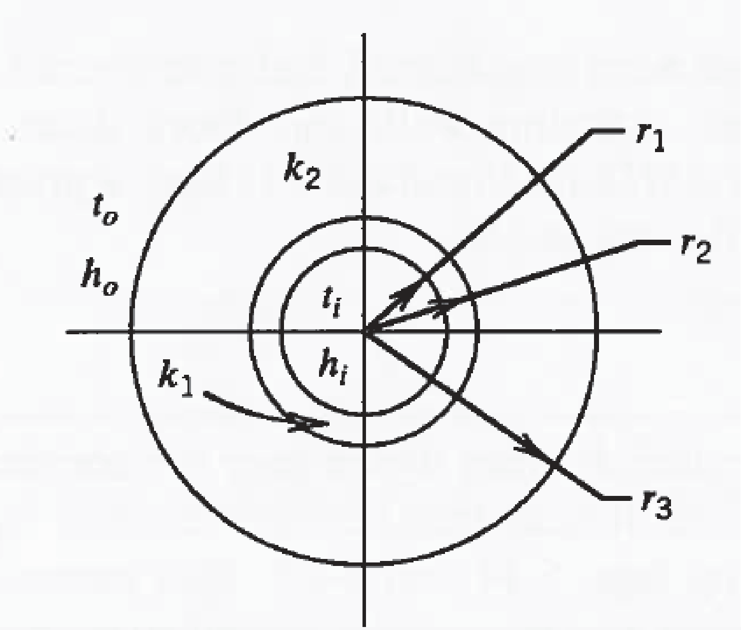
where:

UA = conductance, Btu/(hr-F) or W/C
A = surface area normal to flow, ft^2 or m^2
Δt = overall temperature difference, F or C

Note: Values in Table 5-4 are incorrect.

Ex 5-8

The pipe of Ex 5-5 has water flowing inside with a heat-transfer coefficient of 650 Btu/(hr-ft^2-F) and is exposed to air on the outside with a film coefficient of 1.5 Btu/(hr-ft^2-F). Compute the overall heat-transfer coefficient based on the outer area.



$$R'_e = \frac{1}{h_o A_o} + \frac{In\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L} + \frac{In\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L} + \frac{1}{h_i A_i}$$

Tabulated overall heat transfer coefficients

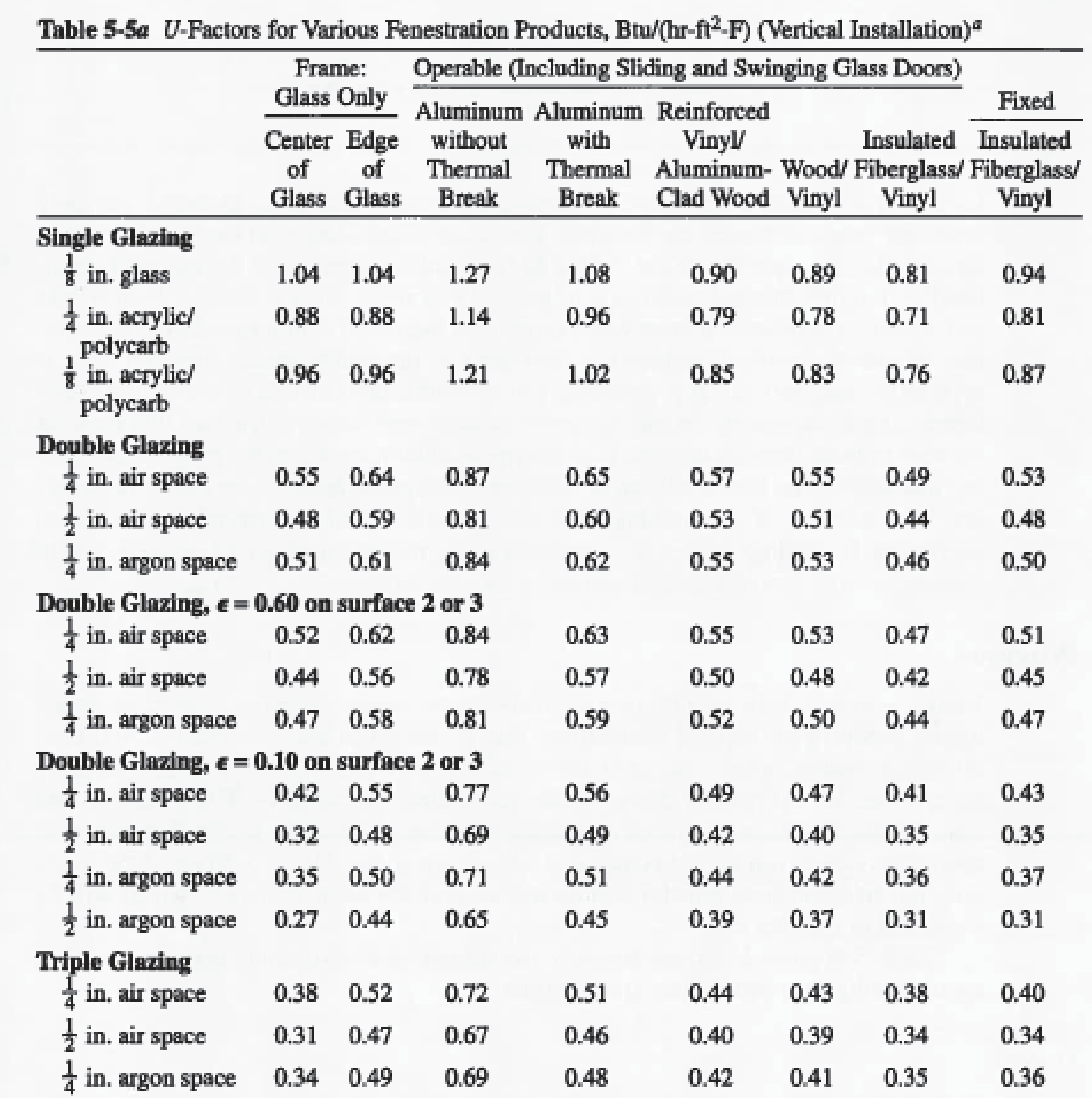


Table 5-5a *U*-Factors for Various Fenestration Products, Btu/(hr-ft^2-F) (Vertical Installation)[a]

	Frame: Glass Only		Operable (Including Sliding and Swinging Glass Doors)					Fixed
	Center of Glass	Edge of Glass	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum-Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Insulated Fiberglass/ Vinyl
Single Glazing								
$\frac{1}{8}$ in. glass	1.04	1.04	1.27	1.08	0.90	0.89	0.81	0.94
$\frac{1}{4}$ in. acrylic/polycarb	0.88	0.88	1.14	0.96	0.79	0.78	0.71	0.81
$\frac{1}{8}$ in. acrylic/polycarb	0.96	0.96	1.21	1.02	0.85	0.83	0.76	0.87
Double Glazing								
$\frac{1}{4}$ in. air space	0.55	0.64	0.87	0.65	0.57	0.55	0.49	0.53
$\frac{1}{2}$ in. air space	0.48	0.59	0.81	0.60	0.53	0.51	0.44	0.48
$\frac{1}{4}$ in. argon space	0.51	0.61	0.84	0.62	0.55	0.53	0.46	0.50
Double Glazing, $\epsilon = 0.60$ on surface 2 or 3								
$\frac{1}{4}$ in. air space	0.52	0.62	0.84	0.63	0.55	0.53	0.47	0.51
$\frac{1}{2}$ in. air space	0.44	0.56	0.78	0.57	0.50	0.48	0.42	0.45
$\frac{1}{4}$ in. argon space	0.47	0.58	0.81	0.59	0.52	0.50	0.44	0.47
Double Glazing, $\epsilon = 0.10$ on surface 2 or 3								
$\frac{1}{4}$ in. air space	0.42	0.55	0.77	0.56	0.49	0.47	0.41	0.43
$\frac{1}{2}$ in. air space	0.32	0.48	0.69	0.49	0.42	0.40	0.35	0.35
$\frac{1}{4}$ in. argon space	0.35	0.50	0.71	0.51	0.44	0.42	0.36	0.37
$\frac{1}{2}$ in. argon space	0.27	0.44	0.65	0.45	0.39	0.37	0.31	0.31
Triple Glazing								
$\frac{1}{4}$ in. air space	0.38	0.52	0.72	0.51	0.44	0.43	0.38	0.40
$\frac{1}{2}$ in. air space	0.31	0.47	0.67	0.46	0.40	0.39	0.34	0.34
$\frac{1}{4}$ in. argon space	0.34	0.49	0.69	0.48	0.42	0.41	0.35	0.36

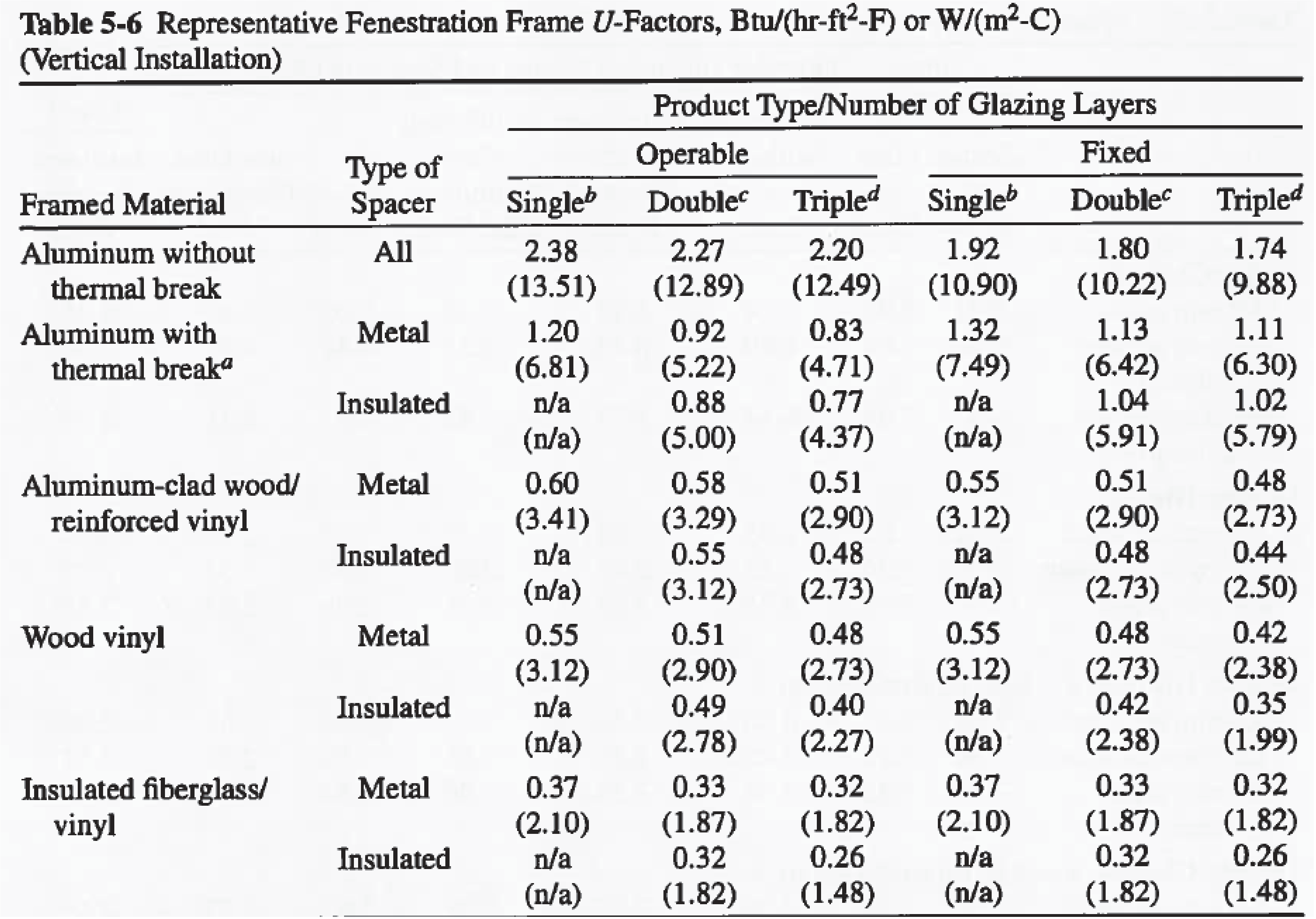


Table 5-6 Representative Fenestration Frame *U*-Factors, Btu/(hr-ft^2-F) or W/(m^2-C) (Vertical Installation)

		Product Type/Number of Glazing Layers					
		Operable			Fixed		
Framed Material	Type of Spacer	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Triple[d]
Aluminum without thermal break	All	2.38 (13.51)	2.27 (12.89)	2.20 (12.49)	1.92 (10.90)	1.80 (10.22)	1.74 (9.88)
Aluminum with thermal break[a]	Metal	1.20 (6.81)	0.92 (5.22)	0.83 (4.71)	1.32 (7.49)	1.13 (6.42)	1.11 (6.30)
	Insulated	n/a (n/a)	0.88 (5.00)	0.77 (4.37)	n/a (n/a)	1.04 (5.91)	1.02 (5.79)
Aluminum-clad wood/ reinforced vinyl	Metal	0.60 (3.41)	0.58 (3.29)	0.51 (2.90)	0.55 (3.12)	0.51 (2.90)	0.48 (2.73)
	Insulated	n/a (n/a)	0.55 (3.12)	0.48 (2.73)	n/a (n/a)	0.48 (2.73)	0.44 (2.50)
Wood vinyl	Metal	0.55 (3.12)	0.51 (2.90)	0.48 (2.73)	0.55 (3.12)	0.48 (2.73)	0.42 (2.38)
	Insulated	n/a (n/a)	0.49 (2.78)	0.40 (2.27)	n/a (n/a)	0.42 (2.38)	0.35 (1.99)
Insulated fiberglass/ vinyl	Metal	0.37 (2.10)	0.33 (1.87)	0.32 (1.82)	0.37 (2.10)	0.33 (1.87)	0.32 (1.82)
	Insulated	n/a (n/a)	0.32 (1.82)	0.26 (1.48)	n/a (n/a)	0.32 (1.82)	0.26 (1.48)

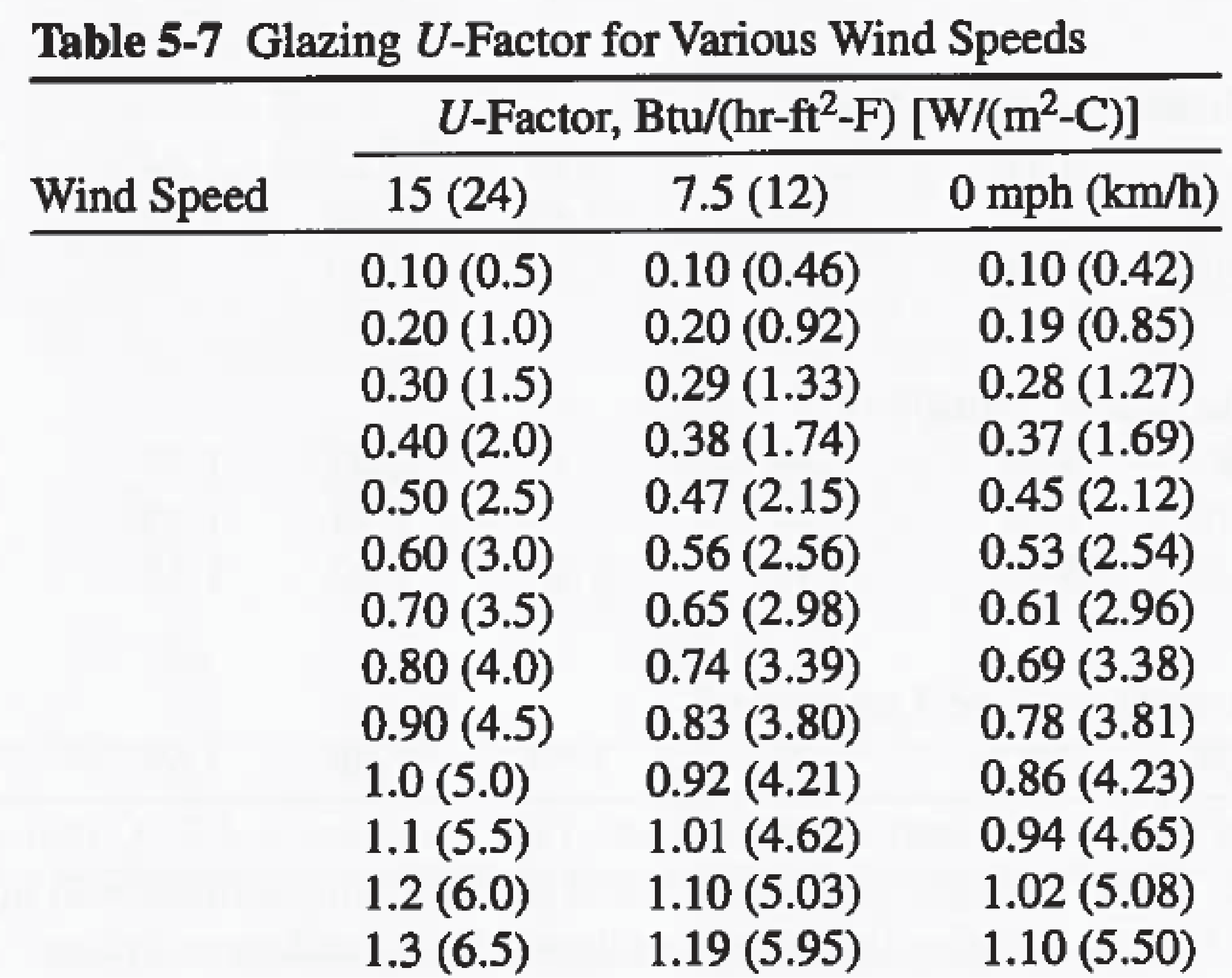


Table 5-7 Glazing *U*-Factor for Various Wind Speeds

	U-Factor, Btu/(hr-ft^2-F) [W/(m^2-C)]		
Wind Speed	15 (24)	7.5 (12)	0 mph (km/h)
	0.10 (0.5)	0.10 (0.46)	0.10 (0.42)
	0.20 (1.0)	0.20 (0.92)	0.19 (0.85)
	0.30 (1.5)	0.29 (1.33)	0.28 (1.27)
	0.40 (2.0)	0.38 (1.74)	0.37 (1.69)
	0.50 (2.5)	0.47 (2.15)	0.45 (2.12)
	0.60 (3.0)	0.56 (2.56)	0.53 (2.54)
	0.70 (3.5)	0.65 (2.98)	0.61 (2.96)
	0.80 (4.0)	0.74 (3.39)	0.69 (3.38)
	0.90 (4.5)	0.83 (3.80)	0.78 (3.81)
	1.0 (5.0)	0.92 (4.21)	0.86 (4.23)
	1.1 (5.5)	1.01 (4.62)	0.94 (4.65)
	1.2 (6.0)	1.10 (5.03)	1.02 (5.08)
	1.3 (6.5)	1.19 (5.95)	1.10 (5.50)

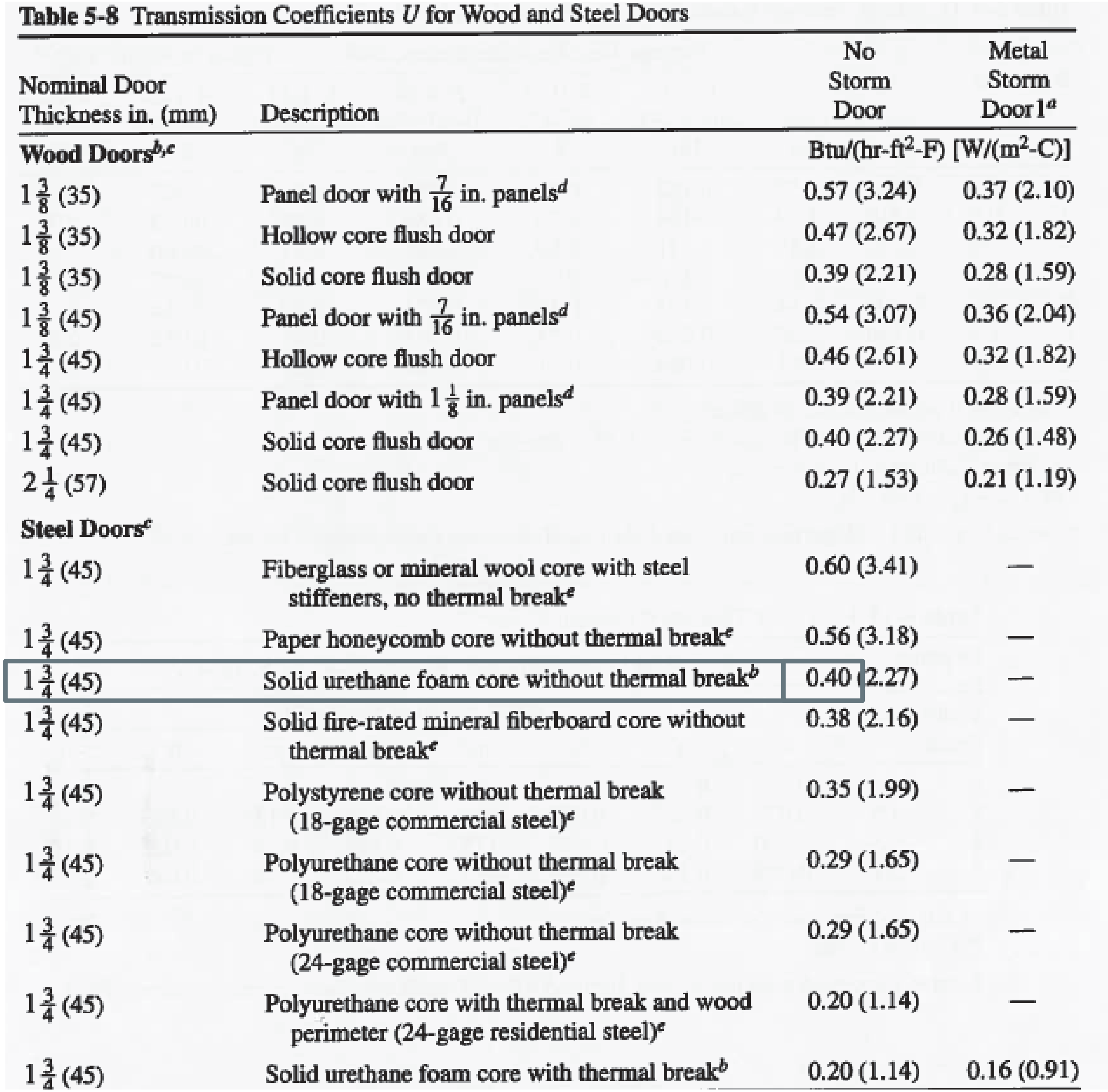


Table 5-8 Transmission Coefficients *U* for Wood and Steel Doors

Nominal Door Thickness in. (mm)	Description	No Storm Door	Metal Storm Door 1[a]
Wood Doors[b,c]		Btu/(hr-ft^2-F) [W/(m^2-C)]	
$1\frac{3}{8}$ (35)	Panel door with $\frac{7}{16}$ in. panels[d]	0.57 (3.24)	0.37 (2.10)
$1\frac{3}{8}$ (35)	Hollow core flush door	0.47 (2.67)	0.32 (1.82)
$1\frac{3}{8}$ (35)	Solid core flush door	0.39 (2.21)	0.28 (1.59)
$1\frac{3}{8}$ (45)	Panel door with $\frac{7}{16}$ in. panels[d]	0.54 (3.07)	0.36 (2.04)
$1\frac{3}{4}$ (45)	Hollow core flush door	0.46 (2.61)	0.32 (1.82)
$1\frac{3}{4}$ (45)	Panel door with $1\frac{1}{8}$ in. panels[d]	0.39 (2.21)	0.28 (1.59)
$1\frac{3}{4}$ (45)	Solid core flush door	0.40 (2.27)	0.26 (1.48)
$2\frac{1}{4}$ (57)	Solid core flush door	0.27 (1.53)	0.21 (1.19)
Steel Doors[c]			
$1\frac{3}{4}$ (45)	Fiberglass or mineral wool core with steel stiffeners, no thermal break[e]	0.60 (3.41)	—
$1\frac{3}{4}$ (45)	Paper honeycomb core without thermal break[e]	0.56 (3.18)	—
$1\frac{3}{4}$ (45)	Solid urethane foam core without thermal break[b]	0.40 (2.27)	—
$1\frac{3}{4}$ (45)	Solid fire-rated mineral fiberboard core without thermal break[e]	0.38 (2.16)	—
$1\frac{3}{4}$ (45)	Polystyrene core without thermal break (18-gage commercial steel)[e]	0.35 (1.99)	—
$1\frac{3}{4}$ (45)	Polyurethane core without thermal break (18-gage commercial steel)[e]	0.29 (1.65)	—
$1\frac{3}{4}$ (45)	Polyurethane core without thermal break (24-gage commercial steel)[e]	0.29 (1.65)	—
$1\frac{3}{4}$ (45)	Polyurethane core with thermal break and wood perimeter (24-gage residential steel)[e]	0.20 (1.14)	—
$1\frac{3}{4}$ (45)	Solid urethane foam core with thermal break[b]	0.20 (1.14)	0.16 (0.91)
]

Ex 5-16

A wall is 20 ft wide and 8 ft high and has an overall heat-transfer coefficient of 0.07 Btu/(hr-ft^2-F). It contains a solid urethane foam core steel door, 80 x 32 x 1¾ in., and a double glass window,120 x 30 in. The window is metal sash with no thermal break [U = 0.81 Btu/(hr-ft^2-F)]. Assuming parallel heat-flow paths for the wall, door, and window, find the overall thermal resistance and overall heat-transfer coefficient for the combination with respect to the wall area. Assume winter conditions.