

THERMAL AND WATER VAPOR TRANSMISSION DATA

Building Envelopes	25.1
Calculating Overall Thermal Resistances	25.2
Mechanical and Industrial Systems	25.15
Calculating Heat Flow for Buried Pipelines	25.20

THIS CHAPTER presents thermal and water vapor transmission data based on steady-state or equilibrium conditions. [Chapter 3](#) covers heat transfer under transient or changing temperature conditions. [Chapter 23](#) discusses selection of insulation materials and procedures for determining overall thermal resistances by simplified methods.

BUILDING ENVELOPES

Thermal Transmission Data for Building Components

The steady-state thermal resistances (R-values) of building components (walls, floors, windows, roof systems, etc.) can be calculated from the thermal properties of the materials in the component; or the heat flow through the assembled component can be measured directly with laboratory equipment such as the guarded hot box (ASTM *Standard C 236*) or the calibrated hot box (ASTM *Standard C 976*).

[Tables 1](#) through [6](#) list thermal values, which may be used to calculate thermal resistances of building walls, floors, and ceilings. The values shown in these tables were developed under ideal conditions. In practice, overall thermal performance can be reduced significantly by such factors as improper installation and shrinkage, settling, or compression of the insulation (Tye and Desjarlais 1983; Tye 1985, 1986).

Most values in these tables were obtained by accepted ASTM test methods described in ASTM *Standards C 177* and *C 518* for materials and ASTM *Standards C 236* and *C 976* for building envelope components. Because commercially available materials vary, not all values apply to specific products.

The most accurate method of determining the overall thermal resistance for a combination of building materials assembled as a building envelope component is to test a representative sample by a hot box method. However, all combinations may not be conveniently or economically tested in this manner. For many simple constructions, calculated R-values agree reasonably well with values determined by hot box measurement.

The performance of materials fabricated in the field is especially subject to the quality of workmanship during construction and installation. Good workmanship becomes increasingly important as the insulation requirement becomes greater. Therefore, some engineers include additional insulation or other safety factors based on experience in their design.

[Figure 1](#) shows how convection affects surface conductance of several materials. Other tests on smooth surfaces show that the average value of the convection part of the surface conductance decreases as the length of the surface increases.

Vapor retarders, which are discussed in [Chapters 23](#) and [24](#), require special attention. Moisture from condensation or other

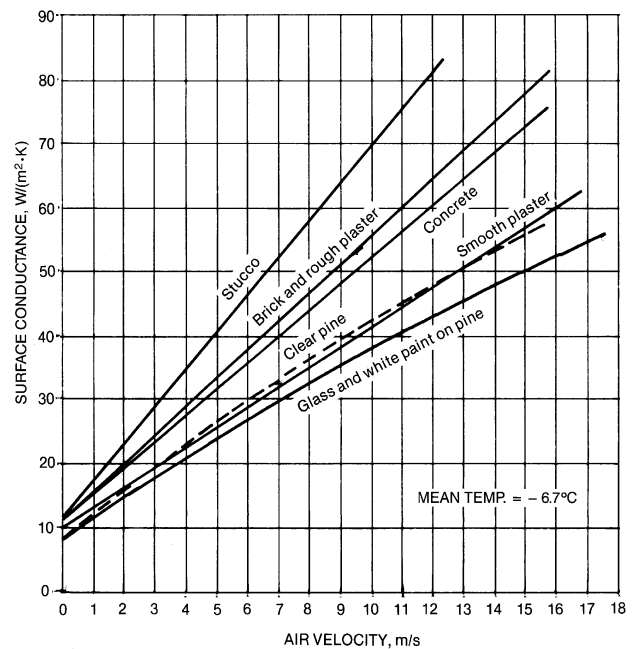


Fig. 1 Surface Conductance for Different Surfaces as Affected by Air Movement

sources may reduce the thermal resistance of insulation, but the effect of moisture must be determined for each material. For example, some materials with large air spaces are not affected significantly if the moisture content is less than 10% by mass, while the effect of moisture on other materials is approximately linear.

Ideal conditions of components and installations are assumed in calculating overall R-values (i.e., insulating materials are of uniform nominal thickness and thermal resistance, air spaces are of uniform thickness and surface temperature, moisture effects are not involved, and installation details are in accordance with design). The National Institute of Standards and Technology Building Materials and Structures Report BMS 151 shows that measured values differ from calculated values for certain insulated constructions. For this reason, some engineers decrease the calculated R-values a moderate amount to account for departures of constructions from requirements and practices.

[Tables 3](#) and [2](#) give values for well-sealed systems constructed with care. Field applications can differ substantially from laboratory test conditions. Air gaps in these insulation systems can seriously degrade thermal performance as a result of air movement due to both natural and forced convection. Sabine et al. (1975) found that the tabular values are not necessarily additive for multiple-layer, low-emittance air spaces, and tests on actual constructions should be conducted to accurately determine thermal resistance values.

The preparation of this chapter is assigned to TC 4.4, Thermal Insulation and Moisture Retarders.

Table 1 Surface Conductances and Resistances for Air

Position of Surface	Direction of Heat Flow	Surface Emittance, ε					
		Non-reflective		Reflective			
		$\varepsilon = 0.90$		$\varepsilon = 0.20$		$\varepsilon = 0.05$	
		h_i	R	h_i	R	h_i	R
STILL AIR							
Horizontal	Upward	9.26	0.11	5.17	0.19	4.32	0.23
Sloping—45°	Upward	9.09	0.11	5.00	0.20	4.15	0.24
Vertical	Horizontal	8.29	0.12	4.20	0.24	3.35	0.30
Sloping—45°	Downward	7.50	0.13	3.41	0.29	2.56	0.39
Horizontal	Downward	6.13	0.16	2.10	0.48	1.25	0.80
MOVING AIR (Any position)		h_o	R				
Wind (for winter)	Any	34.0	0.030	—	—	—	—
6.7 m/s (24 km/h)							
Wind (for summer)	Any	22.7	0.044	—	—	—	—
3.4 m/s (12 km/h)							

Notes:

1. Surface conductance h_i and h_o measured in $W/(m^2 \cdot K)$; resistance R in $m^2 \cdot K/W$.
2. No surface has both an air space resistance value and a surface resistance value.
3. For ventilated attics or spaces above ceilings under summer conditions (heat flow down), see [Table 5](#).
4. 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 5.5 K and for surface temperatures of 21°C.
5. See [Chapter 3](#) for more detailed information, especially [Tables 5](#) and [6](#), and see [Figure 1](#) for additional data.
6. Condensate can have a significant impact on surface emittance (see [Table 2](#)).

Values for foil insulation products supplied by manufacturers must also be used with caution because they apply only to systems that are identical to the configuration in which the product was tested. In addition, surface oxidation, dust accumulation, condensation, and other factors that change the condition of the low-emittance surface can reduce the thermal effectiveness of these insulation systems (Hooper and Moroz 1952). Deterioration results from contact with several types of solutions, either acidic or basic (e.g., wet cement mortar or the preservatives found in decay-resistant lumber). Polluted environments may cause rapid and severe material degradation. However, site inspections show a predominance of well-preserved installations and only a small number of cases in which rapid and severe deterioration has occurred. An extensive review of the reflective building insulation system performance literature is provided by Goss and Miller (1989).

CALCULATING OVERALL THERMAL RESISTANCES

Relatively small, highly conductive elements in an insulating layer called thermal bridges can substantially reduce the average thermal resistance of a component. Examples include wood and metal studs in frame walls, concrete webs in concrete masonry walls, and metal ties or other elements in insulated wall panels. The following examples illustrate the calculation of R-values and U-factors for components containing thermal bridges.

The following conditions are assumed in calculating the design R-values:

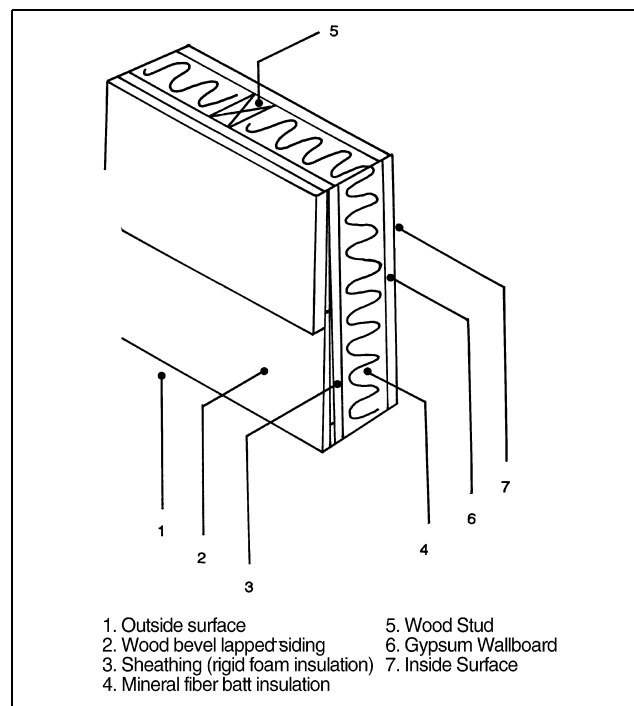
- Equilibrium or steady-state heat transfer, disregarding effects of thermal storage
- Surrounding surfaces at ambient air temperature
- Exterior wind velocity of 6.7 m/s (24 km/h) for winter (surface with $R = 0.03 m^2 \cdot K/W$) and 3.4 m/s (12 km/h) for summer (surface with $R = 0.044 m^2 \cdot K/W$)
- Surface emittance of ordinary building materials is 0.90

Table 2 Emittance Values of Various Surfaces and Effective Emittances of Air Spaces^a

Surface	Average Emittance ε	Effective Emittance ε_{eff} of Air Space	
		One Surface Emittance ε ; Other, 0.9	Both Surfaces Emittance ε
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil, with condensate just visible ($> 0.5 g/m^2$)	0.30 ^b	0.29	—
Aluminum foil, with condensate clearly visible ($> 2.0 g/m^2$)	0.70 ^b	0.65	—
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
Regular glass	0.84	0.77	0.72

^aThese values apply in the 4 to 40 μm range of the electromagnetic spectrum.

^bValues are based on data presented by Bassett and Trethowen (1984).

**Fig. 2 Insulated Wood Frame Wall (Example 1)**

Wood Frame Walls

The average overall R-values and U-factors of wood frame walls can be calculated by assuming either parallel heat flow paths through areas with different thermal resistances or by assuming isothermal planes. Equations (1) through (5) from [Chapter 23](#) are used.

The framing factor or fraction of the building component that is framing depends on the specific type of construction, and it may vary based on local construction practices—even for the same type of construction. For stud walls 400 mm on center (OC), the fraction of insulated cavity may be as low as 0.75, where the fraction of studs, plates, and sills is 0.21 and the fraction of headers is 0.04. For studs 600 mm OC, the respective values are 0.78, 0.18, and 0.04.

These fractions contain an allowance for multiple studs, plates, sills, extra framing around windows, headers, and band joists. These assumed framing fractions are used in the following example, to illustrate the importance of including the effect of framing in determining the overall thermal conductance of a building. The actual framing fraction should be calculated for each specific construction.

Example 1. Calculate the U-factor of the 38 mm by 90 mm stud wall shown in Figure 2. The studs are at 400 mm OC. There is 90 mm mineral fiber batt insulation ($R = 2.3 \text{ m}^2 \cdot \text{K}/\text{W}$) in the stud space. The inside finish is 13 mm gypsum wallboard; the outside is finished with rigid foam insulating sheathing ($R = 0.7 \text{ m}^2 \cdot \text{K}/\text{W}$) and 13 mm by 200 mm wood bevel lapped siding. The insulated cavity occupies approximately 75% of the transmission area; the studs, plates, and sills occupy 21%; and the headers occupy 4%.

Solution: Obtain the R-values of the various building elements from Tables 1 and 4. Assume $R = 7.0 \text{ m}^2 \cdot \text{K}/\text{W}$ for the wood framing. Also, assume the headers are solid wood, in this case, and group them with the studs, plates, and sills.

Because the U-factor is the reciprocal of R-value, $U_1 = 0.297 \text{ W}/(\text{m}^2 \cdot \text{K})$ and $U_2 = 0.588 \text{ W}/(\text{m}^2 \cdot \text{K})$.

If the wood framing (thermal bridging) is not included, Equation (3) from Chapter 23 may be used to calculate the U-factor of the wall as follows:

$$U_{av} = U_1 = \frac{1}{R_1} = 0.30 \text{ W}/(\text{m}^2 \cdot \text{K})$$

Element	R (Insulated Cavity)	R (Studs, Plates, and Headers)
1. Outside surface, 24 km/h wind	0.03	0.03
2. Wood bevel lapped siding	0.14	0.14
3. Rigid foam insulating sheathing	0.70	0.70
4. Mineral fiber batt insulation	2.30	—
5. Wood stud	—	0.63
6. Gypsum wallboard	0.08	0.08
7. Inside surface, still air	0.12	0.12
	3.37	1.70

If the wood framing is accounted for using the parallel-path flow method, the U-factor of the wall is determined using Equation (5) from Chapter 23 as follows:

$$U_{av} = (0.75 \times 0.297) + (0.25 \times 0.588) = 0.37 \text{ W}/(\text{m}^2 \cdot \text{K})$$

If the wood framing is included using the isothermal planes method, the U-factor of the wall is determined using Equations (2) and (3) from Chapter 23 as follows:

$$R_{T(av)} = 4.98 + 1/[(0.75/2.30) + (0.25/0.63)] + 0.22$$

$$= 2.47 \text{ K} \cdot \text{m}^2/\text{W}$$

$$U_{av} = 0.40 \text{ W}/(\text{m}^2 \cdot \text{K})$$

For a frame wall with a 600 mm OC stud space, the average overall R-value is $0.25 \text{ m}^2 \cdot \text{K}/\text{W}$. Similar calculation procedures may be used to evaluate other wall designs, except those with thermal bridges.

Masonry Walls

The average overall R-values of masonry walls can be estimated by assuming a combination of layers in series, one or more of which provides parallel paths. This method is used because heat flows laterally through block face shells so that transverse isothermal planes result. Average total resistance $R_{T(av)}$ is the sum of the resistances of the layers between such planes, each layer calculated as shown in Example 2.

Example 2. Calculate the overall thermal resistance and average U-factor of the 194 mm thick insulated concrete block wall shown in Figure 3. The two-core block has an average web thickness of 25 mm and a face

shell thickness of 30 mm. Overall block dimensions are 194 mm by 194 mm by 395 mm. Measured thermal resistances of $1700 \text{ kg}/\text{m}^3$ concrete and $110 \text{ kg}/\text{m}^3$ expanded perlite insulation are 0.70 and $20 \text{ K} \cdot \text{m}^2/2$, respectively.

Solution: The equation used to determine the overall thermal resistance of the insulated concrete block wall is derived from Equations (2) and (5) from Chapter 23 and is given below:

$$R_{T(av)} = R_i + R_f + \left(\frac{a_w}{R_w} + \frac{a_c}{R_c} \right)^{-1} + R_o$$

where

$R_{T(av)}$ = overall thermal resistance based on assumption of isothermal planes

R_i = thermal resistance of inside air surface film (still air)

R_o = thermal resistance of outside air surface film (24 km/h wind)

R_f = total thermal resistance of face shells

R_c = thermal resistance of cores between face shells

R_w = thermal resistance of webs between face shells

a_w = fraction of total area transverse to heat flow represented by webs of blocks

a_c = fraction of total area transverse to heat flow represented by cores of blocks

From the information given and the data in Table 1, determine the values needed to compute the overall thermal resistance.

$$R_i = 0.12$$

$$R_o = 0.03$$

$$R_f = 2 \times 0.032 \times 0.70 = 0.045$$

$$R_c = (0.194 - 2 \times 0.032)(20) = 2.60$$

$$R_w = (0.194 - 2 \times 0.032)(0.70) = 0.091$$

$$a_w = 3 \times 25/395 = 0.190$$

$$a_c = 1 - 0.190 = 0.810$$

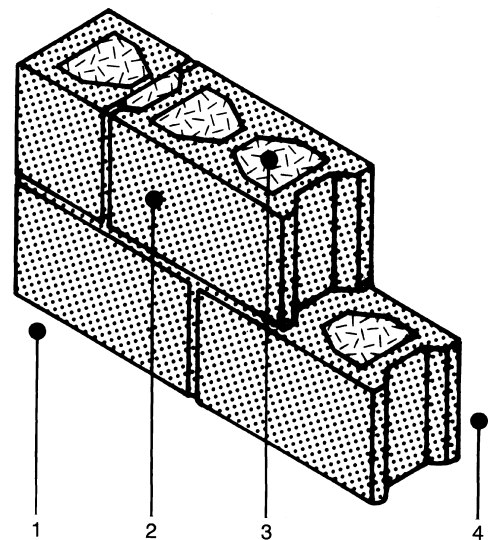
Using the equation given, the overall thermal resistance and average U-factor are calculated as follows:

$$R_{T(av)} = 0.12 + 0.045 + \frac{(0.091 \times 2.60)}{(0.810 \times 0.91) + (0.190 \times 2.60)} + 0.03$$

$$= 0.612 \text{ K} \cdot \text{m}^2/\text{W}$$

$$U_{av} = 1/0.612 = 1.63 \text{ W}/(\text{m}^2 \cdot \text{K})$$

Based on guarded hot box tests of this wall without mortar joints, Tye and Spinney (1980) measured the average R-value for this insulated concrete block wall as $0.551 \text{ m}^2 \cdot \text{K}/\text{W}$.



1. Outside surface
2. Concrete block
3. Expanded perlite insulation
4. Inside surface

Fig. 3 Insulated Concrete Block Wall (Example 2)

Table 3 Thermal Resistances of Plane Air Spaces^{a,b,c}, K·m²/W

Position of Air Space	Direction of Heat Flow	Air Space		13 mm Air Space ^c					20 mm Air Space ^c				
		Mean Temp. ^d , °C	Temp. Diff. ^d , °C	Effective Emittance $\epsilon_{eff}^{d,e}$					Effective Emittance $\epsilon_{eff}^{d,e}$				
				0.03	0.05	0.2	0.5	0.82	0.03	0.05	0.2	0.5	0.82
Horiz.	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	0.20	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
		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
45° Slope	Up 	-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
		32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
		10.0	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
Vertical	Horiz. 	-45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27
		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
		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	0.47	0.45	0.33	0.22	0.16	0.66	0.62	0.42	0.25	0.18
45° Slope	Down 	10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.68	0.63	0.42	0.26	0.18
		-17.8	11.1	0.52	0.50	0.39	0.27	0.20	0.74	0.70	0.50	0.32	0.23
		-17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.75	0.71	0.51	0.32	0.23
		-45.6	11.1	0.57	0.55	0.45	0.33	0.26	0.81	0.78	0.59	0.40	0.30
		-45.6	5.6	0.58	0.56	0.46	0.33	0.26	0.83	0.79	0.60	0.40	0.30
Horiz.	Down 	32.2	5.6	0.45	0.42	0.30	0.19	0.14	0.50	0.47	0.32	0.20	0.14
		10.0	16.7	0.33	0.32	0.26	0.18	0.14	0.27	0.35	0.28	0.19	0.15
		10.0	5.6	0.44	0.42	0.32	0.21	0.16	0.49	0.47	0.34	0.23	0.16
		-17.8	11.1	0.35	0.34	0.29	0.22	0.17	0.40	0.38	0.32	0.23	0.18
		-17.8	5.6	0.43	0.41	0.33	0.24	0.19	0.48	0.46	0.36	0.26	0.20
		-45.6	11.1	0.34	0.34	0.30	0.24	0.20	0.39	0.38	0.33	0.26	0.21
		-45.6	5.6	0.42	0.41	0.35	0.27	0.22	0.47	0.45	0.38	0.29	0.23
		32.2	5.6	0.51	0.48	0.33	0.20	0.14	0.56	0.52	0.35	0.21	0.14
		10.0	16.7	0.38	0.36	0.28	0.20	0.15	0.40	0.38	0.29	0.20	0.15
		10.0	5.6	0.51	0.48	0.35	0.23	0.17	0.55	0.52	0.37	0.24	0.17
45° Slope	Up 	-17.8	11.1	0.40	0.39	0.32	0.24	0.18	0.43	0.41	0.33	0.24	0.19
		-17.8	5.6	0.49	0.47	0.37	0.26	0.20	0.52	0.51	0.39	0.27	0.20
		-45.6	11.1	0.39	0.38	0.33	0.26	0.21	0.41	0.40	0.35	0.27	0.22
		-45.6	5.6	0.48	0.46	0.39	0.30	0.24	0.51	0.49	0.41	0.31	0.24
		32.2	5.6	0.70	0.64	0.40	0.22	0.15	0.65	0.60	0.38	0.22	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.47	0.45	0.33	0.22	0.16
		10.0	5.6	0.67	0.62	0.42	0.26	0.18	0.64	0.60	0.41	0.25	0.18
		-17.8	11.1	0.49	0.47	0.37	0.26	0.20	0.51	0.49	0.38	0.27	0.20
		-17.8	5.6	0.62	0.59	0.44	0.29	0.22	0.61	0.59	0.44	0.29	0.22
		-45.6	11.1	0.46	0.45	0.38	0.29	0.23	0.50	0.48	0.40	0.30	0.24
Vertical	Horiz. 	-45.6	5.6	0.58	0.56	0.46	0.34	0.26	0.60	0.58	0.47	0.34	0.26
		32.2	5.6	0.89	0.80	0.45	0.24	0.16	0.85	0.76	0.44	0.24	0.16
		10.0	16.7	0.63	0.59	0.41	0.25	0.18	0.62	0.58	0.40	0.25	0.18
		10.0	5.6	0.90	0.82	0.50	0.28	0.19	0.83	0.77	0.48	0.28	0.19
		-17.8	11.1	0.68	0.64	0.47	0.31	0.22	0.67	0.64	0.47	0.31	0.22
		-17.8	5.6	0.87	0.81	0.56	0.34	0.24	0.81	0.76	0.53	0.33	0.24
		-45.6	11.1	0.64	0.62	0.49	0.35	0.27	0.66	0.64	0.51	0.36	0.28
		-45.6	5.6	0.82	0.79	0.60	0.40	0.30	0.79	0.76	0.58	0.40	0.30
		32.2	5.6	1.07	0.94	0.49	0.25	0.17	1.77	1.44	0.60	0.28	0.18
		10.0	16.7	1.10	0.99	0.56	0.30	0.20	1.69	1.44	0.68	0.33	0.21
45° Slope	Down 	10.0	5.6	1.16	1.04	0.58	0.30	0.20	1.96	1.63	0.72	0.34	0.22
		-17.8	11.1	1.24	1.13	0.69	0.39	0.26	1.92	1.68	0.86	0.43	0.29
		-17.8	5.6	1.29	1.17	0.70	0.39	0.27	2.11	1.82	0.89	0.44	0.29
		-45.6	11.1	1.36	1.27	0.84	0.50	0.35	2.05	1.85	1.06	0.57	0.38
		-45.6	5.6	1.42	1.32	0.86	0.51	0.35	2.28	2.03	1.12	0.59	0.39
Horiz.	Down 	32.2	5.6	0.45	0.42	0.30	0.19	0.14	0.50	0.47	0.32	0.20	0.14
		10.0	16.7	0.33	0.32	0.26	0.18	0.14	0.27	0.35	0.28	0.19	0.15
		10.0	5.6	0.44	0.42	0.32	0.21	0.16	0.49	0.47	0.34	0.23	0.16
		-17.8	11.1	0.35	0.34	0.29	0.22	0.17	0.40	0.38	0.32	0.23	0.18
		-17.8	5.6	0.43	0.41	0.33	0.24	0.19	0.48	0.46	0.36	0.26	0.20
		-45.6	11.1	0.34	0.34	0.30	0.24	0.20	0.39	0.38	0.33	0.26	0.21
		-45.6	5.6	0.42	0.41	0.35	0.27	0.22	0.47	0.45	0.38	0.29	0.23
		32.2	5.6	0.51	0.48	0.33	0.20	0.14	0.56	0.52	0.35	0.21	0.14
		10.0	16.7	0.38	0.36	0.28	0.20	0.15	0.40	0.38	0.29	0.20	0.15
		10.0	5.6	0.51	0.48	0.35	0.23	0.17	0.55	0.52	0.37	0.24	0.17

^aSee Chapter 23, section Factors Affecting Heat Transfer Across Air Spaces. Thermal resistance values were determined from the relation, $R = 1/C$, where $C = h_c + \epsilon_{eff} h_r$, h_c is the conduction-convection coefficient, $\epsilon_{eff} h_r$ is the radiation coefficient $\approx 0.227 \epsilon_{eff} [(t_m + 273)/100]^3$, and t_m is the mean temperature of the air space. Values for h_c were determined from data developed by Robinson et al. (1954). Equations (5) through (7) in Yarbrough (1983) show the data in this table in analytic form. For extrapolation from this table to air spaces less than 12.5 mm (as in insulating window glass), assume $h_c = 21.8(1 + 0.00274 t_m)/l$ where l is the air space thickness in mm, and h_c is heat transfer in W/(m²·K) through the air space only.

^bValues are based on data presented by Robinson et al. (1954). (Also see Chapter 3, Tables 3 and 4, and Chapter 38). Values apply for ideal conditions (i.e., air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no air leakage to or from the space). When accurate values are required, use overall U-factors deter-

mined through calibrated hot box (ASTM C 976) or guarded hot box (ASTM C 236) testing. Thermal resistance values for multiple air spaces must be based on careful estimates of mean temperature differences for each air space.

^cA single resistance value cannot account for multiple air spaces; each air space requires a separate resistance calculation that applies only for the established boundary conditions. Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

^dInterpolation is permissible for other values of mean temperature, temperature difference, and effective emittance ϵ_{eff} . Interpolation and moderate extrapolation for air spaces greater than 90 mm are also permissible.

^eEffective emittance ϵ_{eff} of the air space is given by $1/\epsilon_{eff} = 1/\epsilon_1 + 1/\epsilon_2 - 1$, where ϵ_1 and ϵ_2 are the emittances of the surfaces of the air space (see Table 2).

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values^a

Description	Density, kg/m ³	Conductivity ^b (k), W/(m·K)	Conductance (C), W/(m ² ·K)	Resistance ^c (R)		Specific Heat, kJ/(kg·K)
				1/k, K·m/W	For Thickness Listed (1/C), K·m ² /W	
BUILDING BOARD						
Asbestos-cement board	1900	0.58	—	1.73	—	1.00
Asbestos-cement board 3.2 mm	1900	—	187.4	—	0.005	—
Asbestos-cement board 6.4 mm	1900	—	93.7	—	0.011	—
Gypsum or plaster board 9.5 mm	800	—	17.6	—	0.056	1.09
Gypsum or plaster board 12.7 mm	800	—	12.6	—	0.079	—
Gypsum or plaster board 15.9 mm	800	—	10.1	—	0.099	—
Plywood (Douglas fir) ^d	540	0.12	—	8.66	—	1.21
Plywood (Douglas fir)..... 6.4 mm	540	—	18.2	—	0.055	—
Plywood (Douglas fir)..... 9.5 mm	540	—	12.1	—	0.083	—
Plywood (Douglas fir)..... 12.7 mm	540	—	9.1	—	0.11	—
Plywood (Douglas fir)..... 15.9 mm	540	—	7.3	—	0.14	—
Plywood or wood panels 19.0 mm	540	—	6.1	—	0.16	1.21
Vegetable fiber board						
Sheathing, regular density ^e 12.7 mm	290	—	4.3	—	0.23	1.30
..... 19.8 mm	290	—	2.8	—	0.36	—
Sheathing intermediate density ^e 12.7 mm	350	—	5.2	—	0.19	1.30
Nail-base sheathing ^e 12.7 mm	400	—	5.3	—	0.19	1.30
Shingle backer..... 9.5 mm	290	—	6.0	—	0.17	1.30
Shingle backer..... 7.9 mm	290	—	7.3	—	0.14	—
Sound deadening board..... 12.7 mm	240	—	4.2	—	0.24	1.26
Tile and lay-in panels, plain or acoustic	290	0.058	—	17.	—	0.59
..... 12.7 mm	290	—	4.5	—	0.22	—
..... 19.0 mm	290	—	3.0	—	0.33	—
Laminated paperboard	480	0.072	—	13.9	—	1.38
Homogeneous board from repulped paper....	480	0.072	—	13.9	—	1.17
Hardboard ^e						
Medium density	800	0.105	—	9.50	—	1.30
High density, service-tempered grade and service grade.....	880	0.82	—	8.46	—	1.34
High density, standard-tempered grade.....	1010	0.144	—	6.93	—	1.34
Particleboard ^e						
Low density.....	590	0.102	—	9.77	—	1.30
Medium density	800	0.135	—	7.35	—	1.30
High density.....	1000	0.170	—	5.90	—	1.30
Underlayment..... 15.9 mm	640	—	6.9	—	0.14	1.21
Waferboard.....	590	0.091	—	11.0	—	—
Wood subfloor..... 19.0 mm	—	—	6.0	—	0.17	1.38
BUILDING MEMBRANE						
Vapor—permeable felt	—	—	94.9	—	0.011	—
Vapor—seal, 2 layers of mopped 0.73 kg/m ² felt.....	—	—	47.4	—	0.21	—
Vapor—seal, plastic film.....	—	—	—	—	Negl.	—
FINISH FLOORING MATERIALS						
Carpet and fibrous pad	—	—	2.73	—	0.37	1.42
Carpet and rubber pad.....	—	—	4.60	—	0.22	1.38
Cork tile 3.2 mm	—	—	20.4	—	0.049	2.01
Terrazzo..... 25 mm	—	—	71.0	—	0.014	0.80
Tile—asphalt, linoleum, vinyl, rubber	—	—	113.6	—	0.009	1.26
vinyl asbestos	—	—	—	—	—	1.01
ceramic.....	—	—	—	—	—	0.80
Wood, hardwood finish 19 mm	—	—	8.35	—	0.12	—
INSULATING MATERIALS						
<i>Blanket and Batt^{f,g}</i>						
Mineral fiber, fibrous form processed						
from rock, slag, or glass						
approx. 75-100 mm.....	6.4-32	—	0.52	—	1.94	—
approx. 90 mm	6.4-32	—	0.44	—	2.29	—
approx. 90 mm	19-26	—	0.38	—	2.63	—
approx. 140-165 mm.....	6.4-32	—	0.30	—	3.32	—
approx. 140 mm	10-16	—	0.27	—	3.67	—
approx. 150-190 mm.....	6.4-32	—	0.26	—	3.91	—
approx. 210-250 mm.....	6.4-32	—	0.19	—	5.34	—
approx. 250-330 mm.....	6.4-32	—	0.15	—	6.77	—
<i>Board and Slabs</i>						
Cellular glass.....	136	0.050	—	19.8	—	0.75
Glass fiber, organic bonded.....	64-140	0.036	—	27.7	—	0.96
Expanded perlite, organic bonded.....	16	0.052	—	19.3	—	1.26
Expanded rubber (rigid).....	72	0.032	—	31.6	—	1.68
Expanded polystyrene, extruded (smooth skin surface) (CFC-12 exp.).....	29-56	—	—	—	—	—

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values^a (Continued)

Description	Density, kg/m ³	Conductivity ^b (<i>k</i>), W/(m·K)	Conductance (<i>C</i>), W/(m ² ·K)	Resistance ^c (<i>R</i>)		Specific Heat, kJ/(kg·K)
				1/ <i>k</i> , K·m/W	For Thickness Listed (1/ <i>C</i>), K·m ² /W	
Expanded polystyrene, extruded (smooth skin surface) (HCFC-142b exp.) ^h	29-56	0.029	—	34.7	—	1.21
Expanded polystyrene, molded beads.....	16	0.037	—	26.7	—	—
	20	0.036	—	27.7	—	—
	24	0.035	—	28.9	—	—
	28	0.035	—	28.9	—	—
	32	0.033	—	30.2	—	—
Cellular polyurethane/polyisocyanurate ⁱ (CFC-11 exp.) (unfaced).....	24	0.023-0.026	—	43.3-38.5	—	1.59
Cellular polyisocyanurate ⁱ (CFC-11 exp.) (gas-permeable facers).....	24-40	0.023-0.026	—	43.3-38.5	—	0.92
Cellular polyisocyanurate ^j (CFC-11 exp.) (gas-impermeable facers).....	32	0.020	—	48.8	—	0.92
Cellular phenolic (closed cell) (CFC-11, CFC-113 exp.) ^k	32	0.017	—	56.8	—	—
Cellular phenolic (open cell).....	29-35	0.033	—	30.5	—	—
Mineral fiber with resin binder.....	240	0.042	—	23.9	—	0.71
Mineral fiberboard, wet felted						
Core or roof insulation.....	260-270	0.049	—	20.4	—	—
Acoustical tile.....	290	0.050	—	19.8	—	0.80
Acoustical tile.....	340	0.053	—	18.7	—	—
Mineral fiberboard, wet molded						
Acoustical tile ^l	370	0.060	—	16.5	—	0.59
Wood or cane fiberboard						
Acoustical tile ^l 12.7 mm	—	—	4.5	—	0.22	1.30
Acoustical tile ^l 19.0 mm	—	—	3.0	—	0.33	—
Interior finish (plank, tile).....	240	0.050	—	19.8	—	1.34
Cement fiber slabs (shredded wood with Portland cement binder).....	400-430	0.072-0.076	—	13.9-13.1	—	—
Cement fiber slabs (shredded wood with magnesia oxysulfide binder).....	350	0.082	—	12.1	—	1.30
<i>Loose Fill</i>						
Cellulosic insulation (milled paper or wood pulp).....	37-51	0.039-0.046	—	25.6-21.7	—	1.38
Perlite, expanded.....	32-66	0.039-0.045	—	25.6-22.9	—	1.09
	66-120	0.045-0.052	—	22.9-19.4	—	—
	120-180	0.052-0.060	—	19.4-16.6	—	—
Mineral fiber (rock, slag, or glass) ^g						
approx. 95-130 mm.....	9.6-32	—	—	—	1.94	0.71
approx. 170-220 mm.....	9.6-32	—	—	—	3.35	—
approx. 190-250 mm.....	9.6-32	—	—	—	3.87	—
approx. 260-350 mm.....	9.6-32	—	—	—	5.28	—
Mineral fiber (rock, slag, or glass) ^g						
approx. 90 mm (closed sidewall application).....	32-56	—	—	—	2.1-2.5	—
Vermiculite, exfoliated.....	110-130	0.068	—	14.8	—	1.34
	64-96	0.063	—	15.7	—	—
<i>Spray Applied</i>						
Polyurethane foam.....	24-40	0.023-0.026	—	43.3-38.5	—	—
Ureaformaldehyde foam.....	11-26	0.032-0.040	—	31.5-24.7	—	—
Cellulosic fiber.....	56-96	0.042-0.049	—	23.9-20.4	—	—
Glass fiber.....	56-72	0.038-0.039	—	26.7-25.6	—	—
<i>Reflective Insulation</i>						
Reflective material ($\epsilon < 0.5$) in center of 20 mm cavity forms two 10 mm vertical air spaces ^m	—	—	1.76	—	0.57	—
METALS						
(See Chapter 38, Table 3)						
ROOFING						
Asbestos-cement shingles.....	1900	—	27.0	—	0.037	1.00
Asphalt roll roofing.....	1100	—	36.9	—	0.026	1.51
Asphalt shingles.....	1100	—	12.9	—	0.077	1.26
Built-up roofing..... 10 mm	1100	—	17.0	—	0.058	1.46
Slate..... 13 mm	—	—	114	—	0.009	1.26
Wood shingles, plain and plastic film faced.....	—	—	6.0	—	0.166	1.30
PLASTERING MATERIALS						
Cement plaster, sand aggregate.....	1860	0.72	—	1.39	—	0.84
Sand aggregate..... 10 mm	—	—	75.5	—	0.013	0.84
Sand aggregate..... 20 mm	—	—	37.8	—	0.026	0.84

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values^a (Continued)

Description	Density, kg/m ³	Conductivity ^b (k), W/(m·K)	Conductance (C), W/(m ² ·K)	Resistance ^c (R)		Specific Heat, kJ/(kg·K)
				1/k, K·m/W	For Thickness Listed (1/C), K·m ² /W	
Gypsum plaster:						
Lightweight aggregate 13 mm	720	—	17.7	—	0.056	—
Lightweight aggregate 16 mm	720	—	15.2	—	0.066	—
Lightweight aggregate on metal lath..... 19 mm	—	—	12.1	—	0.083	—
Perlite aggregate.....	720	0.22	—	4.64	—	1.34
Sand aggregate.....	1680	0.81	—	1.25	—	0.84
Sand aggregate..... 13 mm	1680	—	63.0	—	0.016	—
Sand aggregate..... 16 mm	1680	—	51.7	—	0.019	—
Sand aggregate on metal lath 19 mm	—	—	43.7	—	0.023	—
Vermiculite aggregate.....	720	0.24	—	4.09	—	—
MASONRY MATERIALS						
<i>Masonry Units</i>						
Brick, fired clay	2400	1.21-1.47	—	0.83-0.68	—	—
	2240	1.07-1.30	—	0.94-0.77	—	—
	2080	0.92-1.12	—	1.08-0.89	—	—
	1920	0.81-0.98	—	1.24-1.02	—	0.79
	1760	0.71-0.85	—	1.42-1.18	—	—
	1600	0.61-0.74	—	1.65-1.36	—	—
	1440	—0.52-0.62	—	1.93-1.61	—	—
	1280	0.43-0.53	—	2.31-1.87	—	—
	1120	0.36-0.45	—	2.77-2.23	—	—
Clay tile, hollow						
1 cell deep..... 75 mm	—	—	7.10	—	0.14	0.88
1 cell deep..... 100 mm	—	—	5.11	—	0.20	—
2 cells deep..... 150 mm	—	—	3.75	—	0.27	—
2 cells deep..... 200 mm	—	—	3.07	—	0.33	—
2 cells deep..... 250 mm	—	—	2.56	—	0.39	—
3 cells deep..... 300 mm	—	—	2.27	—	0.44	—
Concrete blocks ^{n, o}						
Limestone aggregate						
200 mm, 16.3 kg, 2210 kg/m ³ concrete, 2 cores.....	—	—	—	—	—	—
Same with perlite filled cores	—	—	2.73	—	0.37	—
300 mm, 25 kg, 2210 kg/m ³ concrete, 2 cores.....	—	—	—	—	—	—
Same with perlite filled cores	—	—	1.53	—	0.65	—
Normal mass aggregate (sand and gravel) 200 mm						
15-16 kg, 2020-2180 kg/m ³ concrete, 2 or 3 cores	—	—	5.1-5.8	—	0.20-0.17	0.92
Same with perlite filled cores	—	—	2.84	—	0.35	—
Same with vermiculite filled cores.....	—	—	3.0-4.1	—	0.34-0.24	—
300 mm, 22.7 kg, 2000 kg/m ³ concrete, 2 cores.....	—	—	4.60	—	0.217	0.92
Medium mass aggregate (combinations of normal and low mass aggregate) 200 mm, 12-13 kg,						
1550-1790 kg/m ³ concrete, 2 or 3 cores.....	—	—	3.3-4.4	—	0.30-0.22	—
Same with perlite filled cores	—	—	1.5-2.5	—	0.65-0.41	—
Same with vermiculite filled cores.....	—	—	1.70	—	0.58	—
Same with molded EPS (beads) filled cores.....	—	—	1.82	—	0.56	—
Same with molded EPS inserts in cores.....	—	—	2.10	—	0.47	—
Low mass aggregate (expanded shale, clay, slate or slag, pumice) 150 mm						
7.3-7.7 kg, 1360-1390 kg/m ³ concrete, 2 or 3 cores	—	—	3.0-3.5	—	0.34-0.29	—
Same with perlite filled cores	—	—	1.36	—	0.74	—
Same with vermiculite filled cores.....	—	—	1.87	—	0.53	—
200 mm, 8.6-10.0 mm, 1150-1380 kg/m ³ concrete,	—	—	1.8-3.1	—	0.56-0.33	0.88
Same with perlite filled cores	—	—	0.9-1.3	—	1.20-0.77	—
Same with vermiculite filled cores.....	—	—	1.1-1.5	—	0.93-0.69	—
Same with molded EPS (beads) filled cores.....	—	—	1.19	—	0.85	—
Same with UF foam filled cores	—	—	1.25	—	0.79	—
Same with molded EPS inserts in cores.....	—	—	1.65	—	0.62	—
300 mm, 14.5-16.3 kg, 1280-1440 kg/m ³ concrete,	—	—	—	—	—	—
2 or 3 cores.....	—	—	2.2-2.5	—	0.46-0.40	—
Same with perlite filled cores	—	—	0.6-0.9	—	1.6-1.1	—
Same with vermiculite filled cores.....	—	—	0.97	—	1.0	—
Stone, lime, or sand						
Quartzitic and sandstone	2880	10.4	—	0.10	—	—
	2560	6.2	—	0.16	—	—
	2240	3.5	—	0.29	—	—
	1920	1.9	—	0.53	—	0.79
Calclitic, dolomitic, limestone, marble, and granite	2880	4.3	—	0.23	—	—
	2560	3.2	—	0.32	—	—
	2240	2.3	—	0.43	—	—
	1920	1.6	—	0.63	—	0.79
	1600	1.1	—	0.90	—	—

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values^a (Continued)

Description	Density, kg/m ³	Conductivity ^b (k), W/(m·K)	Conductance (C), W/(m ² ·K)	Resistance ^c (R)		Specific Heat, kJ/(kg·K)
				1/k, K·m/W	For Thickness Listed (1/C), K·m ² /W	
Gypsum partition tile						
75 by 300 by 760 mm, solid.....	—	—	4.50	—	0.222	0.79
75 by 300 by 760 mm, 4 cells.....	—	—	4.20	—	0.238	—
100 by 300 by 760 mm, 3 cells.....	—	—	3.40	—	0.294	—
<i>Concretes^o</i>						
Sand and gravel or stone aggregate concretes (concretes with more than 50% quartz or quartzite sand have conductivities in the higher end of the range).....	2400 2240 2080	1.4-2.9 1.3-2.6 1.0-1.9	— — —	0.69-0.35 0.77-0.39 0.99-0.53	— — —	— 0.8-1.0 —
Limestone concretes	2240 1920 1600	1.60 1.14 0.79	— — —	0.62 0.88 1.26	— — —	— — —
Gypsum-fiber concrete (87.5% gypsum, 12.5% wood chips)	816	0.24	—	4.18	—	0.88
Cement/lime, mortar, and stucco	1920 1600 1280	1.40 0.97 0.65	— — —	0.71 1.04 1.54	— — —	— — —
Lightweight aggregate concretes						
Expanded shale, clay, or slate; expanded slags; cinders; pumice (with density up to 1600 kg/m ³); and scoria (sanded concretes have conductivities in the higher end of the range)	1920 1600 1280 960	0.9-1.3 0.68-0.89 0.48-0.59 0.30-0.36	— — — —	1.08-0.76 1.48-1.12 2.10-1.69 3.30-2.77	— — — —	— 0.84 0.84 —
	640	0.18	—	5.40	—	—
Perlite, vermiculite, and polystyrene beads	800 640 480 320	0.26-0.27 0.20-0.22 0.16 0.12	— — — —	3.81-3.68 4.92-4.65 6.31 8.67	— — — —	— 0.63-0.96 — —
Foam concretes	1920 1600 1280 1120	0.75 0.60 0.44 0.36	— — — —	1.32 1.66 2.29 2.77	— — — —	— — — —
Foam concretes and cellular concretes	960 640 320	0.30 0.20 0.12	— — —	3.33 4.92 8.67	— — —	— — —
SIDING MATERIALS (on flat surface)						
<i>Shingles</i>						
Asbestos-cement	1900	—	27.0	—	0.037	—
Wood, 400 mm, 190 mm exposure	—	—	6.53	—	0.15	1.30
Wood, double, 400 mm, 300 mm exposure	—	—	4.77	—	0.21	1.17
Wood, plus insul. backer board, 8 mm.....	—	—	4.03	—	0.25	1.30
<i>Siding</i>						
Asbestos-cement, 6.4 mm, lapped	—	—	27.0	—	0.037	1.01
Asphalt roll siding.....	—	—	36.9	—	0.026	1.47
Asphalt insulating siding (12.7 mm bed.).....	—	—	3.92	—	0.26	1.47
Hardboard siding, 11 mm	—	—	8.46	—	0.12	1.17
Wood, drop, 20 by 200 mm.....	—	—	7.21	—	0.14	1.17
Wood, bevel, 13 by 200 mm, lapped.....	—	—	6.98	—	0.14	1.17
Wood, bevel, 19 by 250 mm, lapped.....	—	—	5.40	—	0.18	1.17
Wood, plywood, 9.5 mm, lapped	—	—	9.60	—	0.10	1.22
Aluminum, steel, or vinyl ^{p, q} , over sheathing						
Hollow-backed.....	—	—	9.31	—	0.11	1.22 ^q
Insulating-board backed.....	—	—	—	—	—	—
9.5 mm nominal	—	—	3.12	—	0.32	1.34
9.5 mm nominal, foil backed	—	—	1.93	—	0.52	—
Architectural (soda-lime float) glass.....	—	—	56.8	—	0.018	0.84
WOODS (12% moisture content)^{e,r}						
<i>Hardwoods</i>						1.63 ^s
Oak.....	659-749	0.16-0.18	—	6.2-5.5	—	
Birch.....	682-726	0.167-0.176	—	6.0-5.7	—	
Maple	637-704	0.157-0.171	—	6.4-5.8	—	
Ash	614-670	0.153-0.164	—	6.5-6.1	—	
<i>Softwoods</i>						1.63 ^s
Southern pine	570-659	0.144-0.161	—	6.9-6.2	—	
Douglas fir-Larch.....	536-581	0.137-0.145	—	7.3-6.9	—	
Southern cypress	502-514	0.130-0.132	—	7.7-7.6	—	
Hem-Fir, Spruce-Pine-Fir	392-502	0.107-0.130	—	9.3-7.7	—	
West coast woods, Cedars	347-502	0.098-0.130	—	10.3-7.7	—	
California redwood	392-448	0.107-0.118	—	9.4-8.5	—	

Notes for Table 4

^a Values are for a mean temperature of 24°C. Representative values for dry materials are intended as design (not specification) values for materials in normal use. Thermal values of insulating materials may differ from design values depending on their in-situ properties (e.g., density and moisture content, orientation, etc.) and variability experienced during manufacture. For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

^b The symbol λ is also used to represent thermal conductivity.

^c Resistance values are the reciprocals of C before rounding off C to two decimal places.

^d Lewis (1967).

^e U.S. Department of Agriculture (1974).

^f Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an airspace, see Tables 2 and 3 for the insulating value of an airspace with the appropriate effective emittance and temperature conditions of the space.

^g Conductivity varies with fiber diameter. (See Chapter 23, Factors Affecting Thermal Performance.) Batt, blanket, and loose-fill mineral fiber insulations are manufactured to achieve specified R-values, the most common of which are listed in the table. Due to differences in manufacturing processes and materials, the product thicknesses, densities, and thermal conductivities vary over considerable ranges for a specified R-value.

^h This material is relatively new and data are based on limited testing.

ⁱ For additional information, see Society of Plastics Engineers (SPI) Bulletin U108. Values are for aged, unfaced board stock. For change in conductivity with age of expanded polyurethane/polyisocyanurate, see Chapter 23, Factors Affecting Thermal Performance.

^j Values are for aged products with gas-impermeable facers on the two major surfaces. An aluminum foil facer of 25 μm thickness or greater is generally considered impermeable to gases. For change in conductivity with age of expanded polyisocyanurate, see Chapter 23, Factors Affecting Thermal Performance, and SPI Bulletin U108.

^k Cellular phenolic insulation may no longer be manufactured. The thermal conductivity and resistance values do not represent aged insulation, which may have a higher thermal conductivity and lower thermal resistance.

^l Insulating values of acoustical tile vary, depending on density of the board and on type, size, and depth of perforations.

^m Cavity is framed with 20 mm wood furring strips. Caution should be used in applying this value for other framing materials. The reported value was derived from tests and applies to the reflective path only. The effect of studs or furring strips must be included in determining the overall performance of the wall.

ⁿ Values for fully grouted block may be approximated using values for concrete with a similar unit density.

^o Values for concrete block and concrete are at moisture contents representative of normal use.

^p Values for metal or vinyl siding applied over flat surfaces vary widely, depending on amount of ventilation of airspace beneath the siding; whether airspace is reflective or nonreflective; and on thickness, type, and application of insulating backing-board used. Values are averages for use as design guides, and were obtained from several guarded hot box tests (ASTM C 236) or calibrated hot box (ASTM C 976) on hollow-backed types and types made using backing of wood fiber, foamed plastic, and glass fiber. Departures of $\pm 50\%$ or more from these values may occur.

^q Vinyl specific heat = 1.0 kJ/(kg·K)

^r See Adams (1971), MacLean (1941), and Wilkes (1979). The conductivity values listed are for heat transfer across the grain. The thermal conductivity of wood varies linearly with the density, and the density ranges listed are those normally found for the wood species given. If the density of the wood species is not known, use the mean conductivity value. For extrapolation to other moisture contents, the following empirical equation developed by Wilkes (1979) may be used:

$$k = 0.7494 + \frac{(4.895 \times 10^{-3} + 1.503 \times 10^{-4} M)\rho}{1 + 0.01 M}$$

where ρ is density of the moist wood in kg/m^3 , and M is the moisture content in percent.

^s From Wilkes (1979), an empirical equation for the specific heat of moist wood at 24°C is as follows:

$$c_p = 0.1442 \left[\frac{(0.299 + 0.01 M)}{(1 + 0.01 M)} \right] + \Delta c_p$$

where Δc_p accounts for the heat of sorption and is denoted by

$$\Delta c_p = M(0.008037 - 1.325 \times 10^{-4} M)$$

where M is the moisture content in percent by mass.

Assuming parallel heat flow only, the calculated resistance is higher than that calculated on the assumption of isothermal planes. The actual resistance generally is some value between the two calculated values. In the absence of test values, examination of the construction usually reveals whether a value closer to the higher or lower calculated R-value should be used. Generally, if the construction contains a layer in which lateral conduction is high compared with transmittance through the construction, the calculation with isothermal planes should be used. If the construction has no layer of high lateral conductance, the parallel heat flow calculation should be used.

Hot box tests of insulated and uninsulated masonry walls constructed with block of conventional configuration show that thermal resistances calculated using the isothermal planes heat flow method agree well with measured values (Van Geem 1985, Valore 1980, Shu et al. 1979). Neglecting horizontal mortar joints in conventional block can result in thermal transmittance values up to 16% lower than actual, depending on the density and thermal properties of the masonry, and 1 to 6% lower, depending on the core insulation material (Van Geem 1985, McIntyre 1984). For aerated concrete block walls, other solid masonry, and multicore block walls with full mortar joints, neglecting mortar joints can cause errors in R-values up to 40% (Valore 1988). Horizontal mortar joints usually found in concrete block wall construction are neglected in Example 2.

Constructions Containing Metal

Curtain and metal stud-wall constructions often include metallic and other thermal bridges, which can significantly reduce the ther-

mal resistance. However, the capacity of the adjacent facing materials to transmit heat transversely to the metal is limited, and some contact resistance between all materials in contact limits the reduction. Contact resistances in building structures are only 0.01 to 0.1 $\text{K} \cdot \text{m}^2/\text{W}$ —too small to be of concern in many cases. However, the contact resistances of steel framing members may be important. Also, in many cases (as illustrated in Example 3), the area of metal in contact with the facing greatly exceeds the thickness of the metal, which mitigates the contact resistance effects.

Thermal characteristics for panels of sandwich construction can be computed by combining the thermal resistances of the various layers. R-values for the assembled sections should be determined on a representative sample by using a hot box method. If the sample is a wall section with air cavities on both sides of fibrous insulation, the sample must be of representative height since convective airflow can contribute significantly to heat flow through the test section. Computer modeling can also be useful, but all heat transfer mechanisms must be considered.

In Example 3, the metal member is only 0.5 mm thick, but it is in contact with adjacent facings over a 32 mm-wide area. The steel member is 90 mm deep, has a thermal resistance of approximately 0.0019 $\text{K} \cdot \text{m}^2/\text{W}$, and is virtually isothermal. The calculation involves careful selection of the appropriate thickness for the steel member. If the member is assumed to be 0.5 mm thick, the fact that the flange transmits heat to the adjacent facing is ignored, and the heat flow through the steel is underestimated. If the member is assumed to be 32 mm thick, the heat flow through the steel is overestimated. In Example 3, the steel member behaves in much the same way as a rectangular member 32 mm thick and 90 mm deep

with a thermal resistance of $0.0019 (32/0.5) = 0.12 \text{ K} \cdot \text{m}^2/\text{W}$ does. The Building Research Association of New Zealand (BRANZ) commonly uses this approximation.

Example 3. Calculate the C-factor of the insulated steel frame wall shown in Figure 4. Assume that the steel member has an R-value of $0.12 \text{ K} \cdot \text{m}^2/\text{W}$ and that the framing behaves as though it occupies approximately 8% of the transmission area.

Solution. Obtain the R-values of the various building elements from Table 4.

Element	R (Insul.)	R (Framing)
1. 13 mm gypsum wallboard	0.08	0.08
2. 90 mm mineral fiber batt insulation	1.94	—
3. Steel framing member	—	0.12
4. 13 mm gypsum wallboard	0.08	0.08
	$R_1 = 2.10$	$R_2 = 0.28$

Therefore, $C_1 = 0.476$; $C_2 = 3.57 \text{ W}/(\text{m}^2 \cdot \text{K})$.

If the steel framing (thermal bridging) is not considered, the C-factor of the wall is calculated using Equation (3) from Chapter 23 as follows:

$$C_{av} = C_1 = 1/R_1 = 0.476 \text{ W}/(\text{m}^2 \cdot \text{K})$$

If the steel framing is accounted for using the parallel flow method, the C-factor of the wall is determined using Equation (5) from Chapter 23 as follows:

$$C_{av} = (0.92 \times 0.476) + (0.08 \times 3.57)$$

$$= 0.724 \text{ W}/(\text{m}^2 \cdot \text{K})$$

$$R_{T(av)} = 1.38 \text{ m}^2 \cdot \text{K}/\text{W}$$

If the steel framing is included using the isothermal planes method, the C-factor of the wall is determined using Equations (2) and (3) from Chapter 23 as follows:

$$R_{T(av)} = 0.08 + \frac{1}{(0.92)(1.94) + (0.08/0.12)} + 0.08$$

$$= 1.037 \text{ m}^2 \cdot \text{K}/\text{W}$$

$$C_{av} = 0.96 \text{ W}/(\text{m}^2 \cdot \text{K})$$

For this insulated steel frame wall, Farouk and Larson (1983) measured an average R-value of $1.16 \text{ m}^2 \cdot \text{K}/\text{W}$.

In ASHRAE/IESNA Standard 90.1-1989, one method given for determining the thermal resistance of wall assemblies containing metal framing involves using a parallel path correction factor F_c , which is listed in Table 8C-2 of the standard. For 38 mm by 90 mm

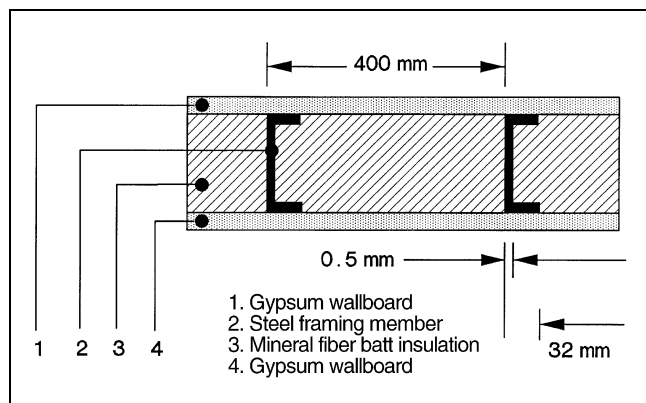


Fig. 4 Insulated Steel Frame Wall (Example 3)

steel framing, 400 mm OC, $F_c = 0.50$. Using the correction factor method, an R-value of $1.13 \text{ m}^2 \cdot \text{K}/\text{W}$ ($0.08 + 1.94 \times 0.50 + 0.08$) is obtained for the wall described in Example 3.

Zone Method of Calculation

For structures with widely spaced metal members of substantial cross-sectional area, calculation by the isothermal planes method can result in thermal resistance values that are too low. For these constructions, the **zone method** can be used. This method involves two separate computations—one for a chosen limited portion, Zone A, containing the highly conductive element; the other for the remaining portion of simpler construction, Zone B. The two computations are then combined using the parallel flow method, and the average transmittance per unit overall area is calculated. The basic laws of heat transfer are applied by adding the area conductances CA of elements in parallel, and adding area resistances R/A of elements in series.

The surface shape of Zone A is determined by the metal element. For a metal beam (see Figure 5), the Zone A surface is a strip of width W that is centered on the beam. For a rod perpendicular to panel surfaces, it is a circle of diameter W . The value of W is calculated from Equation (1), which is empirical. The value of d should not be less than 13 mm for still air.

$$W = m + 2d \quad (1)$$

where

m = width or diameter of metal heat path terminal, mm

d = distance from panel surface to metal, mm

Generally, the value of W should be calculated using Equation (1) for each end of the metal heat path; the larger value, within the limits of the basic area, should be used as illustrated in Example 4.

Example 4. Calculate transmittance of the roof deck shown in Figure 5.

Tee-bars at 600 mm OC support glass fiber form boards, gypsum concrete, and built-up roofing. Conductivities of components are: steel, $45 \text{ W}/(\text{m} \cdot \text{K})$; gypsum concrete, $0.24 \text{ W}/(\text{m} \cdot \text{K})$; and glass fiber form board, $0.036 \text{ W}/(\text{m} \cdot \text{K})$. Conductance of built-up roofing is $17 \text{ W}/(\text{m} \cdot \text{K})$.

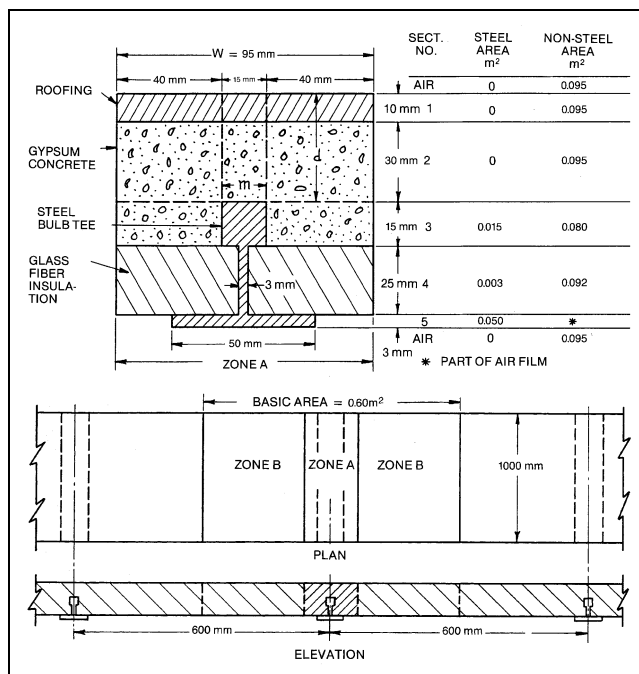


Fig. 5 Gypsum Roof Deck on Bulb Tees (Example 4)

Solution: The basic area is 0.6 m^2 with a tee-bar across the middle. This area is divided into Zones A and B.

Zone A is determined from Equation (1) as follows:

$$\begin{aligned}\text{Top side } W &= m + 2d = 15 + (2 \times 40) = 95 \text{ mm} \\ \text{Bottom side } W &= m + 2d = 50 + (2 \times 13) = 76 \text{ mm}\end{aligned}$$

Using the larger value of W , the area of Zone A is $(1.0 \times 95/1000) = 0.095 \text{ m}^2$. The area of Zone B is $0.600 - 0.095 = 0.505 \text{ m}^2$.

To determine area transmittance for Zone A, divide the structure within the zone into five sections parallel to the top and bottom surfaces (Figure 5). The area conductance CA of each section is calculated by adding the area conductances of its metal and nonmetal paths. Area conductances of the sections are converted to area resistances RA and added to obtain the total resistance of Zone A.

Section	Area	$\times$ Conductance = CA	$\frac{1}{CA} = \frac{R}{A}$
Air (outside, 24 km/h)	0.095×34	3.23	0.31
No. 1, Roofing	0.095×17	1.62	0.62
No. 2, Gypsum concrete	$0.095 \times 0.24/0.030$	0.76	1.32
No. 3, Steel	$0.015 \times 45/0.015$	45	0.022
No. 3, Gypsum concrete	$0.080 \times 0.24/0.015$	1.28	
No. 4, Steel	$0.003 \times 45/0.025$	5.4	0.181
No. 4, Glass fiberboard	$0.092 \times 0.036/0.025$	0.13	
No. 5, Steel	$0.050 \times 45/0.005$	450	0.002
Air (inside)	0.095×9.26	0.88	1.14
Total $R/A = 3.59$			

Area transmittance of Zone A = $1/(R/A) = 1/3.59 = 0.279$.

For Zone B, the unit resistances are added and then converted to area transmittance, as shown in the following table.

Section	Resistance, R
Air (outside, 24 km/h)	$1/34 = 0.029$
Roofing	$1/17 = 0.059$
Gypsum concrete	$0.045/0.24 = 0.188$
Glass fiberboard	$0.025/0.036 = 0.694$
Air (inside)	$1/9.26 = 0.108$
Total resistance	$= 1.078$

Because unit transmittance = $1/R = 0.927$, the total area transmittance UA is calculated as follows:

$$\text{Zone B} = 0.505 \times 0.927 = 0.468$$

$$\text{Zone A} = 0.279$$

$$\text{Total area transmittance of basic area} = 0.747$$

$$\text{Transmittance} = 0.747 \text{ W}/(\text{m}^2 \cdot \text{K})$$

$$\text{Resistance} = 0.80 \text{ K} \cdot \text{m}^2/\text{W}$$

Overall R-values of 0.805 and $0.854 \text{ m}^2 \cdot \text{K}/\text{W}$ have been measured in two guarded hot box tests of a similar construction.

When the steel member represents a relatively large proportion of the total heat flow path, as in Example 4, detailed calculations of resistance in sections 3, 4, and 5 of Zone A are unnecessary; if only the steel member is considered, the final result of Example 4 is the same. However, if the heat flow path represented by the steel member is small, as for a tie rod, detailed calculations for sections 3, 4, and 5 are necessary. A panel with an internal metallic structure and bonded on one or both sides to a metal skin or covering presents special problems of lateral heat flow not covered in the zone method.

Modified Zone Method for Metal Stud Walls with Insulated Cavities

The modified zone method is similar to the parallel path method and the zone method. All three methods are based on parallel-path calculations. Figure 6 shows the width w of the zone of thermal anomalies around a metal stud. This zone can be assumed to equal the length of the stud flange L (parallel path method), or can be calculated as a sum of the length of stud flange and a distance double that from wall surface to metal Σd_i (zone method). In the modified zone method the width of the zone depends on the following three parameters:

- Ratio between thermal resistivity of sheathing material and cavity insulation
- Size (depth) of stud
- Thickness of sheathing material

The modified zone method is explained in Figure 6 (which can be copied and used as a calculation form). The wall cross section

resistances for zone cav: $R_{ins}^I, R_{ins}^{II}, R_{cav}^I, R_{cav}^{II}$

resistances for zone w: $R_A, R_B, R_I, R_{II}, R_{ins}, R_{met}$

thickness: d_{II}, d_I, d_{II}, d_I

$s = \text{stud spacing}; d_I = d_s - 2 \times d_{II} =$

resistivity of sheathing =

resistivity of cav. insul. =

Zf (from Zone Factor Chart) =

$w = L + Zf \times \Sigma d_i =$

$R_A = \Sigma (r_i \times d_i) =$

$R_B = \Sigma (r_j \times d_j) =$

$R_{ins}^I = r_{ins} \times d_i =$

$R_{ins}^{II} = r_{ins} \times d_{II} =$

$R_{met}^I = r_{met} \times d_i =$

$R_{met}^{II} = r_{met} \times d_{II} =$

$R_{tot} = \frac{\Sigma R_w \times \Sigma R_{cav} \times s}{w \times (\Sigma R_{cav} - \Sigma R_w) + s \times \Sigma R_w} =$

Wall Section	Material	Thickness, m	Resistivity, $\text{m} \cdot \text{K}/\text{W}$
A		$d_{i1} =$	$r_{i1} =$
A		$d_{i2} =$	$r_{i2} =$
A		$d_{i3} =$	$r_{i3} =$
B		$d_{j1} =$	$r_{j1} =$
I & II	Metal	$d_{II} =$	r_{met}
I & II	Cavity insulation	$d_s =$	r_{ins}

$R_I = \frac{R_{met}^I \times R_{ins}^I \times w}{d_{II} \times (R_{ins}^I - R_{met}^I) + w \times R_{met}^I} =$

$R_{II} = \frac{R_{met}^{II} \times R_{ins}^{II} \times w}{L \times (R_{ins}^{II} - R_{met}^{II}) + w \times R_{met}^{II}} =$

$\Sigma R_{cav} = R_A + R_B + R_{ins}^I + 2 \times R_{ins}^{II} =$

$\Sigma R_w = R_A + R_B + R_I + 2 \times R_{II} =$

Fig. 6 Modified Zone Method R-Value Calculation Form for Metal Stud Walls

shown in [Figure 6](#), is divided into two zones: the zone of thermal anomalies around metal stud w and the cavity zone cav . Wall material layers are grouped into an exterior and interior surface sections—A (sheathing, siding) and B (wallboard)—and interstitial sections I and II (cavity insulation, metal stud flange).

Assuming that the layers or layer of wall materials in wall section A are thicker than those in wall section B, as show by the cross section in [Figure 6](#), they can be described as follows:

$$\sum_{i=1}^n d_i \geq \sum_{j=1}^m d_j \quad (2)$$

where

n = number of material layer (of thickness d_i) between metal stud flange and wall surface for section A

m = number of material layer (of thickness d_j) for section B

Then, the width of the zone of thermal anomalies around the metal stud w can be estimated by

$$w = L + z_f \sum_{i=1}^n d_i \quad (3)$$

where

L = stud flange size

d_i = thickness of material layer in section A

z_f = zone factor, which is shown in [Figure 7](#) ($z_f = 2$ for zone method)

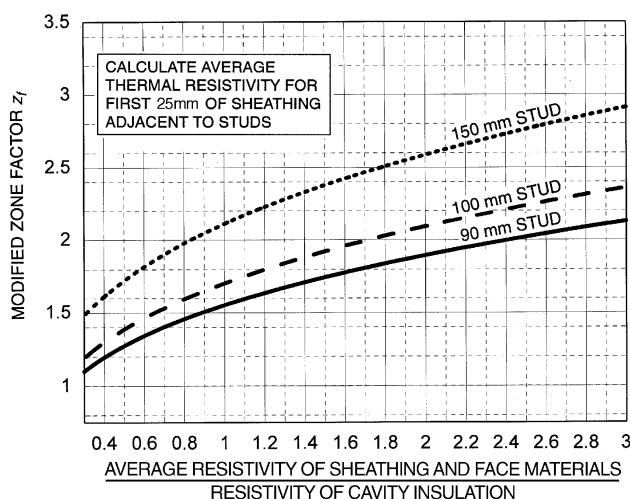


Fig. 7 Modified Zone Factor for Calculating R-Value of Metal Stud Walls with Cavity Insulation

Kosny and Christian (1995) verified the accuracy of the modified zone method for over 200 simulated cases of metal frame walls with insulated cavities. For all configurations considered the discrepancy between results were within $\pm 2\%$. Hot box measured R-values for 15 metal stud walls tested by Barbour et al. (1994) were compared with results obtained by Kosny and Christian (1995) and McGowan and Desjarlais (1997). The modified zone method was found to be the most accurate simple method for estimating the clear wall R-value of light-gage steel stud walls with insulated cavities. However, this analysis does not apply to construction with metal sheathing. Also, *ASHRAE Standard 90.1* may require a different method of analysis.

Ceilings and Roofs

The overall R-value for ceilings of wood frame flat roofs can be calculated using Equations (1) through (5) from [Chapter 23](#). Properties of the materials are found in [Tables 1, 3, 2, and 4](#). The fraction of framing is assumed to be 0.10 for joists at 400 mm OC and 0.07 for joists at 600 mm OC. The calculation procedure is similar to that shown in Example 1. Note that if the ceiling contains plane air spaces (see [Table 3](#)), the resistance depends on the direction of heat flow, i.e., whether the calculation is for a winter (heat flow up) or summer (heat flow down) condition.

For ceilings of pitched roofs under winter conditions, calculate the R-value of the ceiling using the procedure for flat roofs. [Table 5](#) can be used to determine the effective resistance of the attic space under summer conditions for varying conditions of ventilation air temperature, airflow direction and rates, ceiling resistance, roof or sol-air temperatures, and surface emittances (Joy 1958).

The R-value is the total resistance obtained by adding the ceiling and effective attic resistances. The applicable temperature difference is that difference between room air and sol-air temperatures or between room air and roof temperatures (see [Table 5](#), footnote f). [Table 5](#) can be used for pitched and flat residential roofs over attic spaces. When an attic has a floor, the ceiling resistance should account for the complete ceiling-floor construction.

Windows and Doors

[Table 4 of Chapter 30](#) lists U-factors for various fenestration products. [Table 6](#) lists U-factors for exterior wood and steel doors. All U-factors are approximate, because a significant portion of the resistance of a window or door is contained in the air film resistances, and some parameters that may have important effects are not considered. For example, the listed U-factors assume the surface temperatures of surrounding bodies are equal to the ambient air temperature. However, the indoor surface of a window or door in an actual installation may be exposed to nearby radiating surfaces, such as radiant heating panels, or opposite walls with much higher or lower temperatures than the indoor air. Air movement across the indoor surface of a window or door, such as that caused by nearby heating and cooling outlet grilles, increases the U-factor; and air movement (wind) across the outdoor surface of a window or door also increases the U-factor.

U_o Concept

U_o is the combined thermal transmittance of the respective areas of gross exterior wall, roof or ceiling or both, and floor assemblies. The U_o equation for a wall is as follows:

$$U_o = (U_{wall}A_{wall} + U_{window}A_{window} + U_{door}A_{door})/A_o \quad (4)$$

where

U_o = average thermal transmittance of gross wall area

A_o = gross area of exterior walls

Table 5 Effective Thermal Resistance of Ventilated Attics^a (Summer Condition)

NONREFLECTIVE SURFACES											
Ventilation Air Temperature, °C	Sol-Air ^f Temperature, °C	No Ventilation ^b		Natural Ventilation		Power Ventilation ^c					
		Ventilation Rate per Square Metre of Ceiling, L/s									
		0		0.5 ^d		2.5		5.1		7.6	
		Ceiling Resistance R^e , K·m ² /W									
		1.8	3.5	1.8	3.5	1.8	3.5	1.8	3.5	1.8	3.5
27	49	0.33	0.33	0.49	0.60	1.11	1.64	1.69	2.82	1.94	3.52
	60	0.33	0.33	0.49	0.62	1.14	1.76	1.72	2.99	2.11	3.70
	71	0.33	0.33	0.49	0.63	1.18	1.94	1.76	3.17	2.29	3.87
32	49	0.33	0.33	0.44	0.49	0.81	1.18	1.07	1.76	1.21	2.29
	60	0.33	0.33	0.46	0.55	0.92	1.39	1.34	2.11	1.51	2.64
	71	0.33	0.33	0.48	0.60	1.02	1.58	1.50	2.46	1.76	2.99
38	49	0.33	0.33	0.39	0.40	0.58	0.77	0.70	1.06	0.72	1.21
	60	0.33	0.33	0.42	0.48	0.74	1.07	1.02	1.53	1.14	1.76
	71	0.33	0.33	0.46	0.56	0.88	1.34	1.27	1.94	1.46	2.29
REFLECTIVE SURFACES ^g											
27	49	1.14	1.14	1.43	1.55	2.29	2.99	2.99	4.40	3.34	5.28
	60	1.14	1.14	1.44	1.58	2.46	3.17	3.17	4.58	3.52	5.46
	71	1.14	1.14	1.46	1.62	2.64	3.17	3.34	4.75	3.70	5.63
32	49	1.14	1.14	1.32	1.41	1.76	2.29	2.11	2.99	2.29	3.34
	60	1.14	1.14	1.36	1.46	2.11	2.64	2.46	3.52	2.82	3.87
	71	1.14	1.14	1.39	1.51	2.29	2.82	2.82	3.87	3.17	4.40
38	49	1.14	1.14	1.23	1.30	1.41	1.76	1.50	2.11	1.55	2.11
	60	1.14	1.14	1.28	1.37	1.76	2.11	1.94	2.64	2.11	2.82
	71	1.14	1.14	1.34	1.44	1.94	2.46	2.29	3.17	2.64	3.52

^aAlthough the term effective resistance is commonly used when there is attic ventilation, this table includes values for situations with no ventilation. The effective resistance of the attic added to the resistance ($1/U$) of the ceiling yields the effective resistance of this combination based on sol-air (see [Chapter 29](#)) and room temperatures. These values apply to wood frame construction with a roof deck and roofing that has a conductance of 5.7 W/(m²·K).

^bThis condition cannot be achieved in the field unless extreme measures are taken to tightly seal the attic.

^cBased on air discharging outward from attic.

^dWhen attic ventilation meets the requirements stated in [Chapter 26](#), 0.5 L/s per square metre is assumed as the natural summer ventilation rate.

^eWhen determining ceiling resistance, do not add the effect of a reflective surface facing the attic, as it is accounted for in the Reflective Surface part of this table.

^fRoof surface temperature rather than sol-air temperature (see [Chapter 29](#)) can be used if 0.04 is subtracted from the attic resistance shown.

^gSurfaces with effective emittance $\epsilon_{eff} = 0.05$ between ceiling joists facing attic space.

Table 6 Transmission Coefficients U for Wood and Steel Doors, W/(m²·K)

Nominal Door Thickness, mm	Description	No Storm Door	Wood Storm Door ^c	Metal Storm Door ^d
Wood Doors^{a,b}				
35	Panel door with 11 mm panels ^e	3.24	1.87	2.10
35	Hollow core flush door	2.67	1.70	1.82
35	Solid core flush door	2.21	1.48	1.59
45	Panel door with 11 mm panels ^e	3.07	1.82	2.04
45	Hollow core flush door	2.61	1.65	1.82
45	Panel door with 29 mm panels ^e	2.21	1.48	1.59
45	Solid core flush door	2.27	—	1.48
57	Solid core flush door	1.53	1.14	1.19
Steel Doors^b				
45	Fiberglass or mineral wool core with steel stiffeners, no thermal break ^f	3.41	—	—
45	Paper honeycomb core without thermal break ^f	3.18	—	—
45	Solid urethane foam core without thermal break ^a	2.27	—	—
45	Solid fire rated mineral fiberboard core without thermal break ^f	2.16	—	—
45	Polystyrene core without thermal break [18 gage (1.31 mm) commercial steel] ^f	1.99	—	—
45	Polyurethane core without thermal break (18 gage commercial steel) ^f	1.65	—	—
45	Polyurethane core without thermal break [24 gage (0.70 mm) residential steel] ^f	1.65	—	—
45	Polyurethane core with thermal break and wood perimeter (24 gage residential steel) ^f	1.14	—	—
45	Solid urethane foam core with thermal break ^a	1.14	—	0.91

Note: All U -factors for exterior doors in this table are for doors with no glazing, except for the storm doors which are in addition to the main exterior door. Any glazing area in exterior doors should be included with the appropriate glass type and analyzed as a window (see [Chapter 30](#)). Interpolation and moderate extrapolation are permitted for door thicknesses other than those specified.

^aValues are based on a nominal 810 mm by 2030 mm door size with no glazing.

^bOutside air conditions: 24 km/h wind speed, −18°C air temperature; inside air conditions: natural convection, 21°C air temperature.

^cValues for wood storm door are for approximately 50% glass area.

^dValues for metal storm door are for any percent glass area.

^e55% panel area.

^fASTM C 236 hot box data on a nominal 910 mm by 2130 mm door size with no glazing.

U_{wall} = thermal transmittance of all elements of opaque wall area
 A_{wall} = opaque wall area
 U_{window} = thermal transmittance of window area (including frame)
 A_{window} = window area (including frame)
 U_{door} = thermal transmittance of door area
 A_{door} = door area (including frame)

Where more than one type of wall, window, or door is used, the UA term for that exposure should be expanded into its subelements, as shown in Equation (3).

$$\begin{aligned}
 U_o A_o = & U_{wall\ 1} A_{wall\ 1} + U_{wall\ 2} A_{wall\ 2} + \dots + U_{wall\ m} A_{wall\ m} \\
 & + U_{window\ 1} A_{window\ 1} + U_{window\ 2} A_{window\ 2} + \dots \\
 & + U_{window\ n} A_{window\ n} + U_{door\ 1} A_{door\ 1} \\
 & + U_{door\ 2} A_{door\ 2} + \dots + U_{door\ o} A_{door\ o}
 \end{aligned} \quad (5)$$

Example 5. Calculate U_o for a wall 10 m by 2.4 m, constructed as in Example 1. The wall contains two double-glazed (12.7 mm airspace) fixed windows with wood/vinyl frames. (From [Table 4 in Chapter 30](#), $U = 2.98\text{ W}/(\text{m}^2 \cdot \text{K})$.) One window is 1500 mm by 860 mm and the second 900 mm by 760 mm. The wall also contains a 45 mm solid core flush door with a metal storm door 860 mm by 2000 mm ($U = 1.42\text{ W}/(\text{m}^2 \cdot \text{K})$ from [Table 6](#)).

Solution: The U-factor for the wall was obtained in Example 1. The areas of the different components are

$$\begin{aligned}
 A_{window} &= (1.500 \times 0.860) + (0.900 \times 0.760) = 1.97\text{ m}^2 \\
 A_{door} &= (0.860 \times 2.000) = 1.72\text{ m}^2 \\
 A_{wall} &= (10 \times 2.4) - (1.97 + 1.72) = 20.31\text{ m}^2
 \end{aligned}$$

Therefore, the combined thermal transmittance for the wall is

$$\begin{aligned}
 U_o &= \frac{(0.404 \times 20.31) + (2.90 \times 1.97) + (1.42 \times 1.72)}{10 \times 2.4} \\
 &= 0.68\text{ W}/(\text{m}^2 \cdot \text{K})
 \end{aligned}$$

Slab-on-Grade and Below-Grade Construction

Heat transfer through basement walls and floors to the ground depends on the following factors: (1) the difference between the air temperature within the room and that of the ground and outside air, (2) the material of the walls or floor, and (3) the thermal conductivity of the surrounding earth. The latter varies with local conditions and is usually unknown. Because of the great thermal inertia of the surrounding soil, ground temperature varies with depth, and there is a substantial time lag between changes in outdoor air temperatures and corresponding changes in ground temperatures. As a result, ground-coupled heat transfer is less amenable to steady-state representation than above-grade building elements. However, several simplified procedures for estimating ground-coupled heat transfer have been developed. These fall into two principal categories: (1) those that reduce the ground heat transfer problem to a closed form solution, and (2) those that use simple regression equations developed from statistically reduced multidimensional transient analyses.

Closed form solutions, including the ASHRAE arc-length procedure discussed in [Chapter 28](#) by Latta and Boileau (1969), generally reduce the problem to one-dimensional, steady-state heat transfer. These procedures use simple, “effective” U-factors or ground temperatures or both. Methods differ in the various parameters averaged or manipulated to obtain these effective values. Closed form solutions provide acceptable results in climates that have a single dominant season, because the dominant season persists long enough to permit a reasonable approximation of steady-state conditions at shallow depths. The large errors (percentage) that are likely during transition seasons should not seriously affect

building design decisions, since these heat flows are relatively insignificant when compared with those of the principal season.

The ASHRAE arc-length procedure is a reliable method for wall heat losses in cold winter climates. [Chapter 28](#) discusses a slab-on-grade floor model developed by one study. Although both procedures give results comparable to transient computer solutions for cold climates, their results for warmer U.S. climates differ substantially.

Research conducted by Houghten et al. (1942) and Dill et al. (1945) indicates a heat flow of approximately $6.3\text{ W}/\text{m}^2$ through an uninsulated concrete basement floor with a temperature difference of 11 K between the basement floor and the air 150 mm above it. A U-factor of $5.7\text{ W}/(\text{m}^2 \cdot \text{K})$ is sometimes used for concrete basement floors on the ground. For basement walls below grade, the temperature difference for winter design conditions is greater than for the floor. Test results indicate that at the midheight of the below-grade portion of the basement wall, the unit area heat loss is approximately twice that of the floor.

For concrete slab floors in contact with the ground at grade level, tests indicate that for small floor areas (equal to that of a 7.5 m by 7.5 m house) the heat loss can be calculated as proportional to the length of exposed edge rather than total area. This amounts to 1.40 W per linear metre of exposed edge per degree Celsius difference between the indoor air temperature and the average outdoor air temperature. This value can be reduced appreciably by installing insulation under the ground slab and along the edge between the floor and abutting walls. In most calculations, if the perimeter loss is calculated accurately, no other floor losses need to be considered. [Chapter 28](#) contains data for load calculations and heat loss values for below-grade walls and floors at different depths.

The second category of simplified procedures uses transient two-dimensional computer models to generate the ground heat transfer data that are then reduced to compact form by regression analysis (Mitalas 1982, 1983; Shipp 1983). These are the most accurate procedures available, but the database is very expensive to generate. In addition, these methods are limited to the range of climates and constructions specifically examined. Extrapolating beyond the outer bounds of the regression surfaces can produce significant errors.

Apparent Thermal Conductivity of Soil

Effective or apparent soil thermal conductivity is difficult to estimate precisely and may change substantially in the same soil at different times due to changed moisture conditions and the presence of freezing temperatures in the soil. [Figure 8](#) shows the typical apparent soil thermal conductivity as a function of moisture content for different general types of soil. The figure is based on data presented in Salomone and Marlowe (1989) using envelopes of thermal behavior coupled with field moisture content ranges for different soil types. In [Figure 8](#), the term well-graded applies to granular soils with good representation of all particle sizes from largest to smallest. The term poorly graded refers to granular soils with either a uniform gradation, in which most particles are about the same size, or a skip (or gap) gradation, in which particles of one or more intermediate sizes are not present.

Although thermal conductivity varies greatly over the complete range of possible moisture contents for a soil, this range can be narrowed if it is assumed that the moisture contents of most field soils lie between the “wilting point” of the soil (i.e., the moisture content of a soil below which a plant cannot alleviate its wilting symptoms) and the “field capacity” of the soil (i.e., the moisture content of a soil that has been thoroughly wetted and then drained until the drainage rate has become negligibly small). After a prolonged dry spell, the moisture will be near the wilting point, and after a rainy period, the soil will have a moisture content near its field capacity. The moisture contents at these limits have been studied by many agricultural researchers, and data for different types of soil are given by Salomone and Marlowe (1989) and Kersten (1949). The shaded

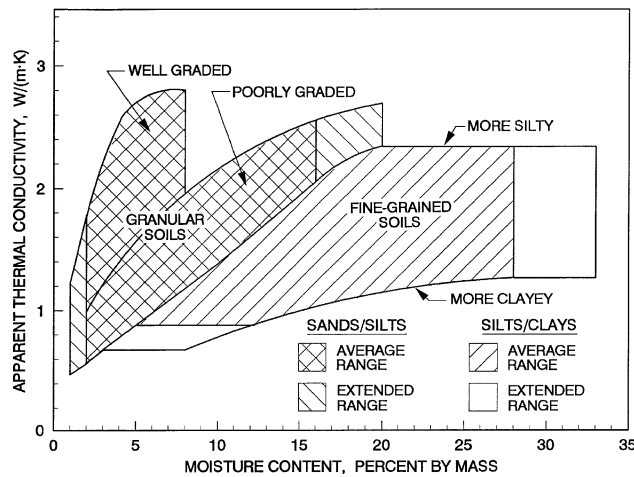


Fig. 8 Trends of Apparent Thermal Conductivity of Moist Soils

Table 7 Typical Apparent Thermal Conductivity Values for Soils, $W/(m^2 \cdot K)$

	Normal Range	Recommended Values for Design ^a	
		Low ^b	High ^c
Sands	0.6 to 2.5	0.78	2.25
Silts	0.9 to 2.5	1.64	2.25
Clays	0.9 to 1.6	1.12	1.56
Loams	0.9 to 2.5	0.95	2.25

^aReasonable values for use when no site- or soil-specific data are available.

^bModerately conservative values for minimum heat loss through soil (e.g., use in soil heat exchanger or earth-contact cooling calculations). Values are from Salomone and Marlowe (1989).

^cModerately conservative values for maximum heat loss through soil (e.g., use in peak winter heat loss calculations). Values are from Salomone and Marlowe (1989).

Table 8 Typical Apparent Thermal Conductivity Values for Rocks, $W/(m^2 \cdot K)$

	Normal Range
Pumice, tuff, obsidian	0.5 to 2.2
Basalt	0.5 to 2.6
Shale	0.9 to 4.0
Granite	1.7 to 4.3
Limestone, dolomite, marble	1.2 to 4.3
Quartzose sandstone	1.4 to 7.8

areas on Figure 8 approximate (1) the full range of moisture contents for different soil types and (2) a range between average values of each limit.

Table 7 gives a summary of design values for thermal conductivities of the basic soil classes. Table 8 gives ranges of thermal conductivity for some basic classes of rock. The value chosen depends on whether heat transfer is being calculated for minimum heat loss through the soil, as in a ground heat exchange system, or a maximum value, as in peak winter heat loss calculations for a basement. Hence, a high and a low value are given for each soil class.

As heat flows through the soil, the moisture tends to move away from the source of heat. This moisture migration provides initial mass transport of heat, but it also dries the soil adjacent to the heat source, hence lowering the apparent thermal conductivity in that zone of soil.

Trends typical in a soil when other factors are held constant are:

- k increases with moisture content
- k increases with increasing dry density of a soil
- k decreases with increasing organic content of a soil
- k tends to decrease for soils with uniform gradations and rounded soil grains (because the grain-to-grain contacts are reduced)
- k of a frozen soil may be higher or lower than that of the same unfrozen soil (because the conductivity of ice is higher than that of water but lower than that of the typical soil grains). Differences in k below moisture contents of 7 to 8% are quite small. At approximately 15% moisture content, differences in k -factors may vary up to 30% from unfrozen values.

When calculating annual energy use, values that represent typical site conditions as they vary during the year should be chosen. In climates where ground freezing is significant, accurate heat transfer simulations should include the effect of the latent heat of fusion of water. The energy released during this phase change significantly retards the progress of the frost front in moist soils.

Water Vapor Transmission Data for Building Components

Table 9 gives typical water vapor permeance and permeability values for common building materials. These values can be used to calculate water vapor flow through building components and assemblies using equations in Chapter 23.

MECHANICAL AND INDUSTRIAL SYSTEMS

Thermal Transmission Data

Table 10 lists the thermal conductivities of various materials used as industrial insulations. These values are functions of the arithmetic mean of the temperatures of the inner and outer surfaces for each insulation.

Heat Loss from Pipes and Flat Surfaces

Tables 11A, 11B, and 12 give heat losses from bare steel pipes and flat surfaces and bare copper tubes. These tables were calculated using ASTM Standard C 680. User inputs for the programs described in the standard include operating temperature, ambient temperature, pipe size, insulation type, number of insulation layers, and thickness for each layer. A program option allows the user to input a surface coefficient or surface emittance, surface orientation, and wind speed. The computer uses this information to calculate the heat flow and the surface temperature. The programs calculate the surface coefficients if the user has not already supplied them.

The equations used in ASTM C 680 are

$$h_{cv} = C \left(\frac{1}{d} \right)^{0.2} \left(\frac{1}{T_{avg}} \right)^{0.181} (\Delta T^{0.266}) \sqrt{1 + 0.7935(Wind)} \quad (6)$$

where

h_{cv} = convection surface coefficient, $W/(m^2 \cdot K)$

d = diameter for cylinder, mm. For flat surfaces and large cylinders ($d > 600$ mm), use $d = 600$ mm.

T_{avg} = average temperature of air film = $(T_a + T_s)/2$, K

T_a = temperature of ambient air, K

T_s = temperature of surface, K

ΔT = surface to air temperature difference, K

Wind = air speed, km/h

C = constant depending on shape and heat flow condition

= 11.58 for horizontal cylinders

= 14.08 for longer vertical cylinders

= 15.89 for vertical plates

= 20.40 for horizontal plates, warmer than air, facing upward

= 10.15 for horizontal plates, warmer than air, facing downward

= 10.15 for horizontal plates, cooler than air, facing upward

= 20.40 for horizontal plates, cooler than air, facing downward

Table 9 Typical Water Vapor Permeance and Permeability Values for Common Building Materials^a

Material	Thickness, mm	Permeance, ng/(s·m ² ·Pa)	Resistance ^h , TPa·m ² ·s/kg	Permeability, ng/(s·m·Pa)	Resistance/m ^h , TPa·m·s/kg
Construction Materials					
Concrete (1:2:4 mix)				4.7	0.21
Brick masonry	100	46 ^f	0.022		
Concrete block (cored, limestone aggregate)	200	137 ^f	0.0073		
Tile masonry, glazed	100	6.9 ^f	0.14		
Asbestos cement board	3	220-458 ^d	0.0017-0.0035		
With oil-base finishes		17-29 ^d	0.0035-0.052		
Plaster on metal lath	19	860 ^f	0.0012		
Plaster on wood lath		630 ^e	0.0016		
Plaster on plain gypsum lath (with studs)		1140 ^f	0.00088		
Gypsum wall board (plain)	9.5	2860 ^f	0.00035		
Gypsum sheathing (asphalt impregnated)	13		29 ^f	0.038	
Structural insulating board (sheathing quality)				29-73 ^f	0.038-0.014
Structural insulating board (interior, uncoated)	13	2860-5150 ^f	0.00035-0.00019		
Hardboard (standard)	3.2	630 ^f	0.0016		
Hardboard (tempered)	3.2	290 ^f	0.0034		
Built-up roofing (hot mopped)		0.0	∞		
Wood, sugar pine				0.58-7.8 ^{f,b}	172.0-131
Plywood (douglas fir, exterior glue)	6.4	40 ^f	0.025		
Plywood (douglas fir, interior glue)	6.4	109 ^f	0.0092		
Acrylic, glass fiber reinforced sheet	1.4	6.9 ^{f*}	0.145		
Polyester, glass fiber reinforced sheet	1.2	2.9 ^f	0.345		
Thermal Insulations					
Air (still)				174 ^f	0.0057
Cellular glass				0.0 ^{d*}	∞
Corkboard				3.0-3.8 ^d	0.33-0.26
				14 ^e	0.076
Mineral wool (unprotected)				245 ^e	0.0059
Expanded polyurethane [R = 1.94 W/(m ² ·K)] board stock				0.58-2.3 ^d	1.72-0.43
Expanded polystyrene—extruded				1.7 ^d	0.57
Expanded polystyrene—bead				2.9-8.4 ^{d*}	0.34-0.12
Phenolic foam (covering removed)				38	0.026
Unicellular synthetic flexible rubber foam				0.029 ^d	34-4.61
Plastic and Metal Foils and Films^c					
Aluminum foil	0.025	0.0 ^d	∞		
Aluminum foil	0.009	2.9 ^d	0.345		
Polyethylene	0.051	9.1 ^d	0.110		2133
Polyethylene	0.1	4.6 ^d	0.217		2133
Polyethylene	0.15	3.4 ^{d*}	0.294		2133
Polyethylene	0.2	2.3 ^{d*}	0.435		2133
Polyethylene	0.25	1.7 ^d	0.588		2133
Polyvinylchloride, unplasticized	0.051	39 ^{d*}	0.026		
Polyvinylchloride, plasticized	0.1	46-80 ^{d*}	0.032		
Polyester	0.025	42 ^d	0.042		
Polyester	0.09	13 ^d	0.075		
Polyester	0.19	4.6 ^d	0.22		
Cellulose acetate	0.25	263 ^d	0.0035		
Cellulose acetate	3.2	18 ^d	0.054		

*Source: Lotz (1964).

$$h_{rad} = \frac{\varepsilon \sigma (T_a^4 - T_s^4)}{T_a - T_s} \quad (7)$$

where

 h_{rad} = radiation surface coefficient, W/(m²·K) ε = surface emittance σ = Stefan-Boltzmann constant = 5.4×10^{-8} W/(m²·K⁴)

Example 6. Compute the total annual heat loss from 50 m of nominal 50 mm bare steel pipe in service 4000 h per year. The pipe is carrying steam at 70 kPa (gage) and is exposed to an average air temperature of 27°C.

Solution: The pipe temperature is taken as the steam temperature, which is 115.2°C, obtained by interpolation from Steam Tables. By interpolation in Table 11A between 82 and 138°C, heat loss from a nominal 50 mm pipe is 274 W/m. Total annual heat loss from the entire line is $274 \times 50 \times 4000 \times 3600 = 197$ GJ.

In calculating heat flow, Equations (8) and (9) from Chapter 23 generally are used. For dimensions of standard pipe and fitting sizes, refer to the *Piping Handbook*. For insulation product dimensions, refer to ASTM Standard C 585, or to the insulation manufacturers' literature.

Table 9 Typical Water Vapor Permeance and Permeability Values for Common Building Materials^a (Concluded)

Material	Unit Mass, kg/m ²	Permeance, ng/(s·m ² ·Pa)			Resistance ^h , TPa·m ² ·s/kg		
		Dry-Cup	Wet-Cup	Other	Dry-Cup	Wet-Cup	Other
Building Paper, Felts, Roofing Papers ^g							
Duplex sheet, asphalt laminated, aluminum foil one side	0.42	0.1	10		10	0.1	
Saturated and coated roll roofing	3.18	2.9	14		0.34	0.071	
Kraft paper and asphalt laminated, reinforced	0.33	17	103		0.059	0.0097	
Blanket thermal insulation backup paper, asphalt coated	0.30	23	34-240		0.043	0.029-0.0042	
Asphalt-saturated and coated vapor retarder paper	0.42	11-17	34		0.091-0.059	0.029	
Asphalt-saturated, but not coated, sheathing paper	0.21	190	1160		0.0053	0.00086	
0.73 kg/m ² asphalt felt	0.68	57	320		0.017	0.0031	
0.73 kg/m ² tar felt	0.68	230	1040		0.0043	0.00096	
Single-kraft, double	0.16	1170	2400		0.00056	0.00042	
Liquid-Applied Coating Materials							
	Thickness,						
Commercial latex paints (dry film thickness) ⁱ	μm						
Vapor retarder paint	70			26			0.038
Primer-sealer	30			360			0.0028
Vinyl acetate/acrylic primer	50			424			0.0024
Vinyl-acrylic primer	40			491			0.0020
Semi-gloss vinyl-acrylic enamel	60			378			0.0026
Exterior acrylic house and trim	40			313			0.0032
Paint—2 coats							
Asphalt paint on plywood			23			0.043	
Aluminum varnish on wood		17-29			0.059-0.034		
Enamels on smooth plaster				29-86			0.034-0.012
Primers and sealers on interior insulation board				51-20			0.020-.0083
Various primers plus 1 coat flat oil paint on plaster				91-172			0.011-0.0058
Flat paint on interior insulation board				229			0.0044
Water emulsion on interior insulation board				1716-4863			0.00058-0.00021
	Unit Mass,						
Paint-3 coats	kg/m ²						
Exterior paint, white lead and oil on wood siding		17-57			0.0059-0.017		
Exterior paint, white lead-zinc oxide and oil on wood		51			0.020		
Styrene-butadiene latex coating	0.6	629			0.0016		
Polyvinyl acetate latex coating	1.2	315			0.0032		
Chlorosulfonated polyethylene mastic	1.1	97			0.010		
	2.2	3.4			0.29		
Asphalt cutback mastic, 1.6 mm, dry		8.0			0.125		
4.8 mm, dry		0			∞		
Hot melt asphalt	0.6	29			0.034		
	1.1	5.7			0.175		

^aThis table permits comparisons of materials; but in the selection of vapor retarder materials, exact values for permeance or permeability should be obtained from the manufacturer or from laboratory tests. The values shown indicate variations among mean values for materials that are similar but of different density, orientation, lot, or source. The values should not be used as design or specification data. Values from dry-cup and wet-cup methods were usually obtained from investigations using ASTM E 96 and C 355; values shown under others were obtained by two-temperature, special cell, and air velocity methods.

^bDepending on construction and direction of vapor flow.

^cUsually installed as vapor retarders, although sometimes used as an exterior finish and elsewhere near the cold side, where special considerations are then required for warm side barrier effectiveness.

^dDry-cup method.

^eWet-cup method.

^fOther than dry- or wet-cup method.

^gLow permeance sheets used as vapor retarders. High permeance used elsewhere in construction.

^hResistance and resistance/mm values have been calculated as the reciprocal of the permeance and permeability values.

ⁱCast at 0.25 mm wet film thickness.

Table 10 Typical Thermal Conductivity for Industrial Insulations at Various Mean Temperatures—Design Values^a

Material	Accepted Max. Temp. for Use, °C	Typical Density, kg/m ³	Typical Conductivity <i>k</i> in W/(m·K) at Mean Temperature, °C													
			-73	-59	-46	-32	-18	-4	10	24	38	93	150	200	370	480
BLANKETS AND FELTS																
ALUMINOSILICATE FIBER	980	64									0.035	0.046		0.078	0.143	0.148
7 to 10 µm diameter fiber	1100	96-128									0.036	0.043		0.069	0.112	0.137
	1200	64									0.032	0.042		0.065	0.085	0.107
3 µm diameter fiber																
MINERAL FIBER (Rock, slag, or glass)	650	96-190									0.037	0.046	0.056	0.078		
Blanket, metal reinforced	540	40-96									0.035	0.045	0.058	0.088		
	180	<12				0.036	0.037	0.040	0.043	0.048	0.052	0.076				
Blanket, flexible, fine-fiber		12				0.035	0.036	0.039	0.042	0.046	0.049	0.069				
organic bonded		16				0.033	0.035	0.036	0.039	0.042	0.046	0.062				
		24				0.030	0.032	0.033	0.036	0.039	0.040	0.053				
		32				0.029	0.030	0.032	0.033	0.036	0.037	0.048				
		48				0.027	0.029	0.030	0.032	0.033	0.035	0.045				
Blanket, flexible, textile fiber,	180	10				0.039	0.040	0.042	0.043	0.045	0.046	0.072	0.098			
organic bonded		12				0.037	0.039	0.040	0.042	0.045	0.046	0.069	0.095			
		16				0.035	0.036	0.037	0.039	0.042	0.045	0.065	0.086			
		24				0.032	0.033	0.035	0.036	0.039	0.042	0.056	0.073			
		48				0.029	0.030	0.032	0.033	0.035	0.036	0.046	0.059			
Felt, semirigid organic bonded	200	48-130							0.035	0.036	0.037	0.039	0.050	0.063		
	450	48	0.023	0.024	0.026	0.027	0.029	0.030	0.032	0.033	0.035	0.050	0.079			
Laminated and felted without binder	650	120											0.050	0.065	0.086	
BLOCKS, BOARDS, AND PIPE INSULATION																
MAGNESIA	320	176-192									0.050	0.055	0.060			
85% CALCIUM SILICATE	650	176-240									0.055	0.059	0.063	0.075	0.089	0.104
	980	192-240												0.091	0.107	0.137
CELLULAR GLASS	480	125-131	0.035	0.036	0.037	0.040	0.042	0.043	0.046	0.048	0.049	0.059	0.071	0.101	0.146	
DIATOMACEOUS SILICA	870	336-352												0.092	0.098	0.104
	1040	368-400												0.101	0.108	0.115
MINERAL FIBER (Glass)																
Organic bonded, block, and boards	200	48-160	0.023	0.024	0.026	0.027	0.029	0.032	0.035	0.036	0.037	0.048	0.058			
Nonpinking binder	540	48-160									0.037	0.045	0.055	0.075		
Pipe insulation, slag, or glass	180	48-64					0.029	0.030	0.032	0.033	0.035	0.042				
	260	48-160					0.039	0.032	0.035	0.036	0.037	0.048	0.058			
Inorganic bonded block	540	160-240									0.048	0.055	0.065	0.079		
	980	240-384									0.046	0.053	0.060	0.075	0.089	0.107
Pipe insulation, slag, or glass	540	160-240									0.048	0.055	0.065	0.079		
Resin binder		240		0.033	0.035	0.036	0.037	0.040	0.042							
RIGID POLYSTYRENE																
Extruded (R-12 exp.)(smooth skin sur- face)	80	29-56	0.023	0.023	0.024	0.023	0.024	0.026	0.027	0.029						
Molded beads	80	16	0.024	0.027	0.029	0.030	0.032	0.035	0.036	0.037	0.040					
		20	0.024	0.026	0.027	0.029	0.032	0.033	0.035	0.036	0.040					
		24	0.023	0.024	0.027	0.029	0.030	0.032	0.033	0.035	0.037					
		28	0.023	0.024	0.026	0.027	0.029	0.032	0.033	0.035	0.036					
RIGID POLYURETHANE/POLYISOCYANURATE ^{c,d}																
Unfaced (R-11 exp.)	120	24-40	0.023	0.025	0.026	0.026	0.026	0.025	0.023	0.025	0.025					
RIGID POLYISOCYANURATE																
Gas-imperm. facers (R-11 exp.)	100	32						0.017	0.019	0.020	0.022					
RIGID PHENOLIC																
Closed cell (R-11, R-113 exp.)		48						0.016	0.017	0.017	0.018					
RUBBER, Rigid foamed	70	72						0.029	0.030	0.032	0.033					
VEGETABLE AND ANIMAL FIBER																
Wool felt (pipe insulation)	80	320						0.040	0.043	0.045	0.048					
INSULATING CEMENTS																
MINERAL FIBER (Rock, slag, or glass)																
With colloidal clay binder	980	380-480									0.071	0.079	0.088	0.105	0.122	
With hydraulic setting binder	650	480-640									0.108	0.115	0.122	0.137		
LOOSE FILL																
Cellulose insulation (milled pulverized paper or wood pulp)		40-48							0.037	0.039	0.042					
Mineral fiber, slag, rock, or glass		32-80			0.027	0.030	0.033	0.036	0.037	0.040	0.045					
Perlite (expanded)		48-80	0.032	0.035	0.036	0.039	0.040	0.043	0.045	0.048	0.050					
Silica aerogel		120			0.019	0.020	0.022	0.022	0.023	0.024	0.026					
Vermiculite (expanded)		110-130			0.056	0.058	0.060	0.063	0.065	0.068	0.071					
		64-96			0.049	0.050	0.055	0.058	0.060	0.063	0.066					

^aRepresentative values for dry materials, which are intended as design (not specification) values for materials in normal use. Insulation materials in actual service may have thermal values that vary from design values depending on their in-situ properties (e.g., density and moisture content). For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

^bThese temperatures are generally accepted as maximum. When operating temperature approaches these limits, follow the manufacturers' recommendations.

^cSome polyurethane foams are formed by means that produce a stable product (with respect to *k*), but most are blown with refrigerant and will change with time.

^dSee Table 4, footnote i.

^eSee Table 4, footnote j.

Examples 7 and 8 illustrate how Equations (8) and (9) from Chapter 23 can be used to determine heat loss from both flat and cylindrical surfaces. Figure 9 shows surface resistance as a function of heat transmission for both flat and cylindrical surfaces. The surface emittance is assumed to be 0.85 to 0.90 in still air at 27°C.

Example 7. Compute the heat loss from a boiler wall if the interior insulation surface temperature is 600°C and ambient still air temperature is 27°C. The wall is insulated with 115 mm of mineral fiber block and 13 mm of mineral fiber insulating and finishing cement.

Solution: Assume that the mean temperature of the mineral fiber block is 370°C, the mean temperature of the insulating cement is 93°C, and the surface resistance R_s is 0.11 m²·K/W.

From Table 10, $k_1 = 0.089$ and $k_2 = 0.115$. Using Equation (8) from Chapter 23,

$$q_s = \frac{600 - 27}{(0.115/0.089) + (0.013/0.115) + 0.11} = 378 \text{ W/m}^2$$

As a check, from Figure 9, at 378 W/m², $R_s \cong 0.10$. The mean temperature of the mineral fiber block is

$$0.115/0.089 = 1.292; 1.292/2 = 0.646$$

$$600 - \frac{0.646}{1.505}(600 - 27) = 354^\circ\text{C}$$

and the mean temperature of the insulating cement is

$$0.013/0.115 = 0.113; 0.113/2 = 0.057; 1.292 - 0.057 = 1.349$$

$$600 - \frac{1.349}{1.505}(600 - 27) = 87^\circ\text{C}$$

From Table 10, at 354°C, $k_1 = 0.087$; at 87°C, $k_2 = 0.114$.

Using these adjusted values to recalculate q_s ,

$$q_s = \frac{573}{(0.115/0.087) + (0.013/0.114) + 0.10} = 372.1 \text{ W/m}^2$$

From Figure 9, at 373 W/m², $R_s = 0.10$. The mean temperature of the mineral fiber block is

$$0.115/0.087 = 1.322; 1.322/2 = 0.661$$

$$600 - \frac{0.661}{1.536}573 = 353^\circ\text{C}$$

and the mean temperature of the insulating cement is

$$0.013/0.114 = 0.1140; 0.1140/2 = 0.057; 1.322 + 0.057 = 1.379$$

$$600 - \frac{1.379}{1.536}573 = 86^\circ\text{C}$$

From Table 10, at 353°C, $k_1 = 0.087$; at 86°C, $k_2 = 0.114$.

Because R_s , k_1 , and k_2 do not change at these values, $q_s = 373.1 \text{ W/m}^2$.

Example 8. Compute heat loss per square foot of outer surface of insulation if pipe temperature is 650°C and ambient still air temperature is 27°C. The pipe is nominal 150 mm steel pipe, insulated with a nominal 75 mm thick diatomaceous silica as the inner layer and a nominal 50 mm thick calcium silicate as the outer layer.

Solution: From Chapter 41 of the *ASHRAE Handbook—Systems and Equipment*, $r_o = 84.1 \text{ mm}$. A nominal 75 mm thick diatomaceous silica insulation to fit a nominal 150 mm steel pipe is 76.7 mm thick. A nominal 50 mm thick calcium silicate insulation to fit over the 52.8 mm diatomaceous silica is 52.8 mm thick. Therefore, $r_i = 160.8 \text{ mm}$ and $r_s = 213.6 \text{ mm}$.

Assume that the mean temperature of the diatomaceous silica is 315°C, the mean temperature of the calcium silicate is 120°C and the surface resistance R_s is 0.09. From Table 10, $k_1 = 0.095$; $k_2 = 0.060$. By Equation (9) from Chapter 23,

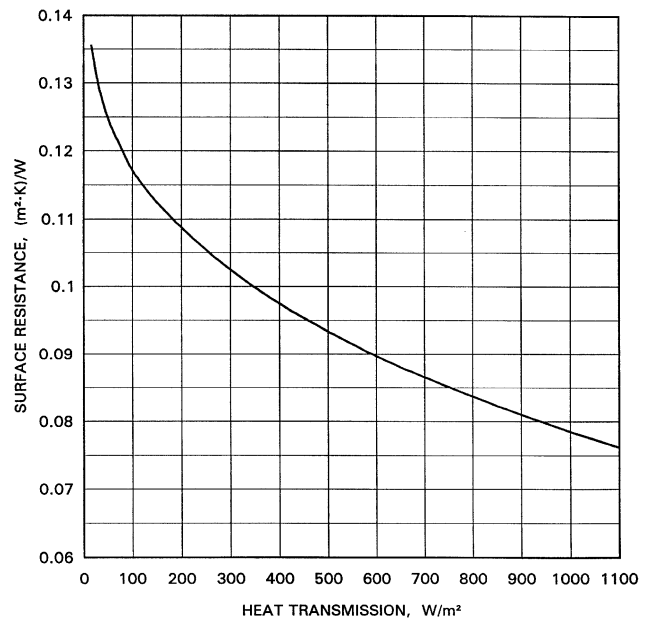


Fig. 9 Surface Resistance as Function of Heat Transmission for Flat Surfaces and Cylindrical Surfaces Greater than 600 mm in Diameter

$$q_s = \frac{650 - 27}{\frac{0.2136 \ln(160.8/84.1)}{0.095} + \frac{0.2136 \ln(213.6/160.8)}{0.060} + 0.09} = \frac{623}{(1.457 + 1.011 + 0.09)} = 243 \text{ W/m}^2$$

From Figure 9, at 243 W/m², $R_s = 0.11$. The mean temperature of the diatomaceous silica is

$$0.2136 \ln(160.8/84.1)/0.095 = 1.46; 1.46/2 = 0.73$$

$$650 - \frac{(650 - 27)0.73}{1.457 + 1.011 + 0.11} = 474^\circ\text{C}$$

and the mean temperature of the calcium silicate is

$$\frac{0.2136 \ln(213.6/160.8)}{0.060} = 1.01; \frac{1.01}{2} = 0.51; 1.46 + 0.51 = 1.97$$

$$650 - \frac{(650 - 27)1.97}{1.457 + 1.011 + 0.11} = 174^\circ\text{C}$$

From Table 10, $k_1 = 0.104$; $k_2 = 0.066$. Recalculating,

$$q_s = \frac{623}{\frac{0.2136 \ln(160.8/84.1)}{0.104} + \frac{0.2136 \ln(213.6/160.8)}{0.066} + 0.11} = 264 \text{ W/m}^2$$

From Figure 9 at 264 W/m², $R_s = 0.11$. The mean temperature of the diatomaceous silica is

$$\frac{0.2136 \ln(160.8/84.1)}{0.104} = 1.33; \frac{1.33}{2} = 0.665$$

$$650 - \frac{0.665/2.360}{623} = 474^\circ\text{C}$$

and the mean temperature of the calcium silicate is

$$\frac{0.2136 \ln(213.6/160.8)}{0.066} = 0.919; \frac{0.919}{2} = 0.46; 1.33 + 0.46 = 1.79$$

$$650 - \frac{1.79}{2.360}623 = 177^\circ\text{C}$$

Table 11A Heat Loss from Bare Steel Pipe to Still Air at 27°C^a, W/m

Nominal Pipe Size ^b , mm	Pipe Inside Temperature, °C									
	82	138	194	249	305	360	416	471	527	582
15	57.0	141.5	252.9	396.2	577.5	804.2	1084.6	1427.7	1843.2	2341.8
20	69.7	173.1	310.0	486.5	710.4	991.0	1338.6	1764.4	2280.9	2901.1
25	85.3	212.2	380.7	598.4	875.4	1223.0	1654.1	2182.9	2824.8	3595.7
32	105.4	262.2	471.3	742.2	1097.6	1522.0	2061.9	2724.8	3530.1	4498.3
40	119.1	296.5	533.5	841.0	1233.7	1728.2	2343.1	3098.8	4017.5	5122.1
50	145.9	363.4	654.8	1034.3	1519.8	2132.4	2895.1	3833.6	4975.3	6349.1
80	207.5	517.8	935.5	1481.7	2182.8	3069.4	4175.4	5537.5	7194.9	9189.4
100	261.0	652.1	1180.3	1872.7	2763.7	3892.5	5302.3	7040.3	9156.5	11703.9
150	372.0	930.9	1689.2	2687.7	3977.8	5613.6	7661.8	10189.6	13269.7	16978.6
200	474.1	1187.5	2158.5	3440.4	5098.6	7207.5	9848.7	13110.2	17084.9	21870.4
250	580.7	1455.7	2649.7	4229.1	6275.4	8880.7	12145.7	16178.5	21093.2	27008.8
300	676.5	1693.6	3078.9	4905.8	7262.6	10246.0	13958.4	18505.7	23993.9	30527.9
400	838.2	2103.6	3837.5	6138.3	9125.6	12933.1	17706.2	23598.9	30772.3	39392.1
500	1030.3	2587.4	4725.0	7566.1	11258.2	15965.5	21865.2	29144.1	37995.6	48617.0
600	1219.8	3064.5	5601.0	8975.6	13363.2	18957.6	25966.0	34605.7	45100.0	57674.1

Table 11B Heat Loss from Flat Surfaces to Still Air at 27°C, W/m

	Surface Inside Temperature, °C									
	82	138	194	249	305	360	416	471	527	582
Vertical surface	668.4	1679.3	3065.9	4909.6	7311.8	10388.7	14269.8	19097.8	25028.3	32229.2
Horizontal surface										
Facing up	739.3	1847.2	3342.5	5303.0	7827.4	11030.0	15042.5	20003.8	26070.3	33409.2
Facing down	578.3	1465.7	2713.4	4408.7	6655.3	9571.0	13286.1	17944.6	23702.2	30727.3

^aCalculations from ASTM C680; steel: $k = 45.3 \text{ W/(m}^2 \cdot \text{K)}$; $\varepsilon = 0.94$.

^bLosses per square metre of pipe for pipes larger than 600 mm can be considered the same as losses per square metre for 600 mm pipe.

From Table 10, at 474°C, $k_1 = 0.104$; at 177°C, $k_2 = 0.066$. Since R_s , k_1 , and k_2 do not change at 264 W/m², this value is q_s . The heat flow per square metre of the inner surface of the insulation is

$$q_o = q_s(r_s/r_o) = 264(213.6/84.1) = 6701 \text{ W/m}^2$$

Because trial-and-error techniques are tedious, the computer programs previously described should be used to estimate heat flows per unit area of flat surfaces or per unit length of piping, and interface temperatures including surface temperatures.

Several methods can be used to determine the most effective thickness of insulation for piping and equipment. Table 13 shows the recommended insulation thicknesses for three different pipe and equipment insulations. Installed cost data can be developed using procedures described by the Federal Energy Administration (1976). Computer programs capable of calculating thickness information are available from several sources. Also, manufacturers of insulations offer computerized analysis programs for designers and owners to evaluate insulation requirements. For more information on determining economic insulation thickness, see Chapter 23.

Chapters 3 and 23 give guidance concerning process control, personnel protection, condensation control, and economics. For specific information on sizes of commercially available pipe insulation, see ASTM Standard C 585 and consult with the North American Insulation Manufacturers Association (NAIMA) and its member companies.

CALCULATING HEAT FLOW FOR BURIED PIPELINES

In calculating heat flow to or from buried pipelines, the thermal properties of the soil must be assumed. Table 7 gives the apparent thermal conductivity values of various soil types, and Figure 8 shows the typical trends of apparent soil thermal conductivity with moisture content for various soil types. Table 8 provides ranges of apparent thermal conductivity for various types of rock. Kernsten (1949) also discusses thermal properties of soils. Carslaw and Jaeger (1959) give methods for calculating the heat flow taking place between one or more buried cylinders and the surroundings.

Table 12 Heat Loss from Bare Copper Tube to Still Air at 27°C^a, W/m

Nominal Tube Size, mm	Tube Inside Temperature, °C							
	120	150	180	210	240	270	300	330
8	6.8	13.6	21.0	29.4	38.3	48.0	58.2	69.1
15	10.6	20.9	32.7	45.6	59.5	74.5	90.4	107.4
20	14.1	28.0	43.6	60.8	79.5	99.6	121.1	144.0
25	17.6	34.8	54.2	75.6	98.8	123.9	150.6	179.2
32	20.9	41.4	64.6	89.9	117.6	147.4	179.4	213.5
40	24.2	47.9	74.6	104.1	136.0	170.5	207.6	247.1
50	30.6	60.4	94.2	131.4	171.8	215.6	262.4	312.7
80	42.9	84.7	131.8	184.0	240.7	302.1	368.3	439.1
100	54.8	107.9	168.2	234.7	307.2	385.7	470.3	561.1
150	77.6	152.8	238.0	332.2	435.1	546.7	667.1	796.7
200	99.7	196.1	305.4	426.4	558.6	702.2	857.3	1024.4
250	121.2	238.2	371.0	518.1	678.9	853.8	1042.9	1246.8
300	142.2	279.6	435.3	607.8	796.9	1002.4	1224.9	1464.9
8	5.2	10.4	16.2	22.6	29.3	36.4	43.7	51.4
15	7.9	15.8	24.7	34.3	44.5	55.2	66.4	78.0
20	10.3	20.8	32.5	45.1	58.5	72.7	87.4	102.6
25	12.7	25.5	39.8	55.4	71.8	89.2	107.2	126.1
32	14.9	30.1	46.9	65.2	84.6	105.0	126.5	148.7
40	17.1	34.4	53.8	74.8	97.0	120.4	144.9	170.5
50	21.3	42.9	67.0	93.0	120.8	150.0	180.6	212.5
80	29.3	58.8	91.9	127.6	165.7	205.8	247.8	291.7
100	36.8	73.8	115.3	160.3	208.2	258.6	311.5	366.5
150	50.9	102.2	159.5	221.7	288.0	358.0	431.2	507.7
200	64.2	128.9	201.2	279.7	363.5	451.8	544.4	641.2
250	77.1	154.5	241.2	335.4	435.7	541.7	653.0	769.2
300	89.4	179.2	279.9	389.1	505.6	628.7	757.9	893.1

Dull $\epsilon = 0.44$ Bright $\epsilon = 0.08$ ^aCalculations from ASTM C680; for copper: $k = 401.5 \text{ W/(m} \cdot \text{K)}$.

CODES AND STANDARDS

- ASTM. 1990. Standard practice for inner and outer diameters of rigid thermal insulation for nominal sizes of pipe and tubing. *Standard C585-90*. American Society for Testing and Materials, West Conshohocken, PA.
- ASTM. 1991. Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the heat flow meter apparatus. *Standard C 518-91*.
- ASTM. 1993. Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus. *Standard C 177-85* (Revised 1993).
- ASTM. 1993. Standard test method for steady-state thermal performance of building assemblies by means of a guarded hot box. *Standard C 236-89* (Revised 1993).
- ASTM. 1995. Standard practice for determination of heat gain or loss and the surface temperatures of insulated pipe and equipment systems by the use of a computer program. *Standard C 680-89* (Revised 1995).
- ASTM. 1996. Standard test method for thermal performance of building assemblies by means of a calibrated hot box. *Standard C 976-90* (Revised 1996).

REFERENCES

- Adams, L. 1971. Supporting cryogenic equipment with wood. *Chemical Engineering* (May):156-58.
- Barbour, E., J. Goodrow, J. Kosny, and J.E. Christian. 1994. Thermal performance of steel-framed walls. Prepared for American Iron and Steel Institute by NAHB Research Center.
- Bassett, M.R. and H.A. Trethowen. 1984. Effect of condensation on emittance of reflective insulation. *Journal of Thermal Insulation* 8 (October):127.
- Carlsaw, H.S. and J.C. Jaeger. 1959. Conduction of heat in solids. Oxford University Press, Amen House, London, England, 449.
- Dill, R.S., W.C. Robinson, and H.E. Robinson. 1945. Measurements of heat losses from slab floors. National Bureau of Standards. Building Materials and Structures Report, BMS 103.
- Economic thickness for industrial insulation. 1976. GPO No. 41-018-001 15-8, Federal Energy Administration, Washington, D.C.
- Farouk, B. and D.C. Larson. 1983. Thermal performance of insulated wall systems with metal studs. Proceedings of the 18th Intersociety Energy Conversion Engineering Conference, Orlando, FL.
- Farouki, O.T. 1981. Thermal properties of soil. CRREL Monograph 81-1, United States Army Corps of Engineers Cold Regions Research and Engineering Laboratory, December.
- Fishenden, M. 1962. Tables of emissivity of surfaces. *International Journal of Heat and Mass Transfer* 5:67-76.
- Goss, W.P. and R.G. Miller. 1989. Literature review of measurement and prediction of reflective building insulation system performance: 1900-1989. *ASHRAE Transactions* 95(2).
- Hooper, F.C. and W.J. Moroz. 1952. The impact of aging factors on the emissivity of reflective insulations. *ASTM Bulletin* (May):92-95.
- Houghten, F.C., S.I. Taimuty, C. Gutberlet, and C.J. Brown. 1942. Heat loss through basement walls and floors. *ASHVE Transactions* 48:369.
- Joy, F.A. 1958. Improving attic space insulating values. *ASHAE Transactions* 64:251.
- Kersten, M.S. 1949. Thermal properties of soils. University of Minnesota, Engineering Experiment Station Bulletin 28, June.

Table 13 Recommended Thicknesses for Pipe and Equipment Insulation

Nom. Dia., mm		MINERAL FIBER (Fiberglass and Rock Wool)										CALCIUM		
		Process Temperature, °C										Process Temp., °C		
		65	120	175	225	300	350	400	450	500	550	65	120	175
15	Thickness	25	38	50	63	75	88	100	100	113	125	25	38	50
	Heat loss	8	15	23	32	41	52	63	81	96	110	12	23	33
	Surface temp.	22	24	24	26	26	27	28	30	31	31	24	26	27
25	Thickness	25	38	50	63	88	100	100	113	125	138	25	50	63
	Heat loss	11	20	29	29	47	59	76	92	110	130	15	25	37
	Surface temp.	23	24	26	27	26	27	29	30	31	32	24	24	26
40	Thickness	25	50	63	75	100	100	100	138	138	150	38	65	75
	Heat loss	13	21	32	43	52	70	90	99	123	146	16	28	40
	Surface temp.	73	74	77	79	79	82	86	84	88	90	73	75	78
50	Thickness	38	50	75	88	100	100	100	138	150	200	38	63	75
	Heat loss	12	24	33	45	59	78	101	110	132	161	18	31	45
	Surface temp.	22	24	24	25	26	28	31	29	31	33	23	24	26
80	Thickness	38	63	88	100	100	113	113	150	163	175	50	75	88
	Heat loss	15	27	37	52	72	90	117	128	148	177	20	36	52
	Surface temp.	22	23	24	25	27	28	31	31	31	32	23	24	26
100	Thickness	38	75	100	100	100	125	138	150	175	188	50	75	100
	Heat loss	18	28	40	61	85	98	121	146	167	198	24	41	56
	Surface temp.	22	23	23	26	28	30	29	31	31	32	21	24	25
150	Thickness	50	75	100	100	113	125	138	163	188	200	50	88	100
	Heat loss	20	37	52	78	100	125	153	174	200	236	32	49	72
	Surface temp.	22	23	24	26	28	29	31	31	32	33	23	24	26
200	Thickness	50	88	100	100	125	125	138	175	200	213	63	88	100
	Heat loss	25	40	82	93	111	149	182	196	225	266	34	60	86
	Surface temp.	22	23	24	27	27	30	32	31	32	33	23	24	26
250	Thickness	50	88	100	100	125	138	138	188	213	225	63	100	100
	Heat loss	31	48	74	111	131	163	211	217	249	295	39	63	102
	Surface temp.	22	23	25	27	28	29	32	31	32	33	23	24	27
300	Thickness	50	88	100	100	125	138	138	188	213	241	63	100	100
	Heat loss	35	55	84	126	148	185	239	243	279	318	45	72	116
	Surface temp.	22	23	25	28	28	30	33	31	32	33	23	24	27
350	Thickness	50	88	100	100	125	138	163	188	225	241	63	100	100
	Heat loss	38	59	90	136	159	198	227	260	285	338	49	78	125
	Surface temp.	22	23	25	28	28	30	31	32	32	33	23	24	27
400	Thickness	63	88	100	100	138	138	175	200	225	250	75	100	100
	Heat loss	36	65	101	151	164	219	237	273	313	357	48	86	138
	Surface temp.	22	23	26	28	28	31	30	31	32	33	22	24	28
450	Thickness	63	88	100	100	138	138	175	200	225	250	75	100	100
	Heat loss	39	72	111	166	180	240	259	298	340	388	53	95	153
	Surface temp.	22	23	26	28	28	31	31	31	32	33	23	24	28
500	Thickness	63	88	100	100	138	138	175	200	225	250	75	100	100
	Heat loss	43	79	121	182	196	261	281	322	368	419	58	104	167
	Surface temp.	22	24	26	28	28	31	31	32	32	33	23	25	28
600	Thickness	63	100	100	100	138	150	188	200	225	250	75	100	100
	Heat loss	51	83	141	212	228	283	308	371	422	479	68	122	195
	Surface temp.	22	23	26	28	28	30	30	32	33	34	23	25	28
750	Thickness	63	100	100	100	138	163	188	213	250	250	75	100	100
	Heat loss	62	101	172	258	275	319	368	422	462	568	83	148	237
	Surface temp.	22	23	26	29	29	29	31	32	32	34	23	25	28
900	Thickness	63	100	100	100	138	175	200	225	250	250	63	100	100
	Heat loss	74	118	203	304	322	350	406	467	534	656	114	174	280
	Surface temp.	22	23	26	29	29	29	30	31	32	34	23	25	28
Flat	Thickness	50	88	100	113	138	213	241	250	250	250	63	88	100
	Heat loss	10	13	19	26	30	26	30	37	45	56	12	19	27
	Surface temp.	22	23	25	27	28	27	28	29	32	34	23	25	27

Consult manufacturer's literature for product temperature limitations. Table is based on typical operating conditions, e.g., 18°C ambient temperature and 12 km/h wind speed, and may not represent actual conditions of use. Units for thickness, heat loss, and surface temperature are in mm, W/m (W/m² for flat surfaces), and °C, respectively.

Table 13 Recommended Thicknesses for Pipe and Equipment Insulation (*Concluded*)

Nom. Dia., mm		SILICATE							CELLULAR GLASS						
		Process Temperature, °C							Process Temperature, °C						
		225	300	350	400	450	500	550	65	120	175	225	300	350	400
15	Thickness	63	75	88	100	100	100	100	38	38	50	63	75	88	100
	Heat loss	40	51	61	72	86	104	123	9	22	33	46	60	75	88
	Surface temp.	27	28	28	29	31	33	34	21	24	26	28	28	29	29
25	Thickness	75	88	100	100	100	100	100	38	50	63	75	88	100	100
	Heat loss	47	58	69	86	105	125	148	12	24	37	50	65	83	108
	Surface temp.	27	28	28	30	32	34	37	22	24	25	26	27	28	31
40	Thickness	88	100	100	100	100	125	125	38	63	75	100	100	100	100
	Heat loss	52	65	83	102	123	134	158	14	27	42	54	76	101	132
	Surface temp.	27	27	29	31	33	33	34	22	24	25	26	28	31	33
50	Thickness	88	100	113	125	138	150	150	38	63	75	100	100	100	113
	Heat loss	59	72	86	102	118	136	160	16	30	45	59	81	109	135
	Surface temp.	27	28	29	29	31	31	33	22	23	25	26	28	30	32
80	Thickness	100	113	125	138	150	150	150	38	75	88	100	100	113	125
	Heat loss	68	84	101	118	137	168	194	21	34	52	72	101	127	155
	Surface temp.	27	28	29	29	31	32	34	23	23	25	26	29	30	32
100	Thickness	100	113	125	138	150	163	175	50	75	100	100	100	113	125
	Heat loss	79	97	116	136	158	180	205	21	39	57	84	117	144	178
	Surface temp.	27	28	29	31	32	32	33	22	23	24	27	29	31	32
150	Thickness	100	113	125	138	150	175	200	50	88	100	100	113	138	150
	Heat loss	101	124	147	171	197	215	235	29	46	71	107	138	164	204
	Surface temp.	28	29	31	32	33	33	33	22	23	25	28	29	30	32
200	Thickness	113	125	125	150	175	200	213	63	88	100	100	125	138	163
	Heat loss	112	138	176	192	211	234	266	29	56	87	129	155	195	229
	Surface temp.	28	29	32	32	32	32	33	22	23	26	28	29	31	32
250	Thickness	100	125	138	150	188	188	225	63	100	100	100	138	138	175
	Heat loss	143	161	192	224	234	259	294	36	61	102	153	171	229	254
	Surface temp.	29	30	30	32	32	32	33	22	23	26	29	29	31	31
300	Thickness	100	125	138	175	200	213	241	63	100	100	100	138	138	188
	Heat loss	163	184	256	227	252	288	317	40	68	116	174	193	259	273
	Surface temp.	30	30	32	31	31	32	33	22	23	26	29	29	32	31
350	Thickness	100	125	138	175	200	225	241	63	100	100	100	138	138	200
	Heat loss	176	197	233	242	252	296	338	45	76	129	191	211	282	282
	Surface temp.	30	31	32	31	31	32	33	22	23	27	29	29	33	31
400	Thickness	100	138	163	188	200	225	250	63	100	100	100	138	138	200
	Heat loss	196	203	228	255	295	325	357	51	85	143	213	233	312	310
	Surface temp.	31	29	30	31	32	32	33	22	24	27	30	30	33	31
450	Thickness	100	138	163	188	213	225	250	63	100	100	100	138	138	200
	Heat loss	216	223	249	278	308	353	387	57	92	158	236	256	342	337
	Surface temp.	31	30	31	31	31	32	33	22	24	27	30	30	33	31
500	Thickness	100	138	163	188	213	241	250	63	100	100	113	138	138	200
	Heat loss	235	242	270	300	333	366	418	62	101	172	234	278	372	364
	Surface temp.	31	30	31	31	32	32	33	22	24	27	29	30	33	31
600	Thickness	100	138	163	188	213	241	250	63	100	100	125	138	138	200
	Heat loss	276	282	312	346	382	420	478	73	118	201	250	323	432	419
	Surface temp.	31	31	31	31	32	32	34	22	24	27	28	31	34	32
750	Thickness	100	138	175	200	225	250	250	63	100	100	138	138	138	200
	Heat loss	335	339	354	393	434	479	566	89	144	244	279	389	521	501
	Surface temp.	31	31	31	31	32	32	34	22	24	27	28	31	34	32
900	Thickness	100	163	188	200	225	250	250	63	100	100	138	138	138	200
	Heat loss	394	345	390	456	504	554	654	106	169	287	327	456	611	583
	Surface temp.	32	29	30	31	32	33	34	23	24	27	28	31	34	32
Flat	Thickness	138	163	188	213	241	250	250	63	100	100	138	138	188	213
	Heat loss	28	32	35	37	41	47	56	11	16	28	30	42	41	48
	Surface temp.	27	28	29	29	31	32	34	23	24	28	29	32	32	34

Consult manufacturer's literature for product temperature limitations. Table is based on typical operating conditions, e.g., 18 °C ambient temperature and 12 km/h wind speed, and may not represent actual conditions of use. Units for thickness, heat loss, and surface temperature are in mm, W/m (W/m² for flat surfaces), and °C, respectively.

- Kosny, J. and J.E. Christian. 1995. Reducing the uncertainties associated with using the ASHRAE zone method for R-value calculations of metal frame walls. *ASHRAE Transactions* 101(2).
- Latta, J.K. and G.G. Boileau. 1969. Heat losses from house basements. *Canadian Building* 19(10).
- Lewis, W.C. 1967. Thermal conductivity of wood-base fiber and particle panel materials. Forest Products Laboratory, Research Paper FPL 77, June.
- Lotz, W.A. 1964. Vapor barrier design, neglected key to freezer insulation effectiveness. *Quick Frozen Foods* (November):122. MacLean, J.D. 1941. Thermal conductivity of wood. *ASHVE Transactions* 47:323.
- McElroy, D.L., D.W. Yarbrough, and R.S. Graves. 1987. Thickness and density of loose-fill insulations after installation in residential attics. *Thermal insulation: Materials and systems*. F.J. Powell and S.L. Matthews, eds. ASTM STP 922:423-505.
- McGowan, A. and A.O. Desjarlais. 1997. An investigation of common thermal bridges in walls. *ASHRAE Transactions* 103(2).
- McIntyre, D.A. 1984. The increase in U-value of a wall caused by mortar joints, ECRC/M1843. The Electricity Council Research Centre, Copenhurst, England, June.
- Mitalas, G.P. 1982. Basement heat loss studies at DBR/NRC, NRCC 20416. Division of Building Research, National Research Council of Canada, September.
- Mitalas, G.P. 1983. Calculation of basement heat loss. *ASHRAE Transactions* 89(1B):420.
- Prangnell, R.D. 1971. The water vapor resistivity of building materials—A literature survey. *Materiaux et Constructions* 4:24 (November).
- Robinson, H.E., F.J. Powell, and L.A. Cosgrove. 1957. Thermal resistance of airspaces and fibrous insulations bounded by reflective surfaces. National Bureau of Standards, Building Materials and Structures Report BMS 151.
- Robinson, H.E., F.J. Powlitch, and R.S. Dill. 1954. The thermal insulation value of airspaces. Housing and Home Finance Agency, Housing Research Paper No. 32.
- Sabine, H.J., M.B. Lacher, D.R. Flynn, and T.L. Quindry. 1975. Acoustical and thermal performance of exterior residential walls, doors and windows. *NBS Building Science Series 77*. National Institute of Standards and Technology, Gaithersburg, MD.
- Salomone, L.A. and J.I. Marlowe. 1989. Soil and rock classification according to thermal conductivity: Design of ground-coupled heat pump systems. EPRI CU-6482, Electric Power Research Institute, August.
- Shipp, P.H. 1983. Basement, crawlspace and slab-on-grade thermal performance. Proceedings of the ASHRAE/DOE Conference, Thermal Performance of the Exterior Envelopes of Buildings II, ASHRAE SP 38:160-79.
- Shu, L.S., A.E. Fiorato, and J.W. Howanski. 1979. Heat transmission coefficients of concrete block walls with core insulation. Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE SP 28:421-35.
- Tye, R.P. 1985. Upgrading thermal insulation performance of industrial processes. *Chemical Engineering Progress* (February):30-34.
- Tye, R.P. 1986. Effects of product variability on thermal performance of thermal insulation. Proceedings of the First Asian Thermal Properties Conference, Beijing, People's Republic of China.
- Tye, R.P. and A.O. Desjarlais. 1983. Factors influencing the thermal performance of thermal insulations for industrial applications. *Thermal insulation, materials, and systems for energy conservation in the '80s*. F.A. Govan, D.M. Greason, and J.D. McAllister, eds. ASTM STP 789:733-48.
- Tye, R.P. and S.C. Spinney. 1980. A study of various factors affecting the thermal performance of perlite insulated masonry construction. Dynatech Report No. PII-2. Holometrix, Inc. (formerly Dynatech R/D Company), Cambridge, MA.
- USDA. 1974. *Wood handbook*. Wood as an engineering material. Forest Products Laboratory, U.S. Department of Agriculture Handbook No. 72, Tables 3-7 and 4-2, and Figures 3-4 and 3-5.
- Valore, R.C. 1980. Calculation of U-values of hollow concrete masonry. American Concrete Institute, *Concrete International* 2(2):40-62.
- Valore, R.C. 1988. Thermophysical properties of masonry and its constituents, Parts I and II. International Masonry Institute, Washington, D.C.
- Valore, R., A. Tuluca, and A. Caputo. 1988. Assessment of the thermal and physical properties of masonry block products (ORNL/Sub/86-22020/1), September.
- Van Geem, M.G. 1985. Thermal transmittance of concrete block walls with core insulation. *ASHRAE Transactions* 91(2).
- Wilkes, K.E. 1979. Thermophysical properties data base activities at Owens-Corning Fiberglas. Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE SP 28:662-77.
- Yarbrough, E.W. 1983. Assessment of reflective insulations for residential and commercial applications (ORNL/TM-8891), October.
- Yellott, J.I. 1965. Thermal and mechanical effects of solar radiation on steel doors. *ASHRAE Transactions* 71(2):42.