CHAPTER 25

THERMAL AND WATER VAPOR TRANSMISSION DATA

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 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 weight, while the effect of moisture on other materials is approximately linear.

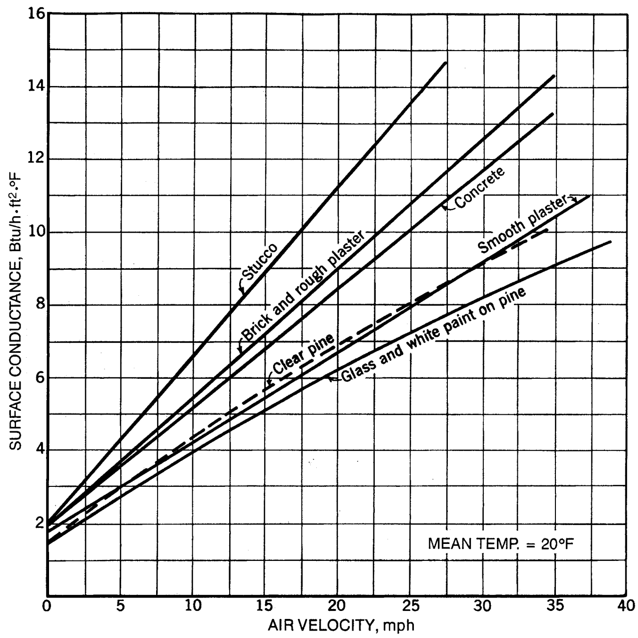

Fig. 1 Surface Conductance for Different Surfaces as Affected by Air Movement

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.

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Table 1 Surface Conductances and Resistances for Air

Position of Surface	Direction of Heat Flow	Surface Emittance, ε: Non-reflective ε = 0.90 h_i	R	Reflective ε = 0.20 h_i	R	Reflective ε = 0.05 h_i	R
STILL AIR							
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32
Sloping—45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70
Sloping—45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55
MOVING AIR (Any position)		h_o	R				
15 mph wind (for winter)	Any	6.00	0.17	—	—	—	—
7.5 mph wind (for summer)	Any	4.00	0.25	—	—	—	—

Notes:
1. Surface conductance h_i and h_o measured in Btu/h·ft²·°F; resistance *R* in ft²·°F·h/Btu.
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 10°F and for surface temperatures of 70°F.
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 15 mph for winter (surface with $R = 0.17$ ft²·°F·h/Btu) and 7.5 mph for summer (surface with $R = 0.25$ ft²·°F·h/Btu)
- 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 (> 0.7 gr/ft²)	0.30[b]	0.29	—
Aluminum foil, with condensate clearly visible (> 2.9 gr/ft²)	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

[a]These values apply in the 4 to 40 μm range of the electromagnetic spectrum.
[b]Values are based on data presented by Bassett and Trethowen (1984).

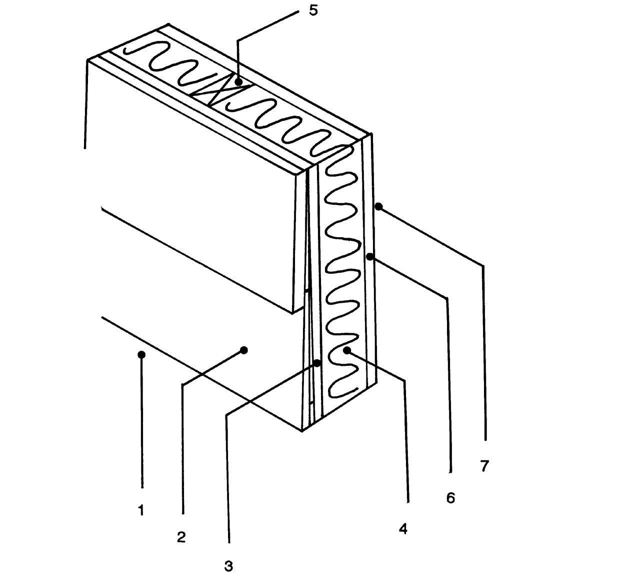


Fig. 2 Insulated Wood Frame Wall (Example 1)

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 16 in. 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 24 in. 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 2 by 4 stud wall shown in Figure 2. The studs are at 16 in. OC. There is 3.5 in. mineral fiber batt insulation (R-13) in the stud space. The inside finish is 0.5 in. gypsum wallboard; the outside is finished with rigid foam insulating sheathing (R-4) and 0.5 in. by 8 in. 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 = 1.25 per inch 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, $U_1 = 0.052$ and $U_2 = 0.095$ Btu/h·ft²·°F.

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

$$U_{av} = U_1 = \frac{1}{R_1} = 0.052 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

Element	*R* (Insulated Cavity)	*R* (Studs, Plates, and Headers)
1. Outside surface, 15 mph wind	0.17	0.17
2. Wood bevel lapped siding	0.81	0.81
3. Rigid foam insulating sheathing	4.0	4.0
4. Mineral fiber batt insulation, 3.5 in.	13.0	—
5. Wood stud, nominal 2 × 4	—	4.38
6. Gypsum wallboard, 0.5 in.	0.45	0.45
7. Inside surface, still air	0.68	0.68
	R_1 = 19.11	R_2 = 10.49

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:

$$U_{av} = (0.75 \times 0.052) + (0.25 \times 0.095) = 0.063 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

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:

$$R_{T(av)} = 4.98 + 1/[(0.75/13.0) + (0.25/4.38)] + 1.13$$

$$= 14.82 \text{ ft}^2 \cdot {}^\circ\text{F} \cdot \text{h/Btu}$$

$$U_{av} = 0.067 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

For a frame wall with a 24 in. OC stud space, the average overall R-value is 15.18 ft²·°F·h/Btu. 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 7-5/8 in. thick insulated concrete block wall shown in Figure 3. The two-core block has an average web thickness of 1 in. and a face shell thickness of 1-1/4 in. Overall block dimensions are 7-5/8 by 7-5/8 by 15-5/8 in. Measured thermal resistances of 112 lb/ft³ concrete and 7 lb/ft³ expanded perlite insulation are 0.10 and 2.90 ft²·°F·h/Btu per inch, 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 (15 mph 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.

$R_i = 0.68$
$R_o = 0.17$
$R_f = (2)(1.25)(0.10) = 0.25$
$R_c = (5.125)(2.90) = 14.86$
$R_w = (5.125)(0.10) = 0.51$
$a_w = 3/15.625 = 0.192$
$a_c = 12.625/15.625 = 0.808$

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

$$R_{T(av)} = 0.68 + 0.25 + \frac{0.51 \times 14.86}{(0.808 \times 0.51) + (0.192 \times 14.86)} + 0.17$$

$$= 3.43 \text{ ft}^2 \cdot {}^\circ\text{F} \cdot \text{h/Btu}$$

$$U_{av} = 1/3.43 = 0.29 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

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 3.13 ft²·°F·h/Btu.

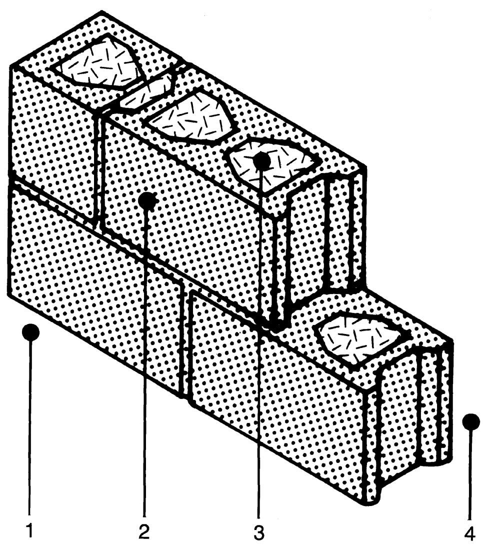


Fig. 3 Insulated Concrete Block Wall (Example 2)

Table 3 Thermal Resistances of Plane Air Spaces[a,b,c], ft²·°F·h/Btu

Position of Air Space	Direction of Heat Flow	Air Space Mean Temp.[d], °F	Air Space Temp. Diff.[d], °F	0.5-in. Air Space[c] Effective Emittance ε_{eff}[d,e] 0.03	0.05	0.2	0.5	0.82	0.75-in. Air Space[c] Effective Emittance ε_{eff}[d,e] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up ↑	90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
		0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		−50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		−50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
45° Slope	Up ↗	90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
		0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		−50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		−50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
Vertical	Horiz. →	90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
		0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		−50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		−50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
45° Slope	Down ↘	90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
		0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		−50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		−50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66
Horiz.	Down ↓	90	10	2.48	2.34	1.67	1.06	0.77	3.55	3.29	2.10	1.22	0.85
		50	30	2.66	2.54	1.88	1.24	0.91	3.77	3.52	2.38	1.44	1.02
		50	10	2.67	2.55	1.89	1.25	0.92	3.84	3.59	2.41	1.45	1.02
		0	20	2.94	2.83	2.20	1.53	1.15	4.18	3.96	2.83	1.81	1.30
		0	10	2.96	2.85	2.22	1.53	1.16	4.25	4.02	2.87	1.82	1.31
		−50	20	3.25	3.15	2.58	1.89	1.47	4.60	4.41	3.36	2.28	1.69
		−50	10	3.28	3.18	2.60	1.90	1.47	4.71	4.51	3.42	2.30	1.71

Position of Air Space	Direction of Heat Flow	Air Space Mean Temp.[d], °F	Air Space Temp. Diff.[d], °F	1.5 in. Air Space[c] 0.03	0.05	0.2	0.5	0.82	3.5 in. Air Space[c] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up ↑	90	10	2.55	2.41	1.71	1.08	0.77	2.84	2.66	1.83	1.13	0.80
		50	30	1.87	1.81	1.45	1.04	0.80	2.09	2.01	1.58	1.10	0.84
		50	10	2.50	2.40	1.81	1.21	0.89	2.80	2.66	1.95	1.28	0.93
		0	20	2.01	1.95	1.63	1.23	0.97	2.25	2.18	1.79	1.32	1.03
		0	10	2.43	2.35	1.90	1.38	1.06	2.71	2.62	2.07	1.47	1.12
		−50	20	1.94	1.91	1.68	1.36	1.13	2.19	2.14	1.86	1.47	1.20
		−50	10	2.37	2.31	1.99	1.55	1.26	2.65	2.58	2.18	1.67	1.33
45° Slope	Up ↗	90	10	2.92	2.73	1.86	1.14	0.80	3.18	2.96	1.97	1.18	0.82
		50	30	2.14	2.06	1.61	1.12	0.84	2.26	2.17	1.67	1.15	0.86
		50	10	2.88	2.74	1.99	1.29	0.94	3.12	2.95	2.10	1.34	0.96
		0	20	2.30	2.23	1.82	1.34	1.04	2.42	2.35	1.90	1.38	1.06
		0	10	2.79	2.69	2.12	1.49	1.13	2.98	2.87	2.23	1.54	1.16
		−50	20	2.22	2.17	1.88	1.49	1.21	2.34	2.29	1.97	1.54	1.25
		−50	10	2.71	2.64	2.23	1.69	1.35	2.87	2.79	2.33	1.75	1.39
Vertical	Horiz. →	90	10	3.99	3.66	2.25	1.27	0.87	3.69	3.40	2.15	1.24	0.85
		50	30	2.58	2.46	1.84	1.23	0.90	2.67	2.55	1.89	1.25	0.91
		50	10	3.79	3.55	2.39	1.45	1.02	3.63	3.40	2.32	1.42	1.01
		0	20	2.76	2.66	2.10	1.48	1.12	2.88	2.78	2.17	1.51	1.14
		0	10	3.51	3.35	2.51	1.67	1.23	3.49	3.33	2.50	1.67	1.23
		−50	20	2.64	2.58	2.18	1.66	1.33	2.82	2.75	2.30	1.73	1.37
		−50	10	3.31	3.21	2.62	1.91	1.48	3.40	3.30	2.67	1.94	1.50
45° Slope	Down ↘	90	10	5.07	4.55	2.56	1.36	0.91	4.81	4.33	2.49	1.34	0.90
		50	30	3.58	3.36	2.31	1.42	1.00	3.51	3.30	2.28	1.40	1.00
		50	10	5.10	4.66	2.85	1.60	1.09	4.74	4.36	2.73	1.57	1.08
		0	20	3.85	3.66	2.68	1.74	1.27	3.81	3.63	2.66	1.74	1.27
		0	10	4.92	4.62	3.16	1.94	1.37	4.59	4.32	3.02	1.88	1.34
		−50	20	3.62	3.50	2.80	2.01	1.54	3.77	3.64	2.90	2.05	1.57
		−50	10	4.67	4.47	3.40	2.29	1.70	4.50	4.32	3.31	2.25	1.68
Horiz.	Down ↓	90	10	6.09	5.35	2.79	1.43	0.94	10.07	8.19	3.41	1.57	1.00
		50	30	6.27	5.63	3.18	1.70	1.14	9.60	8.17	3.86	1.88	1.22
		50	10	6.61	5.90	3.27	1.73	1.15	11.15	9.27	4.09	1.93	1.24
		0	20	7.03	6.43	3.91	2.19	1.49	10.90	9.52	4.87	2.47	1.62
		0	10	7.31	6.66	4.00	2.22	1.51	11.97	10.32	5.08	2.52	1.64
		−50	20	7.73	7.20	4.77	2.85	1.99	11.64	10.49	6.02	3.25	2.18
		−50	10	8.09	7.52	4.91	2.89	2.01	12.98	11.56	6.36	3.34	2.22

[a]See Chapter 23, section on Factors Affecting Heat Transfer Across Air Spaces. Thermal resistance values were determined from the relation, $R = 1/C$, where $C = h_c + \varepsilon_{eff} h_r$, h_c is the conduction-convection coefficient, $\varepsilon_{eff} h_r$ is the radiation coefficient $\approx 0.0068\varepsilon_{eff}[(t_m + 460)/100]^3$, 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 0.5 in. (as in insulating window glass), assume $h_c = 0.159(1 + 0.0016\, t_m)/l$ where l is the air space thickness in inches, and h_c is heat transfer through the air space only.

[b]Values 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 determined 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.

[c]A 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.

[d]Interpolation is permissible for other values of mean temperature, temperature difference, and effective emittance ε_{eff}. Interpolation and moderate extrapolation for air spaces greater than 3.5 in. are also permissible.

[e]Effective emittance ε_{eff} of the air space is given by $1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, 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, lb/ft³	Conductivity[b] (k), Btu·in / h·ft²·°F	Conductance (C), Btu / h·ft²·°F	Resistance[c] (R) Per Inch Thickness (1/k), ft²·°F·h / Btu·in	Resistance[c] (R) For Thickness Listed (1/C), ft²·°F·h / Btu	Specific Heat, Btu / lb·°F
BUILDING BOARD						
Asbestos-cement board	120	4.0	—	0.25	—	0.24
Asbestos-cement board 0.125 in.	120	—	33.00	—	0.03	
Asbestos-cement board 0.25 in.	120	—	16.50	—	0.06	
Gypsum or plaster board 0.375 in.	50	—	3.10	—	0.32	0.26
Gypsum or plaster board 0.5 in.	50	—	2.22	—	0.45	
Gypsum or plaster board 0.625 in.	50	—	1.78	—	0.56	
Plywood (Douglas fir)[d]	34	0.80	—	1.25	—	0.29
Plywood (Douglas fir) 0.25 in.	34	—	3.20	—	0.31	
Plywood (Douglas fir) 0.375 in.	34	—	2.13	—	0.47	
Plywood (Douglas fir) 0.5 in.	34	—	1.60	—	0.62	
Plywood (Douglas fir) 0.625 in.	34	—	1.29	—	0.77	
Plywood or wood panels 0.75 in.	34	—	1.07	—	0.93	0.29
Vegetable fiber board						
Sheathing, regular density[e] 0.5 in.	18	—	0.76	—	1.32	0.31
0.78125 in.	18	—	0.49	—	2.06	
Sheathing intermediate density[e] 0.5 in.	22	—	0.92	—	1.09	0.31
Nail-base sheathing[e] 0.5 in.	25	—	0.94	—	1.06	0.31
Shingle backer 0.375 in.	18	—	1.06	—	0.94	0.31
Shingle backer 0.3125 in.	18	—	1.28	—	0.78	
Sound deadening board 0.5 in.	15	—	0.74	—	1.35	0.30
Tile and lay-in panels, plain or acoustic	18	0.40	—	2.50	—	0.14
0.5 in.	18	—	0.80	—	1.25	
0.75 in.	18	—	0.53	—	1.89	
Laminated paperboard	30	0.50	—	2.00	—	0.33
Homogeneous board from repulped paper	30	0.50	—	2.00	—	0.28
Hardboard[e]						
Medium density	50	0.73	—	1.37	—	0.31
High density, service-tempered grade and service grade	55	0.82	—	1.22	—	0.32
High density, standard-tempered grade	63	1.00	—	1.00	—	0.32
Particleboard[e]						
Low density	37	0.71	—	1.41	—	0.31
Medium density	50	0.94	—	1.06	—	0.31
High density	62	.5	1.18	—	0.85	—
Underlayment 0.625 in.	40	—	1.22	—	0.82	0.29
Waferboard	37	0.63	—	1.59	—	—
Wood subfloor 0.75 in.	—	—	1.06	—	0.94	0.33
BUILDING MEMBRANE						
Vapor—permeable felt	—	—	16.70	—	0.06	
Vapor—seal, 2 layers of mopped 15 lb felt	—	—	8.35	—	0.12	
Vapor—seal, plastic film	—	—	—	—	Negl.	
FINISH FLOORING MATERIALS						
Carpet and fibrous pad	—	—	0.48	—	2.08	0.34
Carpet and rubber pad	—	—	0.81	—	1.23	0.33
Cork tile 0.125 in.	—	—	3.60	—	0.28	0.48
Terrazzo 1 in.	—	—	12.50	—	0.08	0.19
Tile—asphalt, linoleum, vinyl, rubber	—	—	20.00	—	0.05	0.30
vinyl asbestos						0.24
ceramic						0.19
Wood, hardwood finish 0.75 in.	—	—	1.47	—	0.68	
INSULATING MATERIALS						
Blanket and Batt[f,g]						
Mineral fiber, fibrous form processed from rock, slag, or glass						
approx. 3-4 in.	0.4-2.0	—	0.091	—	11	
approx. 3.5 in.	0.4-2.0	—	0.077	—	13	
approx. 3.5 in.	1.2-1.6	—	0.067	—	15	
approx. 5.5-6.5 in.	0.4-2.0	—	0.053	—	19	
approx. 5.5 in.	0.6-1.0	—	0.048	—	21	
approx. 6-7.5 in.	0.4-2.0	—	0.045	—	22	
approx. 8.25-10 in.	0.4-2.0	—	0.033	—	30	
approx. 10-13 in.	0.4-2.0	—	0.026	—	38	
Board and Slabs						
Cellular glass	8.0	0.33	—	3.03	—	0.18
Glass fiber, organic bonded	4.0-9.0	0.25	—	4.00	—	0.23
Expanded perlite, organic bonded	1.0	0.36	—	2.78	—	0.30
Expanded rubber (rigid)	4.5	0.22	—	4.55	—	0.40
Expanded polystyrene, extruded (smooth skin surface) (CFC-12 exp.)	1.8-3.5	0.20	—	5.00	—	0.29

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

Description	Density, lb/ft^3	Conductivity[b] (*k*), Btu·in / h·ft²·°F	Conductance (*C*), Btu / h·ft²·°F	Resistance[c] (*R*) Per Inch Thickness (1/*k*), ft²·°F·h / Btu·in	Resistance[c] (*R*) For Thickness Listed (1/*C*), ft²·°F·h / Btu	Specific Heat, Btu / lb·°F
Expanded polystyrene, extruded (smooth skin surface) (HCFC-142b exp.)[h]	1.8-3.5	0.20	—	5.00	—	0.29
Expanded polystyrene, molded beads	1.0	0.26	—	3.85	—	—
	1.25	0.25	—	4.00	—	—
	1.5	0.24	—	4.17	—	—
	1.75	0.24	—	4.17	—	—
	2.0	0.23	—	4.35	—	—
Cellular polyurethane/polyisocyanurate[i] (CFC-11 exp.) (unfaced)	1.5	0.16-0.18	—	6.25-5.56	—	0.38
Cellular polyisocyanurate[i] (CFC-11 exp.) (gas-permeable facers)	1.5-2.5	0.16-0.18	—	6.25-5.56	—	0.22
Cellular polyisocyanurate[j] (CFC-11 exp.) (gas-impermeable facers)	2.0	0.14	—	7.04	—	0.22
Cellular phenolic (closed cell) (CFC-11, CFC-113 exp.)[k]	3.0	0.12	—	8.20	—	—
Cellular phenolic (open cell)	1.8-2.2	0.23	—	4.40	—	—
Mineral fiber with resin binder	15.0	0.29	—	3.45	—	0.17
Mineral fiberboard, wet felted						
Core or roof insulation	16-17	0.34	—	2.94	—	—
Acoustical tile	18.0	0.35	—	2.86	—	0.19
Acoustical tile	21.0	0.37	—	2.70	—	—
Mineral fiberboard, wet molded						
Acoustical tile[l]	23.0	0.42	—	2.38	—	0.14
Wood or cane fiberboard						
Acoustical tile[l] 0.5 in.	—	—	0.80	—	1.25	0.31
Acoustical tile[l] 0.75 in.	—	—	0.53	—	1.89	—
Interior finish (plank, tile)	15.0	0.35	—	2.86	—	0.32
Cement fiber slabs (shredded wood with Portland cement binder)	25-27.0	0.50-0.53		2.0-1.89	—	
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	22.0	0.57	—	1.75	—	0.31
Loose Fill						
Cellulosic insulation (milled paper or wood pulp)	2.3-3.2	0.27-0.32	—	3.70-3.13	—	0.33
Perlite, expanded	2.0-4.1	0.27-0.31	—	3.7-3.3	—	0.26
	4.1-7.4	0.31-0.36	—	3.3-2.8	—	—
	7.4-11.0	0.36-0.42	—	2.8-2.4	—	—
Mineral fiber (rock, slag, or glass)[g]						
approx. 3.75-5 in.	0.6-2.0	—	—	—	11.0	0.17
approx. 6.5-8.75 in.	0.6-2.0	—	—	—	19.0	—
approx. 7.5-10 in.	0.6-2.0	—	—	—	22.0	—
approx. 10.25-13.75 in.	0.6-2.0	—	—	—	30.0	—
Mineral fiber (rock, slag, or glass)[g]						
approx. 3.5 in. (closed sidewall application)	2.0-3.5	—	—	—	12.0-14.0	—
Vermiculite, exfoliated	7.0-8.2	0.47	—	2.13	—	0.32
	4.0-6.0	0.44	—	2.27	—	—
Spray Applied						
Polyurethane foam	1.5-2.5	0.16-0.18	—	6.25-5.56	—	—
Ureaformaldehyde foam	0.7-1.6	0.22-0.28	—	4.55-3.57	—	—
Cellulosic fiber	3.5-6.0	0.29-0.34	—	3.45-2.94	—	—
Glass fiber	3.5-4.5	0.26-0.27	—	3.85-3.70	—	—
Reflective Insulation						
Reflective material ($\varepsilon < 0.5$) in center of 3/4 in. cavity forms two 3/8 in. vertical air spaces[m]	—	—	0.31	—	3.2	—
METALS						
(See Chapter 38, Table 3)						
ROOFING						
Asbestos-cement shingles	120	—	4.76	—	0.21	0.24
Asphalt roll roofing	70	—	6.50	—	0.15	0.36
Asphalt shingles	70	—	2.27	—	0.44	0.30
Built-up roofing 0.375 in.	70	—	3.00	—	0.33	0.35
Slate 0.5 in.	—	—	20.00	—	0.05	0.30
Wood shingles, plain and plastic film faced	—	—	1.06	—	0.94	0.31
PLASTERING MATERIALS						
Cement plaster, sand aggregate	116	5.0	—	0.20	—	0.20
Sand aggregate 0.375 in.	—	—	13.3	—	0.08	0.20
Sand aggregate 0.75 in.	—	—	6.66	—	0.15	0.20

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

Description	Density, lb/ft^3	Conductivity[b] (*k*), Btu·in / h·ft^2·°F	Conductance (*C*), Btu / h·ft^2·°F	Resistance[c] (*R*): Per Inch Thickness (1/*k*), ft^2·°F·h / Btu·in	Resistance[c] (*R*): For Thickness Listed (1/*C*), ft^2·°F·h / Btu	Specific Heat, Btu / lb·°F
Gypsum plaster:						
Lightweight aggregate ....0.5 in.	45	—	3.12	—	0.32	—
Lightweight aggregate ....0.625 in.	45	—	2.67	—	0.39	—
Lightweight aggregate on metal lath....0.75 in.	—	—	2.13	—	0.47	—
Perlite aggregate....	45	1.5	—	0.67	—	0.32
Sand aggregate	105	5.6	—	0.18	—	0.20
Sand aggregate ....0.5 in.	105	—	11.10	—	0.09	—
Sand aggregate ....0.625 in.	105	—	9.10	—	0.11	—
Sand aggregate on metal lath ....0.75 in.	—	—	7.70	—	0.13	—
Vermiculite aggregate	45	1.7	—	0.59	—	—
MASONRY MATERIALS						
Masonry Units						
Brick, fired clay	150	8.4-10.2	—	0.12-0.10	—	—
	140	7.4-9.0	—	0.14-0.11	—	—
	130	6.4-7.8	—	0.16-0.12	—	—
	120	5.6-6.8	—	0.18-0.15	—	0.19
	110	4.9-5.9	—	0.20-0.17	—	—
	100	4.2-5.1	—	0.24-0.20	—	—
	90	3.6-4.3	—	0.28-0.24	—	—
	80	3.0-3.7	—	0.33-0.27	—	—
	70	2.5-3.1	—	0.40-0.33	—	—
Clay tile, hollow						
1 cell deep ....3 in.	—	—	1.25	—	0.80	0.21
1 cell deep ....4 in.	—	—	0.90	—	1.11	—
2 cells deep....6 in.	—	—	0.66	—	1.52	—
2 cells deep....8 in.	—	—	0.54	—	1.85	—
2 cells deep....10 in.	—	—	0.45	—	2.22	—
3 cells deep....12 in.	—	—	0.40	—	2.50	—
Concrete blocks[n, o]						
Limestone aggregate						
8 in., 36 lb, 138 lb/ft^3 concrete, 2 cores	—	—	—	—	—	—
Same with perlite filled cores	—	—	0.48	—	2.1	—
12 in., 55 lb, 138 lb/ft^3 concrete, 2 cores	—	—	—	—	—	—
Same with perlite filled cores	—	—	0.27	—	3.7	—
Normal weight aggregate (sand and gravel)						
8 in., 33-36 lb, 126-136 lb/ft^3 concrete, 2 or 3 cores	—	—	0.90-1.03	—	1.11-0.97	0.22
Same with perlite filled cores	—	—	0.50	—	2.0	—
Same with vermiculite filled cores	—	—	0.52-0.73	—	1.92-1.37	—
12 in., 50 lb, 125 lb/ft^3 concrete, 2 cores	—	—	0.81	—	1.23	0.22
Medium weight aggregate (combinations of normal weight and lightweight aggregate)						
8 in., 26-29 lb, 97-112 lb/ft^3 concrete, 2 or 3 cores..	—	—	0.58-0.78	—	1.71-1.28	—
Same with perlite filled cores	—	—	0.27-0.44	—	3.7-2.3	—
Same with vermiculite filled cores	—	—	0.30	—	3.3	—
Same with molded EPS (beads) filled cores	—	—	0.32	—	3.2	—
Same with molded EPS inserts in cores....	—	—	0.37	—	2.7	—
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)						
6 in., 16-17 lb 85-87 lb/ft^3 concrete, 2 or 3 cores	—	—	0.52-0.61	—	1.93-1.65	—
Same with perlite filled cores	—	—	0.24	—	4.2	—
Same with vermiculite filled cores	—	—	0.33	—	3.0	—
8 in., 19-22 lb, 72-86 lb/ft^3 concrete	—	—	0.32-0.54	—	3.2-1.90	0.21
Same with perlite filled cores	—	—	0.15-0.23	—	6.8-4.4	—
Same with vermiculite filled cores	—	—	0.19-0.26	—	5.3-3.9	—
Same with molded EPS (beads) filled cores	—	—	0.21	—	4.8	—
Same with UF foam filled cores	—	—	0.22	—	4.5	—
Same with molded EPS inserts in cores....	—	—	0.29	—	3.5	—
12 in., 32-36 lb, 80-90 lb/ft^3 concrete, 2 or 3 cores...	—	—	0.38-0.44	—	2.6-2.3	—
Same with perlite filled cores	—	—	0.11-0.16	—	9.2-6.3	—
Same with vermiculite filled cores	—	—	0.17	—	5.8	—
Stone, lime, or sand....	180	72	—	0.01	—	—
Quartzitic and sandstone	160	43	—	0.02	—	—
	140	24	—	0.04	—	—
	120	13	—	0.08	—	0.19
Calcitic, dolomitic, limestone, marble, and granite	180	30	—	0.03	—	—
	160	22	—	0.05	—	—
	140	16	—	0.06	—	—
	120	11	—	0.09	—	0.19
	100	8	—	0.13	—	—

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

Description	Density, lb/ft³	Conductivity[b] (*k*), Btu·in / h·ft²·°F	Conductance (*C*), Btu / h·ft²·°F	Resistance[c] (*R*): Per Inch Thickness (1/*k*), ft²·°F·h / Btu·in	Resistance[c] (*R*): For Thickness Listed (1/*C*), ft²·°F·h / Btu	Specific Heat, Btu / lb·°F
Gypsum partition tile						
3 by 12 by 30 in., solid	—	—	0.79	—	1.26	0.19
3 by 12 by 30 in., 4 cells	—	—	0.74	—	1.35	—
4 by 12 by 30 in., 3 cells	—	—	0.60	—	1.67	—
Concretes[o]						
Sand and gravel or stone aggregate concretes (concretes	150	10.0-20.0	—	0.10-0.05	—	—
with more than 50% quartz or quartzite sand have	140	9.0-18.0	—	0.11-0.06	—	0.19-0.24
conductivities in the higher end of the range)	130	7.0-13.0	—	0.14-0.08	—	—
Limestone concretes	140	11.1	—	0.09	—	—
	120	7.9	—	0.13	—	—
	100	5.5	—	0.18	—	—
Gypsum-fiber concrete (87.5% gypsum, 12.5% wood chips)	51	1.66	—	0.60	—	0.21
Cement/lime, mortar, and stucco	120	9.7	—	0.10	—	—
	100	6.7	—	0.15	—	—
	80	4.5	—	0.22	—	—
Lightweight aggregate concretes						
Expanded shale, clay, or slate; expanded slags;	120	6.4-9.1	—	0.16-0.11	—	—
cinders; pumice (with density up to 100 lb/ft³); and	100	4.7-6.2	—	0.21-0.16	—	0.20
scoria (sanded concretes have conductivities in the	80	3.3-4.1	—	0.30-0.24	—	0.20
higher end of the range)	60	2.1-2.5	—	0.48-0.40	—	—
	40	1.3	—	0.78	—	—
Perlite, vermiculite, and polystyrene beads	50	1.8-1.9	—	0.55-0.53	—	—
	40	1.4-1.5	—	0.71-0.67	—	0.15-0.23
	30	1.1	—	0.91	—	—
	20	0.8	—	1.25	—	—
Foam concretes	120	5.4	—	0.19	—	—
	100	4.1	—	0.24	—	—
	80	3.0	—	0.33	—	—
	70	2.5	—	0.40	—	—
Foam concretes and cellular concretes	60	2.1	—	0.48	—	—
	40	1.4	—	0.71	—	—
	20	0.8	—	1.25	—	—
SIDING MATERIALS (on flat surface)						
Shingles						
Asbestos-cement	120	—	4.75	—	0.21	—
Wood, 16 in., 7.5 exposure	—	—	1.15	—	0.87	0.31
Wood, double, 16 in., 12 in. exposure	—	—	0.84	—	1.19	0.28
Wood, plus ins. backer board, 0.312 in.	—	—	0.71	—	1.40	0.31
Siding						
Asbestos-cement, 0.25 in., lapped	—	—	4.76	—	0.21	0.24
Asphalt roll siding	—	—	6.50	—	0.15	0.35
Asphalt insulating siding (0.5 in. bed.)	—	—	0.69	—	1.46	0.35
Hardboard siding, 0.4375 in.	—	—	1.49	—	0.67	0.28
Wood, drop, 1 by 8 in.	—	—	1.27	—	0.79	0.28
Wood, bevel, 0.5 by 8 in., lapped	—	—	1.23	—	0.81	0.28
Wood, bevel, 0.75 by 10 in., lapped	—	—	0.95	—	1.05	0.28
Wood, plywood, 0.375 in., lapped	—	—	1.69	—	0.59	0.29
Aluminum, steel, or vinyl[p, q], over sheathing						
Hollow-backed	—	—	1.64	—	0.61	0.29[q]
Insulating-board backed nominal 0.375 in.	—	—	0.55	—	1.82	0.32
Insulating-board backed nominal 0.375 in., foil backed	—	—	0.34	—	2.96	—
Architectural (soda-lime float) glass	158	6.9	—	—	—	0.21
WOODS (12% moisture content)[e,r]						
Hardwoods						0.39[s]
Oak	41.2-46.8	1.12-1.25	—	0.89-0.80	—	
Birch	42.6-45.4	1.16-1.22	—	0.87-0.82	—	
Maple	39.8-44.0	1.09-1.19	—	0.92-0.84	—	
Ash	38.4-41.9	1.06-1.14	—	0.94-0.88	—	
Softwoods						0.39[s]
Southern pine	35.6-41.2	1.00-1.12	—	1.00-0.89	—	
Douglas fir-Larch	33.5-36.3	0.95-1.01	—	1.06-0.99	—	
Southern cypress	31.4-32.1	0.90-0.92	—	1.11-1.09	—	
Hem-Fir, Spruce-Pine-Fir	24.5-31.4	0.74-0.90	—	1.35-1.11	—	
West coast woods, Cedars	21.7-31.4	0.68-0.90	—	1.48-1.11	—	
California redwood	24.5-28.0	0.74-0.82	—	1.35-1.22	—	

Notes for Table 4

[a]Values are for a mean temperature of 75°F. 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]To obtain thermal conductivities in Btu/h·ft·°F, divide the *k*-factor by 12 in/ft.

[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 0.001 in. 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 0.75 in. 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 weight.

[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 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-boards of wood fiber, foamed plastic, and glass fiber. Departures of ±50% or more from these values may occur.

[q]Vinyl specific heat = 0.25 Btu/lb·°F

[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:

$$k = 0.1791 + \frac{(1.874 \times 10^{-2} + 5.753 \times 10^{-4} M)\rho}{1 + 0.01M}$$

where ρ is density of the moist wood in lb/ft³, and *M* is the moisture content in percent.

[s]From Wilkes (1979), an empirical equation for the specific heat of moist wood at 75°F is as follows:

$$c_p = \frac{(0.299 + 0.01M)}{(1 + 0.01M)} + \Delta c_p$$

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

$$\Delta c_p = M(1.921 \times 10^{-3} - 3.168 \times 10^{-5} M)$$

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 thermal 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 0.06 to 0.6 ft²·°F·h/Btu—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 reistance 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 0.020 in. thick, but it is in contact with adjacent facings over a 1.25 in.-wide area. The steel member is 3.50 in. deep, has a thermal resistance of approximately 0.011 ft²·°F·h/Btu, and is virtually isothermal. The calculation involves careful selection of the appropriate thickness for the steel member. If the member is assumed to be 0.020 in. 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 1.25 in. 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 1.25 in. thick and 3.50 in. deep with a thermal resistance of (1.25/0.020) × 0.011 = 0.69 ft²·°F·h/Btu 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 0.69 ft²·°F·h/Btu 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. 0.5-in. gypsum wallboard	0.45	0.45
2. 3.5-in. mineral fiber batt insulation	11	—
3. Steel framing member	—	0.69
4. 0.5-in. gypsum wallboard	0.45	0.45
	$R_1 = 11.90$	$R_2 = 1.59$

Therefore, $C_1 = 0.084$; $C_2 = 0.629$ Btu/h·ft²·°F.

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:

$$C_{av} = C_1 = 1/R_1 = 0.084 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

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:

$$C_{av} = (0.92 \times 0.084) + (0.08 \times 0.629)$$
$$= 0.128 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$
$$R_{T(av)} = 7.81 \text{ ft}^2 \cdot {}^\circ\text{F} \cdot \text{h/Btu}$$

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:

$$R_{T(av)} = 0.45 + 1/[(0.92/11.00) + (0.08/0.69)] + 0.45$$
$$= 5.91 \text{ ft}^2 \cdot {}^\circ\text{F} \cdot \text{h/Btu}$$
$$C_{av} = 0.169 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

For this insulated steel frame wall, Farouk and Larson (1983) measured an average R-value of 6.61 ft²·°F·h/Btu.

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 2 by 4 steel framing, 16 in. OC, $F_c = 0.50$. Using the correction factor method, an R-value of 6.40 ft²·°F·h/Btu [0.45 + 11(0.50) + 0.45] 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 0.5 in. for still air.

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

where

m = width or diameter of metal heat path terminal, in.
d = distance from panel surface to metal, in.

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 24 in. OC support glass fiber form boards, gypsum concrete, and built-up roofing. Conductivities of components are: steel, 314.4 Btu·in/h·ft²·°F; gypsum concrete, 1.66 Btu·in/h·ft²·°F; and glass fiber form board, 0.25 Btu·in/h·ft²·°F. Conductance of built-up roofing is 3.00 Btu/h·ft²·°F.

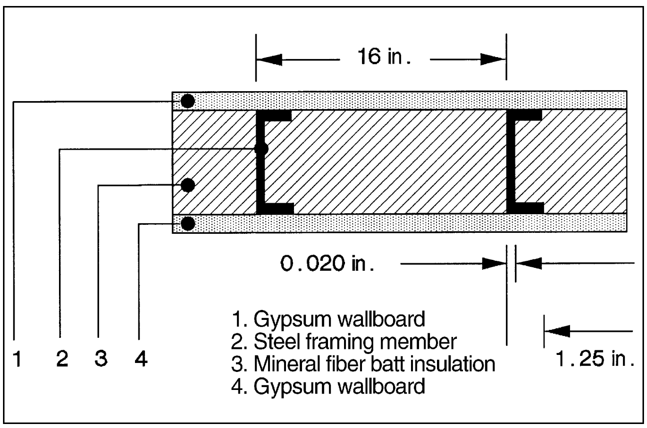


Fig. 4 Insulated Steel Frame Wall (Example 3)

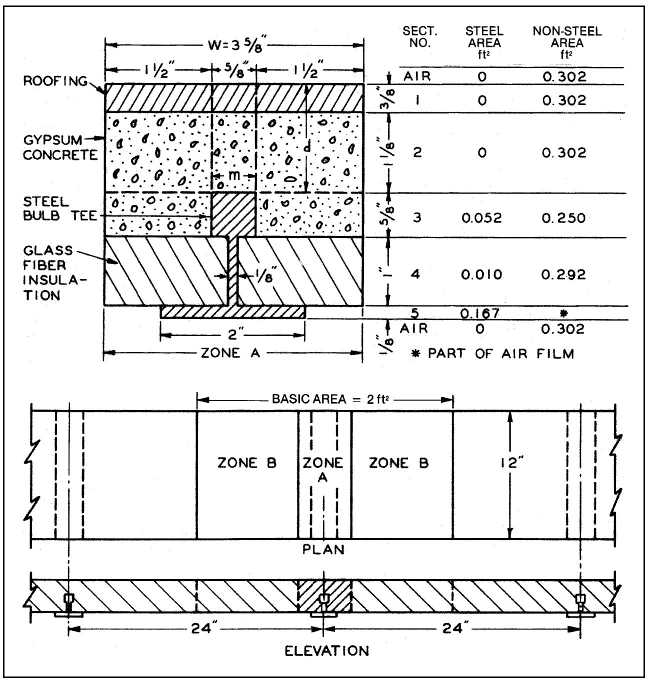


Fig. 5 Gypsum Roof Deck on Bulb Tees (Example 4)

Solution: The basic area is 2 ft^2 (24 in. by 12 in.) with a tee-bar (12 in. long) across the middle. This area is divided into Zones A and B.

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

$$\text{Top side } W = m + 2d = 0.625 + (2 \times 1.5) = 3.625 \text{ in.}$$
$$\text{Bottom side } W = m + 2d = 2.0 + (2 \times 0.5) = 3.0 \text{ in.}$$

Using the larger value of W, the area of Zone A is $(12 \times 3.625)/144 = 0.302$ ft^2. The area of Zone B is $2.0 - 0.302 = 1.698$ ft^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 R/A and added to obtain the total resistance of Zone A.

Section	Area × Conductance =		CA	$\frac{1}{CA} = \frac{R}{A}$
Air (outside, 15 mph)	0.302	× 6.00	1.81	0.55
No. 1, Roofing	0.302	× 3.00	0.906	1.10
No. 2, Gypsum concrete	0.302	× 1.66/1.125	0.446	2.24
No. 3, Steel	0.052	× 314.4/0.625	26.2	0.04
No. 3, Gypsum concrete	0.250	× 1.66/0.625	0.664	
No. 4, Steel	0.010	× 314.4/1.00	3.14	0.31
No. 4, Glass fiberboard	0.292	× 0.25/1.00	0.073	
No. 5, Steel	0.167	× 314.4/0.125	420.0	0.002
Air (inside)	0.302	× 1.63	0.492	2.03
				Total R/A = 6.27

Area transmittance of Zone A = $1/(R/A) = 1/6.27 = 0.159$.

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, 15 mph)	1/6.00 = 0.17
Roofing	1/3.00 = 0.33
Gypsum concrete	1.75/1.66 = 1.05
Glass fiberboard	1.00/0.25 = 4.00
Air (inside)	1/1.63 = 0.61
Total resistance	= 6.16

Because unit transmittance = $1/R$ = 0.162, the total area transmittance UA is calculated as follows:

Zone B = 1.698 × 0.162	=	0.275
Zone A	=	0.159
Total area transmittance of basic area	=	0.434
Transmittance per ft^2 = 0.434/2.0	=	0.217
Resistance per ft^2	=	4.61

Overall R-values of 4.57 and 4.85 ft^2·°F·h/Btu have been measured in two guarded hot box tests of a similar construction.

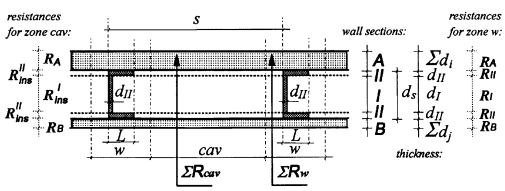
When the steel member represents a relatively large proportion of the total heat flow path, as in Example 4, detailed calculations of resistance in sections 3, 4, and 5 of Zone A are unnecessary; if only the steel member is considered, the final result of Example 4 is the same. However, if the heat flow 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



Wall Section	Material	Thickness, in.	Resistivity, h·ft^2·°F/Btu·in
A		d_{i1} =	n_1 =
A		d_{i2} =	n_2 =
A		d_{i3} =	n_3 =
B		d_{j1} =	r_{j1} =
I & II	Metal	d_{II} =	r_{met}
I & II	Cavity insulation	d_s =	r_{ins}

s= ________ ; $d_I = d_s - 2 \times d_{II}$ = ________

$\dfrac{\text{resistivity of sheathing}}{\text{resistivity of cav. insul.}}$ = ________

z_f (*from Zone Factor Chart*) = ________

$w = L + z_f \times \Sigma d_i$ = ________

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

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

$R^{I}_{ins} = r_{ins} \times d_I$ = ________

$R^{II}_{ins} = r_{ins} \times d_{II}$ = ________

$R^{I}_{met} = r_{met} \times d_I$ = ________

$R^{II}_{met} = r_{met} \times d_{II}$ = ________

$$R_I = \frac{R^{I}_{met} \times R^{I}_{ins} \times w}{d_{II} \times (R^{I}_{ins} - R^{I}_{met}) + w \times R^{I}_{met}} = \text{________} = \text{________}$$

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

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

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

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

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:

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

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

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

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)

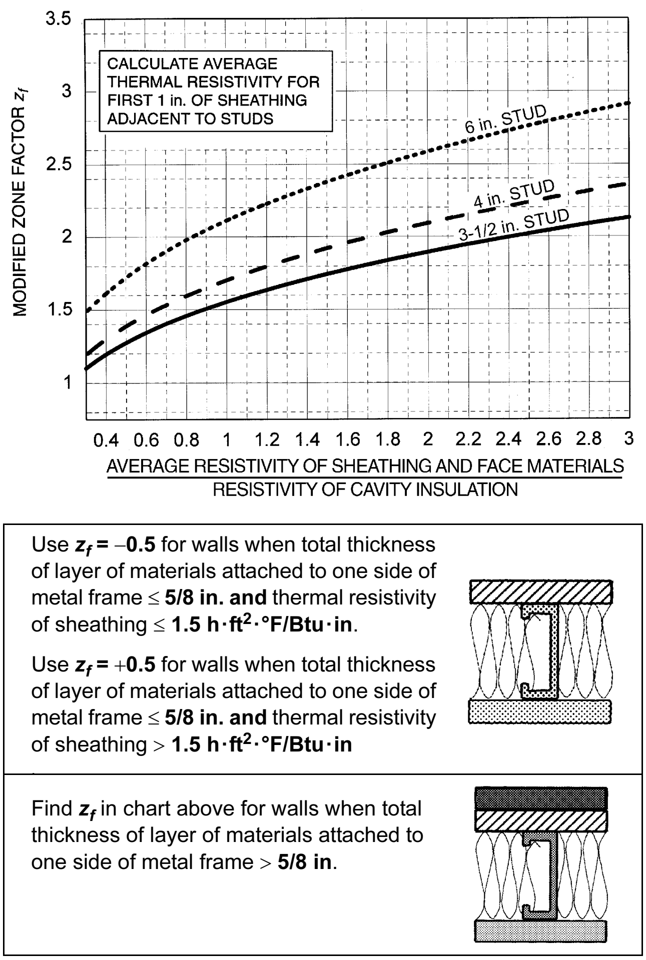


Fig. 7 Modified Zone Factor for Calculating R-Value of Metal Stud Walls with Cavity Insulation

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 ±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 16 in. OC and 0.07 for joists at 24 in. 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:

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

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)

Ventilation Air Temperature, °F	Sol-Air[f] Temperature, °F	No Ventilation[b]		Natural Ventilation		Power Ventilation[c]					
		Ventilation Rate, cfm/ft²									
		0		0.1[d]		0.5		1.0		1.5	
		Ceiling Resistance R^e, ft²·°F·h/Btu									
		10	20	10	20	10	20	10	20	10	20
NONREFLECTIVE SURFACES											
80	120	1.9	1.9	2.8	3.4	6.3	9.3	9.6	16	11	20
	140	1.9	1.9	2.8	3.5	6.5	10	9.8	17	12	21
	160	1.9	1.9	2.8	3.6	6.7	11	10	18	13	22
90	120	1.9	1.9	2.5	2.8	4.6	6.7	6.1	10	6.9	13
	140	1.9	1.9	2.6	3.1	5.2	7.9	7.6	12	8.6	15
	160	1.9	1.9	2.7	3.4	5.8	9.0	8.5	14	10	17
100	120	1.9	1.9	2.2	2.3	3.3	4.4	4.0	6.0	4.1	6.9
	140	1.9	1.9	2.4	2.7	4.2	6.1	5.8	8.7	6.5	10
	160	1.9	1.9	2.6	3.2	5.0	7.6	7.2	11	8.3	13
REFLECTIVE SURFACES[g]											
80	120	6.5	6.5	8.1	8.8	13	17	17	25	19	30
	140	6.5	6.5	8.2	9.0	14	18	18	26	20	31
	160	6.5	6.5	8.3	9.2	15	18	19	27	21	32
90	120	6.5	6.5	7.5	8.0	10	13	12	17	13	19
	140	6.5	6.5	7.7	8.3	12	15	14	20	16	22
	160	6.5	6.5	7.9	8.6	13	16	16	22	18	25
100	120	6.5	6.5	7.0	7.4	8.0	10	8.5	12	8.8	12
	140	6.5	6.5	7.3	7.8	10	12	11	15	12	16
	160	6.5	6.5	7.6	8.2	11	14	13	18	15	20

[a]Although 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 1.0 Btu/h·ft²·°F.
[b]This condition cannot be achieved in the field unless extreme measures are taken to tightly seal the attic.
[c]Based on air discharging outward from attic.
[d]When attic ventilation meets the requirements stated in Chapter 26, 0.1 cfm/ft² is assumed as the natural summer ventilation rate.
[e]When determining ceiling resistance, do not add the effect of a reflective surface facing the attic, as it is accounted for in the Reflective Surfaces part of the table.
[f]Roof surface temperature rather than sol-air temperature (see Chapter 29) can be used if 0.25 is subtracted from the attic resistance shown.
[g]Surfaces with effective emittance ε_{eff} = 0.05 between ceiling joists facing attic space.

Table 6 Transmission Coefficients U for Wood and Steel Doors, Btu/h·ft²·°F

Nominal Door Thickness, in.	Description	No Storm Door	Wood Storm Door[c]	Metal Storm Door[d]
Wood Doors[a,b]				
1-3/8	Panel door with 7/16 in. panels[e]	0.57	0.33	0.37
1-3/8	Hollow core flush door	0.47	0.30	0.32
1-3/8	Solid core flush door	0.39	0.26	0.28
1-3/4	Panel door with 7/16 in. panels[e]	0.54	0.32	0.36
1-3/4	Hollow core flush door	0.46	0.29	0.32
1-3/4	Panel door with 1-1/8 in. panels[e]	0.39	0.26	0.28
1-3/4	Solid core flush door	0.40	—	0.26
2-1/4	Solid core flush door	0.27	0.20	0.21
Steel Doors[b]				
1-3/4	Fiberglass or mineral wool core with steel stiffeners, no thermal break[f]	0.60	—	—
1-3/4	Paper honeycomb core without thermal break[f]	0.56	—	—
1-3/4	Solid urethane foam core without thermal break[a]	0.40	—	—
1-3/4	Solid fire rated mineral fiberboard core without thermal break[f]	0.38	—	—
1-3/4	Polystyrene core without thermal break (18 gage commercial steel)[f]	0.35	—	—
1-3/4	Polyurethane core without thermal break (18 gage commercial steel)[f]	0.29	—	—
1-3/4	Polyurethane core without thermal break (24 gage residential steel)[f]	0.29	—	—
1-3/4	Polyurethane core with thermal break and wood perimeter (24 gage residential steel)[f]	0.20	—	—
1-3/4	Solid urethane foam core with thermal break[a]	0.20	—	0.16

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.
[a]Values are based on a nominal 32 in. by 80 in. door size with no glazing.
[b]Outside air conditions: 15 mph wind speed, 0°F air temperature; inside air conditions: natural convection, 70°F air temperature.
[c]Values for wood storm door are for approximately 50% glass area.
[d]Values for metal storm door are for any percent glass area.
[e]55% panel area.
[f]ASTM C 236 hot box data on a nominal 3 ft by 7 ft 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).

$$U_oA_o = U_{wall\ 1}A_{wall\ 1} + U_{wall\ 2}A_{wall\ 2} + \ldots + U_{wall\ m}A_{wall\ m} + U_{window\ 1}A_{window\ 1} + U_{window\ 2}A_{window\ 2} + \ldots + U_{window\ n}A_{window\ n} + U_{door\ 1}A_{door\ 1} + U_{door\ 2}A_{door\ 2} + \ldots + U_{door\ o}A_{door\ o} \quad (5)$$

Example 5. Calculate U_o for a wall 30 ft by 8 ft, constructed as in Example 1. The wall contains two double-glazed (0.5 in. airspace) fixed windows with wood/vinyl frames. (From Table 4 in Chapter 30, U = 0.52 Btu/h·ft²·°F.) One window is 60 in. by 34 in. and the second 36 in. by 30 in. The wall also contains a 1.75 in. solid core flush door with a metal storm door 34 in. by 80 in. (U = 0.26 Btu/h·ft²·°F from Table 6).

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

$$A_{window} = [(60 \times 34) + (36 \times 30)]/144 = 21.7 \text{ ft}^2$$

$$A_{door} = (34 \times 80)/144 = 18.9 \text{ ft}^2$$

$$A_{wall} = (30 \times 8) - (21.7 + 18.9) = 199.4 \text{ ft}^2$$

Therefore, the combined thermal transmittance for the wall is

$$U_o = \frac{(0.063 \times 199.4) + (0.52 \times 21.7) + (0.26 \times 18.9)}{(30 \times 8)} = 0.119 \text{ Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

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 Hougten et al. (1942) and Dill et al. (1945) indicates a heat flow of approximately 2.0 Btu/h·ft² through an uninsulated concrete basement floor with a temperature difference of 20°F between the basement floor and the air 6 in. above it. A U-factor of 0.10 Btu/h·ft²·°F 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 25 ft by 25 ft house) the heat loss can be calculated as proportional to the length of exposed edge rather than total area. This amounts to 0.81 Btu/h per linear foot of exposed edge per degree Fahrenheit 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

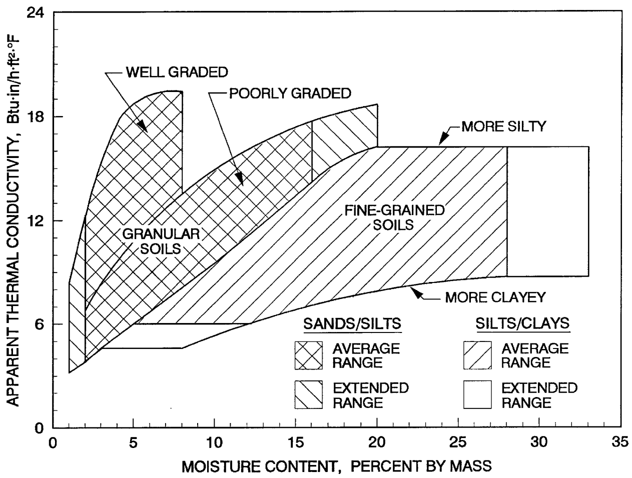


Fig. 8 Trends of Apparent Thermal Conductivity of Moist Soils

Table 7 Typical Apparent Thermal Conductivity Values for Soils, Btu·in/h·ft² · °F

	Normal Range	Recommended Values for Design[a]	
		Low[b]	High[c]
Sands	4.2 to 17.4	5.4	15.6
Silts	6 to 17.4	11.4	15.6
Clays	6 to 11.4	7.8	10.8
Loams	6 to 17.4	6.6	15.6

[a]Reasonable values for use when no site- or soil-specific data are available.
[b]Moderately 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).
[c]Moderately 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, Btu·in/h·ft² · °F

	Normal Range
Pumice, tuff, obsidian	3.6 to 15.6
Basalt	3.6 to 18.0
Shale	6 to 27.6
Granite	12 to 30
Limestone, dolomite, marble	8.4 to 30
Quartzose sandstone	9.6 to 54

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

$$h_{cv} = C\left(\frac{1}{d}\right)^{0.2}\left(\frac{1}{T_{avg}}\right)^{0.181}(\Delta T^{0.266})\sqrt{1 + 1.277(\text{Wind})} \quad (6)$$

where

h_{cv} = convection surface coefficient, Btu/h·ft²·°F
d = diameter for cylinder, in. For flat surfaces and large cylinders (d > 24 in.), use d = 24 in.
T_{avg} = average temperature of air film = $(T_a + T_s)/2$, °R
T_a = temperature of ambient air, °R
T_s = temperature of surface, °R
ΔT = surface to air temperature difference, °R
Wind = air speed, mph
C = constant depending on shape and heat flow condition
= 1.016 for horizontal cylinders
= 1.235 for longer vertical cylinders
= 1.394 for vertical plates
= 1.79 for horizontal plates, warmer than air, facing upward
= 0.89 for horizontal plates, warmer than air, facing downward
= 0.89 for horizontal plates, cooler than air, facing upward
= 1.79 for horizontal plates, cooler than air, facing downward

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

Material	Thickness, in.	Permeance, Perm	Resistance[h], Rep	Permeability, Perm-in.	Resistance/in.[h], Rep/in.
Construction Materials					
Concrete (1:2:4 mix)				3.2	0.31
Brick masonry	4	0.8[f]	1.3		
Concrete block (cored, limestone aggregate)	8	2.4[f]	0.4		
Tile masonry, glazed	4	0.12[f]	8.3		
Asbestos cement board	0.12	4-8[d]	0.1-0.2		
With oil-base finishes		0.3-0.5[d]	2-3		
Plaster on metal lath	0.75	15[f]	0.067		
Plaster on wood lath		11[e]	0.091		
Plaster on plain gypsum lath (with studs)		20[f]	0.050		
Gypsum wall board (plain)	0.375	50[f]	0.020		
Gypsum sheathing (asphalt impregnated)	0.5			20[d]	0.050
Structural insulating board (sheathing quality)				20-50[f]	0.050-0.020
Structural insulating board (interior, uncoated)	0.5	50-90[f]	0.020-0.011		
Hardboard (standard)	0.125	11[f]	0.091		
Hardboard (tempered)	0.125	5[f]	0.2		
Built-up roofing (hot mopped)		0			
Wood, sugar pine				0.4-5.4[b]	2.5-0.19
Plywood (douglas fir, exterior glue)	0.25	0.7[f]	1.4		
Plywood (douglas fir, interior glue)	0.25	1.9[f]	0.53		
Acrylic, glass fiber reinforced sheet	0.056	0.12[d]*	8.3		
Polyester, glass fiber reinforced sheet	0.048	0.05[d]	20		
Thermal Insulations					
Air (still)				120[f]	0.0083
Cellular glass				0[d]*	∞
Corkboard				2.1-2.6[d]	0.48-0.38
				9.5[e]	0.11
Mineral wool (unprotected)				116[e]	0.0086
Expanded polyurethane (R-11 blown) board stock				0.4-1.6[d]	2.5-0.62
Expanded polystyrene—extruded				1.2[d]	0.83
Expanded polystyrene—bead				2.0-5.8[d]*	0.50-0.17
Phenolic foam (covering removed)				26	0.038
Unicellular synthetic flexible rubber foam				0.02-0.15[d]	50-6.7
Plastic and Metal Foils and Films[c]					
Aluminum foil	0.001	0.0[d]	∞		
Aluminum foil	0.00035	0.05[d]	20		
Polyethylene	0.002	0.16[d]	6.3		3100
Polyethylene	0.004	0.08[d]	12.5		3100
Polyethylene	0.006	0.06[d]*	17		3100
Polyethylene	0.008	0.04[d]*	25		3100
Polyethylene	0.010	0.03[d]	33		3100
Polyvinylchloride, unplasticized	0.002	0.68[d]*	1.5		
Polyvinylchloride, plasticized	0.004	0.8-1.4[d]	1.3-0.72		
Polyester	0.001	0.73[d]	1.4		
Polyester	0.0032	0.23[d]	4.3		
Polyester	0.0076	0.08[d]	12.5		
Cellulose acetate	0.01	4.6[d]	0.2		
Cellulose acetate	0.125	0.32[d]	3.1		

**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, Btu/h·ft²·°F
ε = surface emittance
σ = Stefan-Boltzmann constant = 0.1712×10^{-8} Btu/h·ft²·°R⁴

Example 6. Compute the total annual heat loss from 165 ft of nominal 2 in. bare steel pipe in service 4000 h per year. The pipe is carrying steam at 10 psig and is exposed to an average air temperature of 80°F.

Solution: The pipe temperature is taken as the steam temperature, which is 239.4°F, obtained by interpolation from Steam Tables. By interpolation in Table 11A between 180°F and 280°F, heat loss from a nominal 2 in. pipe is 285 Btu/h·ft. Total annual heat loss from the entire line is 285 Btu/h·ft × 165 ft × 4000 h = 188×10^6 Btu.

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 (*Concluded*)[a]

Material	Weight, lb/100 ft^2	Permeance, Perms			Resistance[h] Rep		
		Dry-Cup	Wet-Cup	Other	Dry-Cup	Wet-Cup	Other
Building Paper, Felts, Roofing Papers[g]							
Duplex sheet, asphalt laminated, aluminum foil one side	8.6	0.002	0.176		500	5.8	
Saturated and coated roll roofing	65	0.05	0.24		20	4.2	
Kraft paper and asphalt laminated, reinforced 30-120-30	6.8	0.3	1.8		3.3	0.55	
Blanket thermal insulation backup paper, asphalt coated	6.2	0.4	0.6-4.2		2.5	1.7-0.24	
Asphalt-saturated and coated vapor retarder paper	8.6	0.2-0.3	0.6		5.0-3.3	1.7	
Asphalt-saturated, but not coated, sheathing paper	4.4	3.3	20.2		0.3	0.05	
15-lb asphalt felt	14	1.0	5.6		1.0	0.18	
15-lb tar felt	14	4.0	18.2		0.25	0.055	
Single-kraft, double	3.2	31	42		0.032	0.024	
Liquid-Applied Coating Materials	**Thickness, in.**						
Commercial latex paints (dry film thickness)[i]							
Vapor retarder paint	0.0031			0.45			2.22
Primer-sealer	0.0012			6.28			0.16
Vinyl acetate/acrylic primer	0.002			7.42			0.13
Vinyl-acrylic primer	0.0016			8.62			0.12
Semi-gloss vinyl-acrylic enamel	0.0024			6.61			0.15
Exterior acrylic house and trim	0.0017			5.47			0.18
Paint—2 coats							
Asphalt paint on plywood			0.4			2.5	
Aluminum varnish on wood		0.3-0.5			3.3-2.0		
Enamels on smooth plaster				0.5-1.5			2.0-0.66
Primers and sealers on interior insulation board				0.9-2.1			1.1-0.48
Various primers plus 1 coat flat oil paint on plaster				1.6-3.0			0.63-0.33
Flat paint on interior insulation board				4			0.25
Water emulsion on interior insulation board				30-85			0.03-0.012
	Weight, oz/ft^2						
Paint-3 coats							
Exterior paint, white lead and oil on wood siding		0.3-1.0			3.3-1.0		
Exterior paint, white lead-zinc oxide and oil on wood		0.9			1.1		
Styrene-butadiene latex coating	2	11			0.09		
Polyvinyl acetate latex coating	4	5.5			0.18		
Chlorosulfonated polyethylene mastic	3.5	1.7			0.59		
	7.0	0.06			16		
Asphalt cutback mastic, 1/16 in., dry		0.14			7.2		
3/16 in., dry		0.0			—		
Hot melt asphalt	2	0.5			2		
	3.5	0.1			10		

[a]This 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. Permeance, resistance, permeability, and resistance per unit thickness values are given in the following units:

Permeance	Perm	= $gr/h \cdot ft^2 \cdot in.\ Hg$
Resistance	Rep	= $in.\ Hg \cdot ft^2 \cdot h/gr$
Permeability	Perm-in.	= $gr/h \cdot ft^2 \cdot (in.\ Hg/in.)$
Resistance/unit thickness	Rep/in.	= $(in.\ Hg \cdot ft^2 \cdot h/gr)/in.$

[b]Depending on construction and direction of vapor flow.

[c]Usually 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.

[d]Dry-cup method.

[e]Wet-cup method.

[f]Other than dry- or wet-cup method.

[g]Low permeance sheets used as vapor retarders. High permeance used elsewhere in construction.

[h]Resistance and resistance/in. values have been calculated as the reciprocal of the permeance and permeability values.

[i]Cast at 10 mils (0.01 in.) wet film thickness.

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

Material	Max. Temp.,[b] °F	Typical Density, lb/ft^3	Typical Conductivity *k* in $Btu \cdot in/h \cdot ft^2 \cdot °F$ at Mean Temperature, °F													
			−100	−75	−50	−25	0	25	50	75	100	200	300	500	700	900
BLANKETS AND FELTS																
ALUMINOSILICATE FIBER																
7 to 10 μm diameter fiber	1800	4								0.24		0.32		0.54	0.99	1.03
	2000	6-8								0.25		0.30		0.48	0.78	0.95
3 μm diameter fiber	2200	4								0.22		0.29		0.45	0.59	0.74
MINERAL FIBER (Rock, slag, or glass)																
Blanket, metal reinforced	1200	6-12									0.26	0.32	0.39	0.54		
	1000	2.5-6									0.24	0.31	0.40	0.61		
Blanket, flexible, fine-fiber organic bonded	350	0.75				0.25	0.26	0.28	0.30	0.33	0.36	0.53				
		0.75				0.24	0.25	0.27	0.29	0.32	0.34	0.48				
		1.0				0.23	0.24	0.25	0.27	0.29	0.32	0.43				
		1.5				0.21	0.22	0.23	0.25	0.27	0.28	0.37				
		2.0				0.20	0.21	0.22	0.23	0.25	0.26	0.33				
		3.0				0.19	0.20	0.21	0.22	0.23	0.24	0.31				
Blanket, flexible, textile fiber, organic bonded	350	0.65				0.27	0.28	0.29	0.30	0.31	0.32	0.50	0.68			
		0.75				0.26	0.27	0.28	0.29	0.31	0.32	0.48	0.66			
		1.0				0.24	0.25	0.26	0.27	0.29	0.31	0.45	0.60			
		1.5				0.22	0.23	0.24	0.25	0.27	0.29	0.39	0.51			
		3.0				0.20	0.21	0.22	0.23	0.24	0.25	0.32	0.41			
Felt, semirigid organic bonded	400	3-8						0.24	0.25	0.26	0.27	0.35	0.44			
Laminated and felted without binder	850	3	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.35	0.55			
	1200	7.5											0.35	0.45	0.60	
BLOCKS, BOARDS, AND PIPE INSULATION																
MAGNESIA	600	11-12									0.35	0.38	0.42			
85% CALCIUM SILICATE	1200	11-15									0.38	0.41	0.44	0.52	0.62	0.72
	1800	12-15												0.63	0.74	0.95
CELLULAR GLASS	900	7.8-8.2	0.24	0.25	0.26	0.28	0.29	0.30	0.32	0.33	0.34	0.41	0.49	0.70	1.01	
DIATOMACEOUS SILICA	1600	21-22												0.64	0.68	0.72
	1900	23-25												0.70	0.75	0.80
MINERAL FIBER (Glass)																
Organic bonded, block and boards	400	3-10	0.16	0.17	0.18	0.19	0.20	0.22	0.24	0.25	0.26	0.33	0.40			
Nonpunking binder	1000	3-10									0.26	0.31	0.38	0.52		
Pipe insulation, slag, or glass	350	3-4					0.20	0.21	0.22	0.23	0.24	0.29				
	500	3-10					0.20	0.22	0.24	0.25	0.26	0.33	0.40			
Inorganic bonded block	1000	10-15									0.33	0.38	0.45	0.55		
	1800	15-24									0.32	0.37	0.42	0.52	0.62	0.74
Pipe insulation, slag, or glass	1000	10-15									0.33	0.38	0.45	0.55		
Resin binder		15	0.23	0.24	0.25	0.26	0.28	0.29								
RIGID POLYSTYRENE																
Extruded (CFC-12 exp.)(smooth skin surface)	165	1.8-3.5	0.16	0.16	0.17	0.16	0.17	0.18	0.19	0.20						
Molded beads	165	1	0.17	0.19	0.20	0.21	0.22	0.24	0.25	0.26	0.28					
		1.25	0.17	0.18	0.19	0.20	0.22	0.23	0.24	0.25	0.27					
		1.5	0.16	0.17	0.19	0.20	0.21	0.22	0.23	0.24	0.26					
		1.75	0.16	0.17	0.18	0.19	0.20	0.22	0.23	0.24	0.25					
		2.0	0.15	0.16	0.18	0.19	0.20	0.21	0.22	0.23	0.24					
RIGID POLYURETHANE/POLYISOCYANURATE[c,d]																
Unfaced (CFC-11 exp.)	210	1.5-2.5	0.16	0.17	0.18	0.18	0.18	0.17	0.16	0.16	0.17					
RIGID POLYISOCYANURATE																
Gas-impermeable facers (CFC-11 exp.)	250	2.0						0.12	0.13	0.14	0.15					
RIGID PHENOLIC																
Closed cell (CFC-11, CFC-113 exp.)		3.0						0.11	0.115	0.12	0.125					
RUBBER, Rigid foamed	150	4.5						0.20	0.21	0.22	0.23					
VEGETABLE AND ANIMAL FIBER																
Wool felt (pipe insulation)	180	20						0.28	0.30	0.31	0.33					
INSULATING CEMENTS																
MINERAL FIBER (Rock, slag, or glass)																
With colloidal clay binder	1800	24-30									0.49	0.55	0.61	0.73	0.85	
With hydraulic setting binder	1200	30-40									0.75	0.80	0.85	0.95		
LOOSE FILL																
Cellulose insulation (milled pulverized paper or wood pulp)		2.5-3							0.26	0.27	0.29					
Mineral fiber, slag, rock, or glass		2-5			0.19	0.21	0.23	0.25	0.26	0.28	0.31					
Perlite (expanded)		3-5	0.22	0.24	0.25	0.27	0.28	0.30	0.31	0.33	0.35					
Silica aerogel		7.6			0.13	0.14	0.15	0.15	0.16	0.17	0.18					
Vermiculite (expanded)		7-8.2			0.39	0.40	0.42	0.44	0.45	0.47	0.49					
		4-6			0.34	0.35	0.38	0.40	0.42	0.44	0.46					

[a]Representative 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.

[b]These temperatures are generally accepted as maximum. When operating temperature approaches these limits, follow the manufacturers' recommendations.

[c]Some 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.

[d]See Table 4, footnote i.

[e]See 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 80°F.

Example 7. Compute the heat loss from a boiler wall if the interior insulation surface temperature is 1100°F and ambient still air temperature is 80°F. The wall is insulated with 4.5 in. of mineral fiber block and 0.5 in. of mineral fiber insulating and finishing cement.

Solution: Assume that the mean temperature of the mineral fiber block is 700°F, the mean temperature of the insulating cement is 200°F, and the surface resistance R_s is 0.60 ft²·°F·h/Btu.

From Table 10, k_1 = 0.62 and k_2 = 0.80. Using Equation (8) from Chapter 23:

$$q_s = \frac{1100 - 80}{(4.5/0.62) + (0.5/0.80) + 0.60} = 120.2 \text{ Btu/h} \cdot \text{ft}^2$$

As a check, from Figure 9, at 120.2 Btu/h·ft², R_s = 0.56. The mean temperature of the mineral fiber block is

$$4.5/0.62 = 7.26;\ 7.26/2 = 3.63$$

$$1100 - \frac{3.63}{8.48}(1020) = 663°\text{F}$$

and the mean temperature of the insulating cement is

$$0.5/0.80 = 0.63;\ 0.63/2 = 0.31;\ 7.26 + 0.31 = 7.57$$

$$1100 - \frac{7.57}{8.48}(1020) = 189°\text{F}$$

From Table 10, at 663°F, k_1 = 0.60; at 189°F, k_2 = 0.79.

Using these adjusted values to recalculate q_s

$$q_s = \frac{1020}{(4.5/0.60) + (0.5/0.79) + 0.56} = \frac{1020}{8.69}$$

$$= 117.4 \text{ Btu/h} \cdot \text{ft}^2$$

From Figure 9, at 117.4 Btu/h·ft², R_s = 0.56. The mean temperature of the mineral fiber block is

$$4.5/0.6 = 7.50;\ 7.50/2 = 3.75$$

$$1100 - \frac{3.75}{8.69}(1020) = 660°\text{F}$$

and the mean temperature of the insulating cement is

$$0.5/0.79 = 0.63;\ 0.63/2 = 0.31;\ 7.50 + 0.31 = 7.81$$

$$1100 - \frac{7.81}{8.69}(1020) = 183°\text{F}$$

From Table 10, at 660°F, k_1 = 0.60; at 183°F, k_2 = 0.79.

Because R_s, k_1, and k_2 do not change at these values, q_s = 117.4 Btu/h·ft.

Example 8. Compute heat loss per square foot of outer surface of insulation if pipe temperature is 1200°F and ambient still air temperature is 80°F. The pipe is nominal 6 in. steel pipe, insulated with a nominal 3 in. thick diatomaceous silica as the inner layer and a nominal 2-in. thick calcium silicate as the outer layer.

Solution: From Chapter 41 of the *ASHRAE Handbook—Systems and Equipment*, r_o = 3.31 in. A nominal 3 in. thick diatomaceous silica insulation to fit a nominal 6 in. steel pipe is 3.02 in. thick. A nominal 2 in. thick calcium silicate insulation to fit over the 3.02 in. diatomaceous silica is 2.08 in. thick. Therefore, r_i = 6.33 in. and r_s = 8.41 in.

Assume that the mean temperature of the diatomaceous silica is 600°F, the mean temperature of the calcium silicate is 250°F and the surface resistance R_s is 0.50. From Table 10, k_1 = 0.66; k_2 = 0.42. By Equation (9) from Chapter 23,

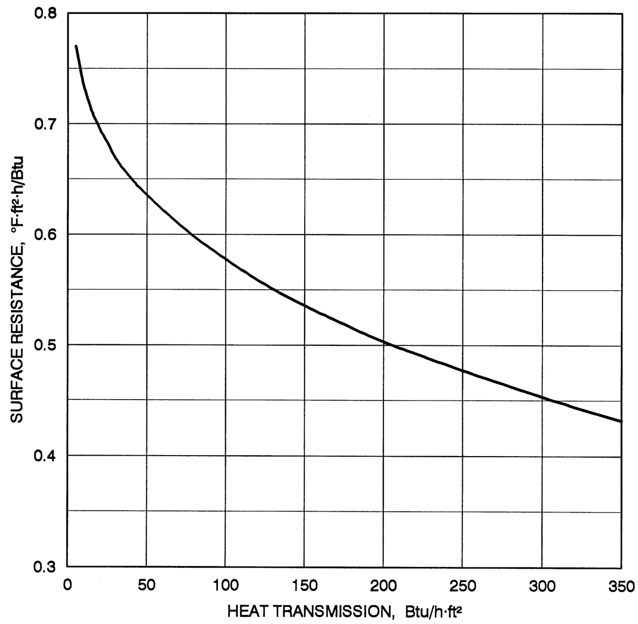


Fig. 9 Surface Resistance as Function of Heat Transmission for Flat Surfaces and Cylindrical Surfaces Greater than 24 in. in Diameter

$$q_s = \frac{1200 - 80}{[8.41 \ln(6.33/3.31)/0.66] + [8.41 \ln(8.41/3.31)/0.40] + 0.50}$$

$$= \frac{1120}{(5.45/0.66) + (2.39/0.40) + 0.50} = 76.0 \text{ Btu/h} \cdot \text{ft}^2$$

From Figure 9, at 76.0 Btu/h·ft², R_s = 0.60. The mean temperature of the diatomaceous silica is

$$5.45/0.66 = 8.26;\ 8.26/2 = 4.13$$

$$1200 - \frac{4.13}{14.83}(1120) = 888°\text{F}$$

and the mean temperature of the calcium silicate is

$$2.39/0.40 = 5.98;\ 5.98/2 = 2.99;\ 8.26 + 2.99 = 11.25$$

$$1200 - \frac{11.25}{14.83}(1120) = 350°\text{F}$$

From Table 10, k_1 = 0.72; k_2 = 0.46. Recalculating,

$$q_s = \frac{1120}{(5.45/0.72) + (2.39/0.46) + 0.60} = 83.8 \text{ Btu/h} \cdot \text{ft}^2$$

From Figure 9 at 83.8 Btu/h·ft², R_s = 0.59. The mean temperature of the diatomaceous silica is

$$5.45/0.72 = 7.57;\ 7.57/2 = 3.78$$

$$1200 - \frac{3.78}{13.36}(1120) = 883°\text{F}$$

and the mean temperature of the calcium silicate is

$$2.39/0.40 = 5.98;\ 5.98/2 = 2.99;\ 8.26 + 2.99 = 11.25$$

$$1200 - \frac{11.25}{14.83}(1120) = 350°\text{F}$$

From Table 10, k_1 = 0.72; k_2 = 0.46. Recalculating,

$$2.39/0.46 = 5.20;\ 5.20/2 = 2.60;\ 7.57 + 2.60 = 10.17$$

$$1200 - \frac{10.17}{13.36}(1120) = 347°\text{F}$$

Table 11A Heat Loss from Bare Steel Pipe to Still Air at 80°F[a], Btu/h·ft

Nominal Pipe Size[b], in.	Pipe Inside Temperature, °F									
	180	280	380	480	580	680	780	880	980	1080
0.50	59.3	147.2	263.2	412.3	600.9	836.8	1128.6	1485.6	1918.0	2436.8
0.75	72.5	180.1	322.6	506.2	739.2	1031.2	1392.9	1836.0	2373.5	3018.8
1.00	88.8	220.8	396.1	622.7	910.9	1272.6	1721.2	2271.5	2939.4	3741.6
1.25	109.7	272.8	490.4	772.3	1131.7	1583.8	2145.6	2835.4	3673.4	4680.9
1.50	123.9	308.5	555.1	875.1	1283.8	1798.3	2438.2	3224.6	4180.5	5330.0
2.00	151.8	378.1	681.4	1076.3	1581.5	2218.9	3012.6	3989.2	5177.2	6606.8
2.50	180.5	450.0	811.9	1284.0	1888.8	2652.6	3604.3	4775.3	6199.5	7912.5
3.00	215.9	538.8	973.5	1541.8	2271.4	3194.0	4344.9	5762.2	7486.9	9562.3
3.50	243.9	609.0	1101.4	1746.1	2574.7	3623.6	4933.0	6546.4	8510.4	10874.3
4.00	271.6	678.6	1228.2	1948.7	2875.9	4050.5	5517.5	7326.0	9528.1	12178.9
4.50	299.2	747.7	1354.4	2150.9	3176.8	4477.7	6103.8	8109.5	10553.2	13496.2
5.00	329.8	824.7	1494.8	2375.4	3510.6	4950.7	6751.3	8972.5	11678.4	14936.3
6.00	387.1	968.7	1757.8	2796.8	4138.0	5841.4	7972.7	10603.1	13808.2	17667.6
7.00	440.5	1102.8	2003.0	3189.9	4723.9	6673.5	9114.2	12127.4	15799.4	20220.8
8.00	493.3	1235.7	2246.1	3580.0	5305.5	7500.0	10248.4	13642.2	17778.2	22758.0
9.00	545.9	1368.1	2488.8	3970.2	5888.7	8331.0	11392.1	15174.5	19787.1	25343.6
10.00	604.3	1514.8	2757.2	4400.7	6530.1	9241.1	12638.6	16835.1	21949.2	28104.9
11.00	656.0	1644.8	2995.5	4783.8	7102.1	10054.9	13756.2	18328.4	23900.3	30606.1
12.00	704.0	1762.3	3203.8	5104.9	7557.3	10661.8	14524.9	19256.7	24967.6	31766.8
14.00	771.0	1934.2	3525.9	5636.0	8373.9	11862.4	16235.5	21635.6	28212.3	36120.3
16.00	872.2	2189.0	3993.2	6387.4	9495.9	13458.0	18424.8	24556.6	32021.1	40990.7
18.00	972.5	2441.7	4456.7	7132.9	10609.4	15041.3	20596.7	27453.2	35795.6	45813.1
20.00	1072.1	2692.4	4916.8	7873.2	11715.1	16613.4	22752.5	30326.8	39537.6	50590.0
24.00	1269.3	3188.9	5828.3	9339.9	13905.5	19726.9	27019.7	36010.1	46930.3	60014.7

Table 11B Heat Loss from Flat Surfaces to Still Air at 80°F, Btu/h·ft²

	Surface Inside Temperature, °F									
	180	280	380	480	580	680	780	880	980	1080
Vertical surface	212.2	533.1	973.3	1558.6	2321.2	3298.0	4530.1	6062.8	7945.5	10231.5
Horizontal surface										
Facing up	234.7	586.4	1061.1	1683.5	2484.9	3501.9	4775.4	6350.4	8276.3	10606.1
Facing down	183.6	465.3	861.4	1399.6	2112.8	3038.4	4217.8	5696.7	7524.5	9754.7

[a]Calculations from ASTM C 680; steel: k = 314.4 Btu·in/h·ft²·°F; ε = 0.94.

[b]Losses per square foot of pipe for pipes larger than 24 in. can be considered the same as losses per square foot for 24 in. pipe.

Because R_s, k_1, and k_2 do not change at 83.8 Btu/h·ft², this is q_s. The heat flow per ft² of the inner surface of the insulation is

$$q_o = q_s(r_s/r_o) = 83.8(8.41/3.31) = 213 \text{ Btu/h} \cdot \text{ft}^2$$

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 80°F[a], Btu/h·ft

Nominal Tube Size, in.	Tube Inside Temperature, °F								
	120	150	180	210	240	270	300	330	
0.250	7.1	14.1	21.9	30.6	39.9	49.9	60.6	71.9	
0.375	9.1	18.0	28.1	39.1	51.1	63.9	77.6	92.2	
0.500	11.0	21.8	34.0	47.4	61.9	77.5	94.1	111.8	
0.750	14.7	29.1	45.4	63.3	82.7	103.6	126.0	149.8	
1.000	18.3	36.2	56.4	78.7	102.8	128.9	156.7	186.5	
1.250	21.8	43.1	67.2	93.6	122.4	153.4	186.7	222.2	
1.500	25.2	49.8	77.6	108.3	141.5	177.4	216.0	257.1	
2.000	31.8	62.9	98.0	136.7	178.8	224.3	273.1	325.4	
2.500	38.3	75.6	117.9	164.4	215.1	269.8	328.7	391.8	Dull ε = 0.44
3.000	44.6	88.1	137.2	191.5	250.5	314.4	383.2	456.9	
3.500	50.8	100.3	156.3	218.0	285.4	358.2	436.7	520.8	
4.000	57.0	112.3	175.0	244.2	319.7	401.4	489.4	583.9	
5.000	69.0	135.9	211.7	295.5	386.9	486.0	592.8	707.6	
6.000	80.7	159.0	247.7	345.7	452.8	568.9	694.2	829.0	
8.000	103.7	204.1	317.8	443.7	581.3	730.7	892.1	1066.0	
10.000	126.1	247.9	386.1	539.1	706.5	888.4	1085.2	1297.4	
12.000	148.0	290.9	453.0	632.5	829.2	1043.1	1274.6	1524.4	
0.250	5.4	10.8	16.9	23.5	30.5	37.9	45.5	53.5	
0.375	6.8	13.7	21.4	29.7	38.6	47.9	57.6	67.6	
0.500	8.2	16.4	25.7	35.7	46.3	57.4	69.1	81.2	
0.750	10.7	21.6	33.8	46.9	60.9	75.6	90.9	106.8	
1.000	13.2	26.5	41.4	57.6	74.7	92.8	111.6	131.2	
1.250	15.5	31.3	48.8	67.8	88.0	109.3	131.6	154.7	
1.500	17.8	35.8	56.0	77.8	100.9	125.3	150.8	177.4	
2.000	22.2	44.6	69.7	96.8	125.7	156.1	187.9	221.1	Bright ε = 0.08
2.500	26.4	53.0	82.8	115.1	149.5	185.6	223.5	263.0	
3.000	30.5	61.2	95.6	132.8	172.4	214.2	257.9	303.5	
3.500	34.4	69.1	107.9	150.0	194.8	242.0	291.4	342.9	
4.000	38.3	76.8	120.0	166.8	216.6	269.1	324.1	381.4	
5.000	45.7	91.8	143.4	199.3	258.8	321.6	387.4	456.1	
6.000	53.0	106.3	166.0	230.7	299.7	372.5	448.7	528.3	
8.000	66.8	134.1	209.4	291.1	378.2	470.1	566.5	667.2	
10.000	80.2	160.8	251.0	349.0	453.4	563.7	679.5	800.4	
12.000	93.0	186.5	291.3	404.9	526.1	654.2	788.7	929.3	

[a]Calculations from ASTM C 680; for copper: k = 2784 Btu·in/h·ft^2·°F.

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).

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Table 13 Recommended Thicknesses for Pipe and Equipment Insulation

Nom Dia., in.		MINERAL FIBER (Fiberglass and Rock Wool)										CALCIUM		
		Process Temperature, °F										Process Temp., °F		
		150	250	350	450	550	650	750	850	950	1050	150	250	350
	Thickness	1	1½	2	2½	3	3½	4	4	4½	5½	1	1½	2
½	Heat loss	8	16	24	33	43	54	66	84	100	114	13	24	34
	Surface temp.	72	75	76	78	79	81	82	86	87	87	75	78	80
	Thickness	1	1½	2	2½	3½	4	4	4½	5	5½	1	2	2½
1	Heat loss	11	21	30	41	49	61	79	96	114	135	16	26	38
	Surface temp.	73	76	78	80	79	81	84	86	88	89	76	76	79
	Thickness	1	2	2½	3	4	4	4	5½	5½	6	1½	2½	3
1½	Heat loss	14	22	33	45	54	73	94	103	128	152	17	29	42
	Surface temp.	73	74	77	79	79	82	86	84	88	90	73	75	78
	Thickness	1½	2	3	3½	4	4	4	5½	6	6	1½	2½	3
2	Heat loss	13	25	34	47	61	81	105	114	137	168	19	32	47
	Surface temp.	71	75	75	77	79	83	87	85	87	91	74	76	79
	Thickness	1½	2½	3½	4	4	4½	4½	6	6½	7	2	3	3½
3	Heat loss	16	28	39	54	75	94	122	133	154	184	21	37	54
	Surface temp.	72	74	75	77	81	83	87	86	87	90	73	75	78
	Thickness	1½	3	4	4	4	5	5½	6	7	7½	2	3	4
4	Heat loss	19	29	42	63	88	102	126	152	174	206	25	43	58
	Surface temp.	72	73	74	78	82	86	85	87	88	90	70	76	77
	Thickness	2	3	4	4	4½	5	5½	6½	7½	8	2	3½	4
6	Heat loss	21	38	54	81	104	130	159	181	208	246	33	51	75
	Surface temp.	71	74	75	79	82	84	87	88	89	91	74	75	79
	Thickness	2	3½	4	4	5	5	5½	7	8	8½	2½	3½	4
8	Heat loss	26	42	65	97	116	155	189	204	234	277	35	62	90
	Surface temp.	71	73	76	80	81	86	89	88	89	92	73	76	79
	Thickness	2	3½	4	4	5	5½	5½	7½	8½	9	2½	4	4
10	Heat loss	32	50	77	115	136	170	220	226	259	307	41	66	106
	Surface temp.	72	74	77	81	82	85	90	87	89	91	73	75	80
	Thickness	2	3½	4	4	5	5½	5½	7½	8½	9½	2½	4	4
12	Heat loss	36	57	87	131	154	192	249	253	290	331	47	75	121
	Surface temp.	72	74	77	82	82	86	91	88	89	91	73	76	81
	Thickness	2	3½	4	4	5	5½	6½	7½	9	9½	2½	4	4
14	Heat loss	40	61	94	141	165	206	236	271	297	352	51	81	130
	Surface temp.	72	74	77	82	83	86	87	89	89	91	73	76	81
	Thickness	2½	3½	4	4	5½	5½	7	8	9	10	3	4	4
16	Heat loss	37	68	105	157	171	228	247	284	326	372	50	90	144
	Surface temp.	71	74	78	83	82	87	86	88	89	91	72	76	82
	Thickness	2½	3½	4	4	5½	5½	7	8	9	10	3	4	4
18	Heat loss	41	75	115	173	187	250	270	310	354	404	55	99	159
	Surface temp.	71	74	78	83	83	87	87	88	90	91	73	76	82
	Thickness	2½	3½	4	4	5½	5½	7	8	9	10	3	4	4
20	Heat loss	45	82	126	189	204	272	292	335	383	436	60	108	174
	Surface temp.	71	75	78	83	83	87	87	89	90	92	73	77	82
	Thickness	2½	4	4	4	5½	6	7½	8	9	10	3	4	4
24	Heat loss	53	86	147	221	237	295	320	386	439	498	71	127	203
	Surface temp.	71	74	78	83	83	86	86	89	91	93	73	77	82
	Thickness	2½	4	4	4	5½	6½	7½	8½	10	10	3	4	4
30	Heat loss	65	105	179	268	286	332	383	439	481	591	86	154	247
	Surface temp.	71	74	79	84	84	85	87	89	89	94	73	77	83
	Thickness	2½	4	4	4	5½	7	8	9	10	10	2½	4	4
36	Heat loss	77	123	211	316	335	364	422	486	556	683	119	181	291
	Surface temp.	71	74	79	84	84	84	86	88	90	94	74	77	83
	Thickness	2	3½	4	4½	5½	8½	9½	10	10	10	2½	3½	4
Flat	Heat loss	10	14	20	27	31	27	31	38	47	58	12	20	28
	Surface temp.	72	74	77	80	82	80	82	85	89	93	73	77	81

Consult manufacturer's literature for product temperature limitations. Table is based on typical operating conditions, e.g., 65°F ambient temperature and 7.5 mph wind speed, and may not represent actual conditions of use. Units for thickness, heat loss, and surface temperature are in inches, Btu/h·ft (Btu/h·ft^2 for flat surfaces), and °F, respectively.

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

Nom. Dia., in.		SILICATE Process Temperature, °F 450	550	650	750	850	950	1050	CELLULAR GLASS Process Temperature, °F 150	250	350	450	550	650	750
	Thickness	2½	3	3½	4	4	4	4	1½	1½	2	2½	3	3½	4
½	Heat loss	42	53	63	75	90	108	128	9	23	34	48	62	78	92
	Surface temp.	81	82	83	84	87	91	94	70	76	78	82	83	85	84
	Thickness	3	3½	4	4	4	4	4	1½	2	2½	3	3½	4	4
1	Heat loss	49	60	72	89	109	130	154	12	25	38	52	68	86	112
	Surface temp.	80	82	83	86	90	94	98	71	75	77	79	81	83	88
	Thickness	3½	4	4	4	4	5	5	1½	2½	3	4	4	4	4
1½	Heat loss	54	68	86	106	128	139	164	15	28	44	56	79	105	137
	Surface temp.	80	81	85	88	92	91	94	72	75	77	78	82	87	92
	Thickness	3½	4	4½	5	5½	6	6	1½	2½	3	4	4	4	4½
2	Heat loss	61	75	90	106	123	142	167	17	31	47	61	84	113	140
	Surface temp.	81	82	84	85	87	88	91	72	74	77	78	82	86	89
	Thickness	4	4½	5	5½	6	6	6	1½	3	3½	4	4	4½	5
3	Heat loss	71	87	105	123	143	71	202	22	35	54	75	105	132	161
	Surface temp.	80	82	84	85	87	90	94	73	74	77	79	84	86	89
	Thickness	4	4½	5	5½	6	6½	7	2	3	4	4	4	4½	5
4	Heat loss	82	101	121	142	164	187	213	22	41	59	87	122	150	185
	Surface temp.	81	83	85	87	89	90	92	71	74	76	80	85	87	90
	Thickness	4	4½	5	5½	6	7	8	2	3½	4	4	4½	5½	6
6	Heat loss	105	129	153	178	205	224	245	30	48	74	111	144	171	212
	Surface temp.	83	85	87	89	91	91	91	72	74	77	82	85	86	89
	Thickness	4½	5	5	6	7	8	8½	2½	3½	4	4	5	5½	6½
8	Heat loss	117	144	183	200	220	243	277	30	58	90	134	161	203	238
	Surface temp.	82	85	89	89	89	90	92	71	74	78	83	84	87	89
	Thickness	4	5	5½	6	7½	8½	9	2½	4	4	4	5½	5½	7
10	Heat loss	149	168	200	233	243	269	306	37	63	106	159	178	238	264
	Surface temp.	85	86	88	90	89	89	91	71	74	79	84	84	87	88
	Thickness	4	5	5½	7	8	8½	9½	2½	4	4	4	5½	5½	7½
12	Heat loss	170	191	266	236	262	300	330	42	71	121	181	201	269	284
	Surface temp.	86	86	89	88	88	90	91	71	74	79	85	84	90	88
	Thickness	4	5	5½	7	8	9	9½	2½	4	4	4	5½	5½	8
14	Heat loss	183	205	242	252	262	308	352	47	79	134	199	219	293	293
	Surface temp.	86	87	89	88	88	89	91	72	74	80	85	85	91	87
	Thickness	4	5½	6½	7½	8	9	10	2½	4	4	4	5½	5½	8
16	Heat loss	204	211	237	265	307	338	372	53	88	149	222	242	325	322
	Surface temp.	87	85	86	87	89	90	91	72	75	80	86	86	91	88
	Thickness	4	5½	6½	7½	8½	9	10	2½	4	4	4	5½	5½	8
18	Heat loss	225	232	259	289	320	367	403	59	96	164	245	266	356	351
	Surface temp.	87	86	87	87	88	90	91	72	75	80	86	86	92	88
	Thickness	4	5½	6½	7½	8½	9½	10	2½	4	4	4½	5½	5½	8
20	Heat loss	245	252	281	312	346	381	435	64	105	179	243	289	387	379
	Surface temp.	87	86	87	88	89	90	92	72	75	81	84	86	92	88
	Thickness	4	5½	6½	7½	8½	9½	10	2½	4	4	5	5½	5½	8
24	Heat loss	287	293	325	360	397	437	497	76	123	209	260	336	449	436
	Surface temp.	88	87	88	88	89	90	93	72	75	81	83	87	93	89
	Thickness	4	5½	7	8	9	10	10	2½	4	4	5½	5½	5½	8
30	Heat loss	349	353	368	409	452	498	589	93	150	254	290	405	542	521
	Surface temp.	88	87	87	88	89	90	94	72	75	81	82	87	93	90
	Thickness	4	6½	7½	8	9	10	10	2½	4	4	5½	5½	5½	8
36	Heat loss	410	359	406	475	524	576	681	110	176	229	340	474	635	606
	Surface temp.	89	84	86	88	89	91	94	73	76	81	82	88	94	90
	Thickness	5½	6½	7½	8½	9½	10	10	2½	4	4	5½	5½	7½	8½
Flat	Heat loss	29	33	36	39	43	49	58	11	17	29	31	44	43	50
	Surface temp.	81	83	84	85	87	89	93	73	76	83	84	90	90	93

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