Ser
TH1
N21d
no. 1235
c. 2
BLDG

12039

National Research Council Canada
Conseil national de recherches Canada

DESIGN HEAT TRANSMISSION COEFFICIENTS

Chapter 23, ASHRAE 1981 Fundamentals Handbook

ANALYZED

NRC – CISTI
BLDG. RES.
LIBRARY
84- 11 19
BIBLIOTHÈQUE
Rech. Bâtim.
CNRC – ICIST

Reprinted with permission

DBR Paper No. 1235
Division of Building Research

Price $3.00 OTTAWA NRCC 23748

Canada

4965562

CHAPTER 23

DESIGN HEAT TRANSMISSION COEFFICIENTS

Heat Transfer Definitions and Symbols; Surface Conductance; Calculating Overall Coefficients; Alternate Method of Calculation; Overall Coefficients and Their Practical Use; Insulating Constructions; Adjustment for Framing; Curtain Walls; Ventilated Attics; Foundation Coefficients; Glass and Door Coefficients; Estimated Heat Loss Due to Infiltration; Calculating Surface Temperatures; Conductivity of Industrial Insulations; Bare Surface Heat Losses; Heat Flow Calculations; Buried Pipe Lines; Thermal Characteristics and Response Factors for Floors, Walls, and Roofs

THE design of a heating, refrigerating, or air-conditioning system, including selection of building insulation, sizing of piping and ducts, or evaluation of thermal performance of system parts is based on the principles of heat transfer given in Chapter 2. The equations most widely used to estimate heat transfer loads chargeable to the various parts will usually determine the heat transfer rate under steady state conditions. For a given part under standard conditions, this rate is a specific value, *U*, the *overall coefficient of heat transmission* or thermal transmittance.

This chapter is concerned with the concepts and procedures for determining such coefficients, and includes a brief discussion of factors that may affect the values of these coefficients and performance of thermal insulations. Coefficients may be determined by testing, or computed from known values of thermal conductance of the various components. Procedures for calculating coefficients are illustrated by examples and, because it is impracticable to test all combinations of materials, tables of computed design values for the more common constructions are given.

Units in this chapter are in the customary (i.e., U.S., English, and cgs) systems. In the following definitions of heat transfer, the customary unit, followed by the SI unit, is given. Note that although the SI unit of temperature is the kelvin (K), the degree Celsius (formerly centigrade) is properly used with SI units. The temperature interval one degree Celsius equals one kelvin exactly. Factors for converting to SI are given in Table 18 and in Chapter 37.

HEAT TRANSFER DEFINITIONS AND SYMBOLS

q = *thermal transmission* or rate of heat flow; the quantity of heat flowing due to all mechanisms in unit time under the conditions prevailing at that time; in Btu/h or W.

Note: Mechanisms relate to modes of heat transfer by solid conduction, mass transfer, gas conduction, convection, and radiation. These may occur separately or in combination, partially or totally depending upon specific circumstances.

k or λ = *thermal conductivity*; the thermal transmission, by conduction only, in unit time through unit area of an infinite slab in a direction perpendicular to the surface, when unit difference in temperature is established between the surfaces; in Btu · in./h · ft^2 · F or W/m · K.

Note 1: A body is considered homogeneous when the above property is found by measurement to be independent of sample dimensions.

Note 2: The property must be identified with a specific mean temperature. Thermal conductivity varies with temperature; and direction and orientation of thermal transmission, since some bodies are not isotropic with respect to the property.

Note 3: For many thermal insulation materials, thermal transmission occurs by a combination of modes of heat transfer. The measured property should be referred to as an effective or apparent thermal conductivity for the specific test conditions (sample thickness and orientation, environment, environmental pressure, and temperature difference).

r or w = *thermal resistivity;* the reciprocal of thermal conductivity; ft^2 · F · h/Btu · in. or m · K/W.

C = *thermal conductance*; the thermal transmission in unit time through unit area of a particular body or assembly having defined surfaces, when unit average temperature difference is established between the surfaces; Btu/h · ft^2 · F or W/m^2 · K.

Note 1: The average temperature of a surface is one that adequately approximates that obtained by integrating the temperature over the body.

Note 2: When the two defined surfaces of a mass-type thermal insulation are not of equal areas, as in the case of thermal transmission in a radial direction (see Chapter 2, Table 2), or are not of uniform separation (thickness), an appropriate average area and average thickness must be given.

Note 3: When heat transfer is by conduction alone, the average thermal conductivity is the product of the thermal conductance per unit area and the thickness. The average thermal resistivity is the reciprocal of the average thermal conductivity. When conduction is supplemented by any or all of the other modes of heat transfer, the *apparent or effective thermal conductivity* is obtained by multiplying the thermal conductance by the thickness. The apparent or effective resistivity is the reciprocal of the apparent or effective thermal conductivity.

Note 4: Where there is air passage through the body, the effective thermal conductance (resistance) must include details of the pressure difference across the body. For a body which is transparent to light, the effective thermal conductance (resistance) may include fenestration, but the optical properties or shading coefficient of the body must be given.

Note 5: The thermal conductance of some bodies is related to their thickness. In such cases, the apparent thermal conductivity is a function of thickness. For this reason, it is preferable to express results as effective thermal conductances (resistances) rather than effective thermal conductivities (resistivities).

Note 6: *"Total" and "areal" thermal conductance* are often used as synonyms for thermal conductance.

Note 7: Values of thermal conductance (referred to as *conductances*) and their inverses (*resistances*) of the more common building materials are tabulated later in this chapter.

R = *thermal resistance*; the reciprocal of thermal conductance; ft^2 · F · h/Btu or m^2 · K/W.

U = *thermal transmittance*; the thermal transmission in unit time through unit area of a particular body or assembly, including its boundary films, divided by the difference between the environmental temperatures on either side of the body or assembly; Btu/h · ft^2 · F or W/m^2 · K.

Note 1: This is often referred to as the *overall coefficient of heat transfer*.

Note 2: In practice, the fluid is air, the boundary film is thin, and the average temperature of the fluid is that obtained by averaging over a finite region of the fluid near this film.

h = film or surface conductance; the thermal transmission in unit time to or from unit area of a surface in contact with its surroundings for unit difference between the temperature

The preparation of this chapter is assigned to TC 4.4, Thermal Insulation and Moisture Retarders (Total Thermal Performance Design Criteria).

of the surface and the environmental fluid temperature; Btu/h · ft^2 · F or W/m^2 · K.

Note 1: The surroundings must involve air or other fluids for radiation and convection to take place.

Note 2: Subscripts i and o are often used to denote inside and outside surface conductances, respectively.

ε = *emittance*; the ratio of the radiant flux emitted by a specimen to that emitted by a blackbody at the same temperature.

Note: The combined effect of the surface emittances of boundary surfaces of an air space where the boundaries are assumed to be parallel and of large dimensions, as compared to the distance between them, is often referred to as *effective emittance* (E). Values for a range of air spaces and conditions are tabulated later in this chapter.

ρ = *surface reflectance*; the ratio of the radiant flux reflected by an opaque surface to that falling upon it; dimensionless.

SURFACE CONDUCTANCE

The convection part of surface conductance is affected by air movement. Fig. 1 shows results of tests[1] made on 12-in. square samples of different materials at a mean temperature of 20 F for wind velocities up to 40 mph. These conductances include the radiation portion of the coefficient which, for the test conditions, was about 0.7 Btu/h · ft^2 · F. More recent tests[2] on smooth surfaces show surface length also significantly affects the convection part of conductance; the average value decreases as surface length increases. Moreover, observations[3] of the magnitude of low temperature radiant energy received from outdoor surroundings show that only under certain conditions may the outdoors be treated as a blackbody radiating at air temperature.

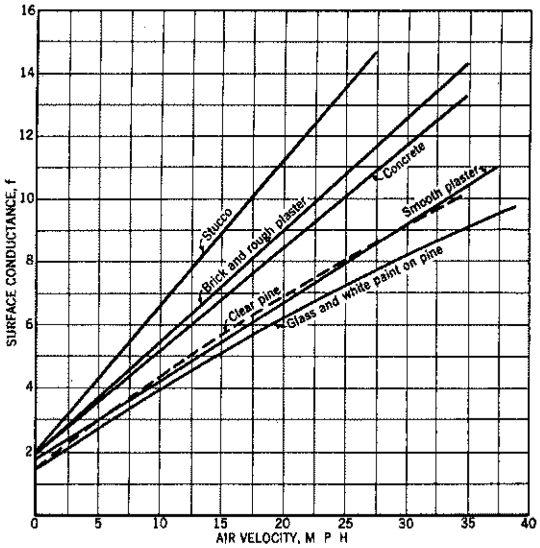


Fig. 1 Surface Conductance for Different 12-in. Square Surfaces as Affected by Air Movement[1]

CALCULATING OVERALL COEFFICIENTS

Using the principles of heat transfer in Chapter 2, it is possible to calculate overall coefficients with the resistance method. The total resistance to heat flow through a flat ceiling, floor, or wall (or a curved surface if the curvature is small) is equal numerically to the sum of the resistances in series.

$$R_T = R_1+R_2+R_3+R_4+\ldots+R_n \tag{1}$$

where R_1, R_2, etc., are the individual resistances of the wall components, and R_T is total resistance.

For a wall of a single homogeneous material of conductivity k and thickness L with surface coefficients h_i and h_o:

$$R_T = \frac{1}{h_i} + \frac{L}{k} + \frac{1}{h_o} \tag{2}$$

Then, by definition:

$$U = 1/R_T$$

For a wall with air space construction, consisting of two homogeneous materials of conductivities k_1 and k_2 and thicknesses L_1 and L_2, respectively, separated by an air space of conductance C:

$$R_T = \frac{1}{h_i} + \frac{L_1}{k_1} + \frac{1}{C} + \frac{L_2}{k_2} + \frac{1}{h_o} \tag{3}$$

and

$$U = 1/R_T$$

The temperature at any interface can be calculated, since the temperature drop through any component of the wall is proportional to its resistance. Thus, the temperature drop Δt_1 through R_1 in Eq 1 is:

$$\Delta t_1 = R_1(t_i - t_o)/R_T \tag{4}$$

where t_i and t_o are the indoor and outdoor temperatures, respectively.

Hence, the temperature at the interface between R_1 and R_2 is:

$$t_{1-2} = t_i - \Delta t_1 \tag{5}$$

For types of building materials having nonuniform or irregular sections such as hollow clay tile or concrete blocks, it is necessary to use the conductance C of the section unit as manufactured. The resistance R of the section $1/C$ would be used as one of the resistances in an equation similar to Eqs 2 and 3.

Note that in order to compute the U-value of a construction, it is first necessary to know the conductivity and thickness of homogeneous materials, conductance of nonhomogeneous materials (such as concrete blocks), surface conductances of both sides of the construction, and conductances of any air spaces or the thermal resistances of individual elements.

If the conductivities of materials in a wall are highly dependent on temperature, the mean temperature must be known to assign the correct value. In such cases, it is perhaps most convenient to use a trial and error procedure for the calculation of the total resistance, R_T. First, the mean operating temperature for each layer is estimated and conductivities k or conductances C are selected. The total resistance R_T is then calculated as in Eq 3 and then the temperature at each interface is calculated from Eqs 4 and 5.

The mean temperature of each component (arithmetic mean of its surface temperatures) can then be used to obtain conductivities k or conductances C. For nonlinear relationships, see Chapter 20, Fig. 2. This procedure can then be repeated until the conductivities or conductances have been correctly selected for the resulting mean temperatures. Generally, this can be done in two or three trial calculations.

Series and Parallel Heat Flow Paths

In many installations, components are arranged so that parallel heat flow paths of different conductances result. If there is no lateral heat flow between paths, each path may be considered to extend from inside to outside, and transmittance of each path may be calculated using Eq 1 or 3. The average transmittance is then:

$$U_{(av)} = a(U_a) + b(U_b) + ... + n(U_n) \qquad (6)$$

where a, b, ···, *n* are respective fractions of a typical basic area composed of several different paths whose transmittances are U_a, U_b, ··· U_n.

If heat can flow laterally in any continuous layer so that transverse isothermal planes result, total average resistance $R_{T(av)}$ will be the sum of the resistances of the layers between such planes, each layer being calculated by the appropriate Eq 1 or a modification of Eq 6, using the resistance values. This is a series combination of layers, of which one (or more) provides parallel paths.

The calculated transmittance, assuming parallel heat flow only, is usually considerably lower than that calculated with the assumption of combined series-parallel heat flow. The actual transmittance will be some value between the two calculated values. In the absence of test values for the combination, an intermediate value should be used; examination of the construction will usually reveal whether a value closer to the higher or lower calculated value should be used. Generally, if the construction contains any highly conducting layer in which lateral conduction is very high compared to transmittance through the wall, a value closer to the series parallel calculation should be used. If, however, there is no layer of high lateral conductance, a value closer to the parallel heat flow calculation should be used, as illustrated in *Example 1*.

Example 1: Consider a construction consisting of:

1. Inside surface having film coefficient $h_i = 2$.
2. A continuous layer of material of resistance $R_1 = 1$.
3. A parallel combination containing two heat flow paths of proportionate areas, $a = 0.1$, and $b = 0.9$, with resistances $R_{a2} = 1$ and $R_{b2} = 8$.
4. A continuous layer of material of resistance $R_3 = 0.5$.
5. Outside surface having film coefficient $h_o = 4$.

Solution: If parallel heat flow paths are assumed from air to air, the total resistance through area *a* will be:

$$R_{aT} = 1/h_i + R_1 + R_{a2} + R_3 + 1/h_o$$

$$= 0.5 + 1 + 1 + 0.5 + 0.25 = 3.25$$

and

$$U_a = 1/R_{aT} = 1/3.25$$

The resistance and transmittance through area *b* will be:

$$R_{bT} = 1/h_i + R_1 + R_{b2} + R_3 + 1/h_o$$

$$= 0.5 + 1 + 8 + 0.5 + 0.25 = 10.25$$

and

$$U_b = 1/R_{bT} = 1/10.25$$

Then the average calculated transmittances will be:

$$U_{(av)} = a(U_a) + b(U_b) = \frac{0.1}{3.25} + \frac{0.9}{10.25} = 0.119$$

If, however, isothermal planes are assumed to occur at both surfaces of R_1 and of R_3, the total calculated resistance will be:

$$R_T = 1/h_i + R_1 + \frac{(R_{a2})(R_{b2})}{aR_{b2} + bR_{a2}} + R_3 + 1/h_o$$

$$\frac{(R_{a2})(R_{b2})}{aR_{b2}+bR_{a2}} = \text{combined resistance of } R_{a2} \text{ and } R_{b2} = 4.71$$

Then, $R_T = 0.5 + 1 + 4.71 + 0.5 + 0.25 = 6.96$

and $U_{(av)} = 1/6.96 = 0.144$

If R_1 and R_3 are values for homogeneous materials, a value of about 0.125 might be selected; whereas, if they contain a highly conducting layer, a value of 0.135 might be selected.

When the construction contains one or more paths of small area having a high conductance compared to the conductance of the remaining area, the following method is suggested.

Heat Flow Through Panels Containing Metal

The transmittance of a panel which includes metal or other highly conductive material extending wholly or partly through insulation should, if possible, be determined by test in the guarded hot box. When a calculation is required, a good approximation can be made by a *Zone Method.* This 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, called *Zone B*. The two computations are then combined, and the average transmittance per unit of overall area is calculated. The basic laws of heat transfer are applied, by adding area conductances $C \cdot A$ of *elements in parallel*, and adding area resistances $R \cdot A$ of *elements in series.*

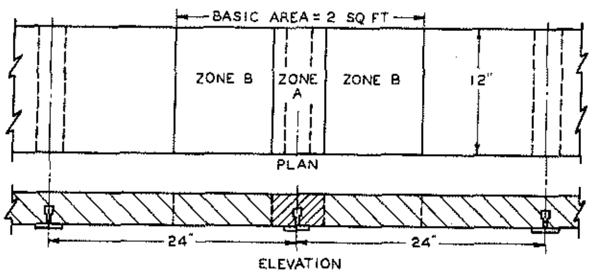
The surface shape of *Zone A* is determined by the metal element. For a metal beam (Figs. 2 and 3), the *Zone A* surface is a strip of width *W*, centered on the beam. For a rod perpendicular to panel surfaces, it is a circle of diameter *W*. The value of *W* is calculated from Eq 7, which is empirical.

$$W = m + 2d \qquad (7)$$

where

m = width or diameter of the metal heat path terminal, inches.
d = distance from panel surface to metal, inches. The value of d should not be taken as less than 0.5 in. (for still air).

In general, the value of *W* should be calculated by Eq 7 for



For enlarged section of Zone A, see Fig. 3

Fig. 2 Gypsum Roof Deck on Bulb Tees

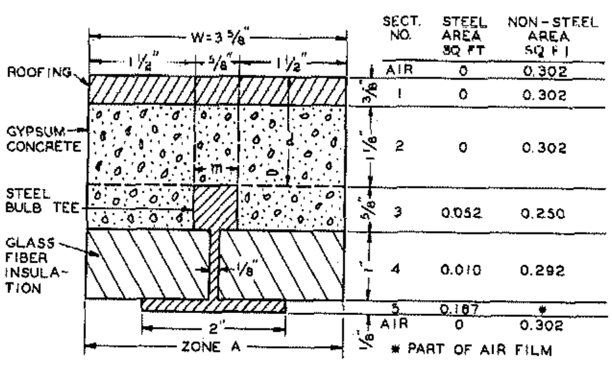


Fig. 3 Enlarged Section of Zone A of Fig. 2

each end of the metal heat path, and the larger value, within the limits of the *basic area*, should be used as illustrated in *Example 2*.

Example 2: Calculate transmittance of the roof deck shown in Figs. 2 and 3. Tee-bars on 24-in. centers support glass fiber form boards, gypsum concrete, and built-up roofing. Conductivities of components are: steel 312; gypsum concrete 1.66; glass fiber 0.25. Conductance of built-up roofing is 3.0.

Solution: The basic area is 2 ft^2 (24 in.×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 Eq 7 as follows:

Top Side $W = m + 2d = 0.625 + 2 \times 1.5 = 3.625$ in.

Bottom Side $W = m + 2d = 2.0 + 2 \times 0.5 = 3.0$ 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*, the structure within the zone is divided into five sections parallel to the top and bottom surfaces as shown in Fig. 3. The area conductance $C \cdot A$ 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 $1/R \cdot A$ and added, to obtain total resistance of *Zone A*.

Section	Area × Conductance	C · A	1/C · A = R/A
Air (outside, 15 mph)	0.302 × 6.0	1.812	0.552
No. 1, Roofing	0.302 × 3.0	0.906	1.104
No. 2, Gypsum concrete	0.302 × 1.66/1.125	0.446	2.242
No. 3, Steel	0.052 × 312.0/0.625	26.0	}0.038
No. 3, Gypsum concrete	0.250 × 1.66/0.625	0.664	
No. 4, Steel	0.0104 × 312/1.00	3.24	}0.302
No. 4, Glass fiber	0.292 × 0.25/1.00	0.073	
No. 5, Steel	0.167 × 312/0.125	416.83	0.002
Air (inside)	0.302 × 1.63	0.492	2.031
			Total R/A = 6.271

Area transmittance of *Zone A* = $1(R/A) = 1/6.271 = 0.159$.

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)	1/6.0	= 0.167
Roofing	1/3.0	= 0.333
Gypsum concrete	1.75/1.66	= 1.054
Glass fiber	1.00/0.25	= 4.000
Air (inside)	1/1.63	= 0.613
Total resistance		= 6.167

Unit transmittance = $1/R = 0.162$

Area transmittance $U \cdot A$

for *Zone B* = 1.698 × 0.162 = 0.275

for *Zone A* 0.159

Total area transmittance of *basic area* = 0.434

Transmittance per ft^2 = 0.434/2.0 = 0.217

In tests on similar construction, made by the guarded hot-box method, one laboratory reported a U-value of 0.219 Btu/h · ft^2 · F, and another laboratory reported a U-value of 0.206 Btu/h · ft^2 · F.

When the steel is a large proportion of the heat path, as in *Example 2*, detailed calculations of resistance in sections 3, 4, and 5 of *Zone A* are not justified. If only the steel were considered, the final result of *Example 2* would be unchanged.

If the steel path is small, as for a tie rod, detailed calculations for sections 3, 4, and 5 are necessary (see Table 4H).

Caution

A panel with internal metallic structure, bonded on one or both sides to a metal skin or covering, presents special problems of lateral heat flow not covered in the foregoing *Zone Method. Other methods in greater detail are available, such as* the Unified Code of Practice (Rules Th-K77)—rules for calculating practical thermal properties of structural components by C. S.T. B.

Series Heat Flow through Unequal Areas

A construction may be made up of two or more layers (flat or of small curvature) of unequal area, separated by an air space and arranged so that heat flows through the layers in series. The most common such construction is a ceiling and roof combination where the attic space is unheated and unventilated. A combined coefficient based on the most convenient area from air inside to air outside can be calculated from Eq 8.

$$R_T = \frac{1}{U_1} + \frac{1}{n_2 U_2} + \frac{1}{n_3 U_3} + \cdots + \frac{1}{n_p U_p} \quad (8)$$

The combined coefficient U is the reciprocal of R_T, or $U = 1/R_T$

where

U = combined coefficient to be used with A_1.

R_T = total resistance to all elements in series.

$U_1, U_2, \ldots, U_p$ = coefficient of transmission of $A_1, A_2, \cdots, A_p$, respectively.

$n_2, n_3, \cdots, n_p$ = area ratios $A_2/A_1, A_3/A_1, \cdots, A_p/A_1$, respectively.

Note that the overall coefficient should be multiplied by the area A_1 to determine the heat loss. Values of $U_1, U_2, U_3, \cdots, U_p$ should be calculated using Eq 1, 2, or 3; if any layer contains parallel heat flow paths (i.e., windows or dormers on roofs), Eq 6 may be used.

In the calculation, the resistance of the air spaces between layers should be accounted for by assigning one-half of an appropriate air space resistance to each of the layers, rather than the conductance of the surface.

ALTERNATE METHOD OF CALCULATION

Another method for empirical calculations based on known thermal resistance of component material is given below.

U_o Concept

In section 4.0 of ASHRAE *Standard* 90-80, *Energy Conservation in New Building Design*, requirements are stated in terms of U_o, *where* U_o is the combined thermal transmittance of the respective areas of gross exterior wall, roof/ceiling, and floor assemblies. The U_o equation for a wall is as follows:

$$U_o = \frac{U_{wall}A_{wall} + U_{window}A_{window} + U_{door}A_{door}}{A_o}$$

where

U_o = the average thermal transmittance of the gross wall area, Btu/h · ft^2 · F.

A_o = the gross area of exterior walls, ft^2.

U_{wall} = the thermal transmittance of all elements of the opaque wall area, Btu/h · ft^2 · F.

A_{wall} = opaque wall area, ft^2.

U_{window} = the thermal transmittance of the window area, Btu/h · ft^2 · F.

A_{window} = window area (including sash) ft^2.

U_{door} = the thermal transmittance of the door area, Btu/h · ft² · F.
U_{door} = door area, ft².

NOTE: *Where more than one type of wall, window and/or door is used, the U × A term for that exposure shall be expanded into its sub-elements, as:*

$$U_{wall_1} A_{wall_1} + U_{wall_2} A_{wall_2}, \text{ etc.}$$

OVERALL COEFFICIENTS AND THEIR PRACTICAL USE

The values in Tables 1, 2, 2C, 3A, and 3B for component elements and materials were selected by ASHRAE Technical Committee 4.4, as representative. They are based on available published data obtained by the guarded hot plate method (*ASTM* C177), heat flow meter method *ASTM* C518), or by the guarded hot box method (*ASTM* C236). Because of variations in commercially available materials of the same type, not all of these selected representative values will be in exact agreement with data for individual products. The value for a particular manufacturer's material can be secured from unbiased tests or from guaranteed manufacturer's data.

The most exact method of determining the heat transmission coefficient for a given combination of building materials assembled as a building section is to test a representative section in a guarded hot box. However, it is not practicable to test all the combinations of interest. Experience has indicated that *U*-values for many constructions, when calculated by the methods given in this chapter, using accurate values for component materials, and with corrections for framing member heat loss, are in good agreement with the values determined by guarded hot box measurements, when there are no free air cavities within the construction.

Remember, the values shown for materials used in calculating overall heat transmission are representative of laboratory specimens tested under idealized conditions. In actual practice, if insulation is improperly installed (for example), shrinkage, settling, insulation compression, and similar factors may have a significant effect on the overall *U*-value numbers. Materials that are field fabricated, and consequently especially sensitive to the skills of the mechanic, are especially prone to variations resulting in performance less than the idealized numbers.

Simplified Procedure for Determining *U*- Values

Tables 4A through 4K illustrate the procedure which enables the engineer to determine and compare values for many types of construction. To determine the *U*-value for uninsulated construction, use Tables 4A through 4K; for pre-engineered metal buildings use Table 4L. The benefit derived from addition of insulation materials is shown in Tables 5A and 5B. The average *U*-value is then determined by Eq 9. Additional summer values for ventilated and nonventilated attics are given in Table 6.

This simplified procedure provides a means of evaluating economic considerations involved in selection of insulating material, as adapted to various building constructions.

Special attention must be given to vapor retarders, outlined in Chapters 20 and 21. Moisture from condensation or other sources reduces the heat flow resistance of insulation.

Values Used in Calculation of *U*-Value Tables

Tables 4A through 4K are based on values given in Tables 1, 2, and 3A. The following conditions have been used to calculate the *U*-value by including framing members or other areas of through conduction.

Equilibrium or steady state heat transfer, disregarding effects of heat storage.

Surrounding surfaces at ambient air temperatures.

Exterior wind velocity of 15 mph for winter (surface $R = 0.17$) and 7.5 mph for summer (surface $R = 0.25$).

Surface emittance of ordinary building materials $\varepsilon = 0.90$.

Eq 9 is used to correct for the effect of framing members.

$$U_{av} = \frac{S}{100}(U_s) + \left(1 - \frac{S}{100}\right)(U_i) \quad (9)$$

where

U_{av} = average *U*-value for building section.
U_i = *U*-value for area between framing members.
U_s = *U*-value for area backed by framing members.
S = percentage of area backed by framing members.

For those systems with complicated geometry, U_{av} should be measured by laboratory tests on a large, representative area of the building section including the framing system.

Example 3: Parallel heat flow through framing (studs, joists, plates, furring, etc.) and insulated areas is calculated by Eq 9. Consider a frame wall with *R*-11 insulation, a U_i-value across the insulated space of 0.069 ($R = 14.43$), and a U_s-value across the framing of 0.128 ($R = 7.81$). Assuming a 20% framing (typical for 16-in. in o.c. framing including multiple studs, plates, headers, sills, band joists, etc.), the average *U*-value of this wall can be calculated.

$$U_i = 0.069; \; U_s = 0.128; \; S = 20$$

$$U_{av} = (0.2)(0.128) + (0.8)(0.069) = 0.026 + 0.055 = 0.081$$

For a frame wall with 24-in. o.c. stud space, the framing factor is estimated at 15%. In this case, the average *U*-value becomes 0.078. Depending on the care and installation of the insulation, *U*-values obtained in practice may be higher than those calculated here.

In construction involving air spaces, the *U*-values shown are calculated for areas between framing. See examples in Table 4 if an allowance is to be made for this effect.

To condense the tables, an average resistance value (avg *R*) has been used in some tables for types of materials having approximately the same thermal resistance values. The difference between the average value and the exact value for any given material usually causes no significant change in the resulting *U*-value.

Actual thicknesses of lumber assumed to be as follows:

Nominal	*Actual*	*Nominal*	*Actual*
1 in. (S-2-S)	0.75 in.	8 in.	7.25 in.
2 in. (S-2-S)	1.5 in.	10 in.	9.25 in.
3 in. (S-2-S)	2.5 in.	12 in.	11.25 in.
4 in. (S-2-S)	3.5 in	Finish flooring	
6 in.	5.5 in.	(maple or oak)	0.75 in.

Note that the effects of poor workmanship in construction and installation have an increasingly greater percentage effect on heat transmission as the *U*-value becomes numerically smaller. Failure to meet design estimates may be caused by lack of attention to exact compliance with specifications. A factor of safety may be employed as a precaution when desirable.

Caution

Although the validity of calculating *U*-values for all the types of constructions in Tables 4A through 4K, 5A, 5B, 6, and 7 has not been fully demonstrated, calculated values are given because measured values are not available.[4] It is emphasized where calculated values are shown in this chapter they are for the convenience of the reader.

In calculating *U*-values, exemplary conditions of components and installations are assumed (i.e., that insulating materials are uniformly of the nominal thickness and conductivity, air spaces are of uniform thickness and surface temperatures, effects due to moisture are not involved, and installation details are in accordance with design). Some evidence of departures of measured from calculated values for certain insulated constructions is given in *Building Materials and Structures Report* BMS 151, National Bureau of Standards. To provide a factor of safety to account for departures of constructions from requirements and practices, some may wish to moderately increase the calculated U-values of the insulated walls, floors, and ceiling sections obtained from Tables 4A through 4K before making adjustments for framing (as indicated in Eq 9).

Where reflective air spaces are involved in building construction, caution should be exercised in use of values found in Table 2. The resistance values shown are achievable under ideal conditions but are not normally achieved in standard building construction because of surface irregularities, air leakage, etc. Air spaces created by lapped metal siding should be treated as nonreflective space. Even where an air space is purposely created as with furring strips or brick veneer, tests show that the resulting air space resistance is less than values found in Table 2. Where reflective air spaces constitute a major share of the installed resistance of the insulation, increases of U-values up to 25% for applications where heat flow is horizontal or upward, and up to 20% where heat flow is downward, appear reasonable, on the basis of present information. However, to accurately determine thermal resistance values of multiple air spaces, tests on the actual construction should be conducted.[4]

INSULATED CONSTRUCTIONS—HOW TO USE TABLES 5A AND 5B

In Tables 4A through 4K, U-values are given for many common types of building wall, floor, and ceiling constructions. For any of these constructions that contain an air space, the tabulated U-value is based on the assumption that the air space is empty, and its surfaces are of ordinary building materials of high thermal emittance, such as wood, masonry, plaster, or paper. The exception is the example shown in Table 4K where the construction utilizes a reflective air space under winter and summer heat flow conditions. Considerable benefit in reducing the heat transmission coefficient of a construction can be effected by application of thermal insulating materials in the air space.

Table 5A provides a means of determining, without calculation, the U-value of the between-framing area of various types of construction with added insulation installed in the air space. The left column of Table 5A refers to the U- or R-values of designed building sections. The right-hand portion of the table consists of a tabulation of U-values resulting from the combination of U- or R-values shown in the left column with the addition of the R-values heading each column. In order to use Table 5A, the designer enters the left column with a known U- or R-value of a designed building section. Proceeding horizontally across the right-hand portion of the table, he will find U-values showing improved performance resulting from addition of thermal resistances as shown at the head of each column.

Any and all U-values are based on a series of assumptions as to nominal characteristics. Common variations in conditions, materials, workmanship, etc., can introduce much greater variations in U-values than the variations resulting from the assumed mean temperatures and temperature differences described. From this, it is also clear that the use of more than two significant figures in stating a U-value may assume more precision than can possibly exist.

Example of the Use of Table 5A

Example 4: Table 4A shows a wood frame construction without insulation and a $U_i = 0.206$ with adjustment for framing. Refer to Table 5A, left-hand column. Enter table at $U = 0.20$. For improvement of thermal performance of the designed section to $U = 0.07$, move horizontally to ($U = 0.08$) or ($U = 0.06$). Read vertically to top of columns, finding that $R = 8$ and $R = 12$ respectively. Interpolating to the desired $U = 0.07$, it is seen that material having an R-value of 10 or 11 will satisfy the requirement.

Table 5B is constructed and used similar to Table 5A. However, after having selected the desired U-value for a roof deck insulation, the values are shown in conductance C of roof deck insulation. This facilitates specification of materials, since roof deck insulations are available by conductance values (C).

ADJUSTMENT FOR FRAMING

Adjustment for parallel heat flow through framing and insulated areas may be made by using Eq 9. (See Example 3.)

CURTAIN WALLS

Curtain wall constructions present a combination of metals, insulating materials, and thermal bridges. Few panels are of true sandwich construction for which the thermal characteristics can be computed by combining the thermal resistances of the several layers. Many panels have ribs and stiffeners which may create complicated heat flow paths for which it is very difficult to calculate the heat transfer coefficients with reliability. Coefficients for the assembled sections should be determined on a representative sample by the guarded hot box method (ASTM C236) for sections which have no free air cavities within the construction. In lieu of an ASTM 236 test for these complex sections, a heat transfer coefficient may be estimated by techniques shown in Ref 16.

VENTILATED ATTICS: SUMMER CONDITIONS (HOW TO USE TABLE 6)

Table 6 is intended to be used with Table 4K (heat flow down), Table 5A, and Eq 9, or when ceiling resistance is known. Its purpose is to determine heat flow resistance of the attic space under varying conditions of ventilating air temperatures and rates, ceiling resistance, roof or sol-air temperatures, and surface emittances.[5] Ventilating air temperature is the outdoor design temperature.

The total resistance, $R = 1/U$, obtained by adding the ceiling and attic resistances, can be converted to a U-value so that the heat gain may be calculated. The applicable temperature difference is that difference between room air and sol-air temperature or between room air and roof temperatures. (See footnote d, Table 6.)

Table 6 may be used for both pitched and flat residential roofs over attic spaces. When there is an attic floor, the ceiling resistance should be that which applies to the complete ceiling-floor construction.

BASEMENT FLOOR, BASEMENT WALL, AND CONCRETE SLAB FLOOR COEFFICIENTS

The heat transfer through basement walls and floors to the ground depends on: (1) temperature difference between the air within the room and that of the ground; (2) material constituting the wall or floor; and (3) conductivity of the surrounding earth. Conductivity of the earth will vary with local conditions, and is usually unknown. Laboratory tests[6] indicate a heat flow of approximately 2.0 Btu/h · ft^2 through an uninsulated concrete basement floor, with a temperature difference of 20 deg F between basement floor and the air temperature 6 in. above the floors. The U-value 0.10 is sometimes used for concrete basement floors on the ground.

For more detailed procedures, see Chapter 25 (text and Tables 2 and 3), and Refs 7, 17, and 18.

For basement walls below grade only, the temperature difference for winter design conditions will be greater than for the floor. Test results indicate a unit area heat loss, at midheight of the basement wall portion below grade, of approximately twice that of the same floor area.

For concrete slab floors laid in contact with the ground at grade level, tests[7] indicate that, for *small floor areas* (equal to that of a house 25 ft square), the heat loss may be calculated as proportional to the length of exposed edge rather than total area. This amounts to 0.81 Btu/(h)(linear ft of exposed edge)(deg F difference between the indoor air temperature and the average outdoor air temperature). Note that this may be appreciably reduced by insulating under the ground slab and along the edges between the floor and abutting walls. In most calculations, if the perimeter loss is calculated accurately, no other floor loss need be considered. Chapter 25 contains data for load calculations and gradient values of below grade walls and floors.

GLASS AND DOOR COEFFICIENTS

The *U*-values given in Table 8 for flat glass, glass block, and plastic panels were obtained from ASHRAE Research Reports[8] in cases where the panels have been tested. In other instances, values were computed using procedures outlined in Chapter 27. Values in Table 9 for doors were calculated or taken from available published papers. For winter conditions, an outdoor surface conductance of 6.0 Btu/h · ft² · F was used; for summer conditions, 4.0 Btu/h · ft² · F. The indoor surface conductance was taken as 1.46 Btu/h · ft² · F for vertical surfaces, 1.63 for horizontal surfaces with heat flow up, and 1.08 for horizontal surfaces with heat flow down. The outdoor surfaces conductances are for wind velocities of 15 and 7.5 mph, respectively. Adjustments for other wind velocities may be made using factors in Table 10.

All values are approximate, since some parameters which may have important effects were not considered. For example, in an actual installation, the indoor surface of a glazing panel may be exposed to nearby radiating surfaces, such as radiant-heating panels or exposed windows in adjacent or opposite walls having much higher or lower temperature than the indoor air. Use of the listed *U*-value assumes that the surface temperature of surrounding bodies is equal to the ambient air temperature. Air movement across the indoor surface of a panel, such as caused by outlet grilles in the sill, will increase the *U*-value.

Shading devices such as venetian blinds, draperies, and roller shades will reduce the *U*-value substantially if they fit tightly to the window jambs, head, and sill, and are made of a nonporous material. As a rough approximation, tight-fitting shading devices may be considered to reduce the *U*-value of vertical exterior single glazing by 25% and of vertical exterior double glazing and glass block by 15%. These adjustments should not be considered in choosing heating equipment, but may be used for calculating design cooling loads.

For panels not vertical or horizontal, such as sloped glass in some types of skylights, calculation procedures outlined in Chapter 27 should be followed. Since data are presented for only vertical, horizontal, and 45-degree sloped surfaces and air spaces, an orientation which most closely approximates the application condition could be used (see Chapter 27).

ESTIMATED HEAT LOSS DUE TO INFILTRATION

Table 7 lists factors which, when multiplied by the room or building volume, will give the estimated heat loss due to infiltration. Additional information is available in Chapters 22 and 25.

CALCULATING SURFACE TEMPERATURES

In many heating and cooling load calculations, it is necessary to determine the inside surface temperature or the temperature of the surfaces within the structure. The resistances through any two paths of heat flow are proportional to the temperature drops through these paths, and can be expressed as:

$$\frac{R_1}{R_2} = \frac{(t_i - t_x)}{(t_i - t_o)} \tag{10}$$

where

R_1 = the resistance from the indoor air to any point in the structure at which the temperature is to be determined.
R_2 = the overall resistance of the wall from indoor air to outdoor air.
t_i = indoor air temperature.
t_x = temperature to be determined.
t_o = outdoor air temperature.

Example 5: Determine the inside surface temperature for a wall having an overall coefficient of heat transmission $U = 0.25$, indoor air temperature = 70 F, outdoor air temperature = −20 F, and $h_i = 1.46$ (see Table 1).

Solution:

$$R_1 = 1/h_i = 1/1.46 = 0.68$$

$$R_2 = 1/U = 1/0.25 = 4.00$$

Then, by Eq 10:

$$\frac{0.685}{4.000} = \frac{70 - t_x}{70 - (-20)}$$

$$t_x = 54.6 \text{ F}$$

Example 6: Determine the temperature of the bottom of a 4-in. insulated concrete roof slab to which has been glued 0.5-in. acoustical tile ($C = 0.80$) as the interior finish. The roof-ceiling overall coefficient of heat transmission, U, is 0.14 for heat flow up. The indoor air temperature is assumed to be 70 F, and the outdoor air temperature, −20 F.

Solution:

$$R_1 = (1/h_i) + (1/C) = (1/1.63) + (1/0.80) = 1.863$$

$$R_2 = (1/U) = (1/0.14) = 7.143$$

Then, by Eq 10:

$$\frac{1.863}{7.143} = \frac{70 - t_x}{70 - (-20)}$$

$$t_x = 46.5 \text{ F}$$

The concrete surface temperature is of interest since reference to a psychrometric chart or table will show that moisture condensation can occur on this surface under the above conditions (46.5 F) if the relative humidity in the room exceeds about 44%. Additional roof insulation should be considered above the slab to avoid condensation at this point if higher relative humidities in the room are anticipated.

The same procedure can be used for determining the temperature at any point within the structure.

A chart for determining inside wall surface temperature is given in Figs. 7 and 8, Chapter 8, 1980 SYSTEMS VOLUME.

CONDUCTIVITY OF INDUSTRIAL INSULATIONS

The conductivities of various materials used as industrial insulations are given in Table 3B. They are given as functions of the mean temperatures of the arithmetic mean of the inner and outer surface temperature of the insulations.

BARE SURFACE HEAT LOSSES—FLAT SURFACES AND PIPE

Heat losses from horizontal bare steel pipes, based on tests at Mellon Institute and calculated from the fundamental radiation and convection equations (Chapter 2), are given in Table 11. This table also gives the heat losses or surface conductances for flat, vertical, and horizontal surfaces for surface temperatures up to 1080 F with the surrounding air at 80 F. The surface per linear ft of pipe is given in the second column of Table 11.

Heat losses from tarnished copper pipe and tube[9] are given in Table 12. The surface per linear ft of tube is given in Table 13. Table 1, Section A, also gives surface conductances for flat surfaces of different emittances and orientations in contact with still air. Table 14 gives area, in ft², of flanges and fittings for various standard pipe sizes. These tables can be used in estimating the amount of insulation required.

Example 7 shows how the annual heat loss from uncovered pipe may be computed from the data in Table 11.

Example 7: Compute total annual heat loss from 165 ft of 2-in. bare pipe in service 4000 h/yr. The pipe is carrying steam at 10 psi pressure 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. The temperature difference between the pipe and air = 239.4 − 80 = 159.4 F. By interpolation in Table 11 between temperature differences of 150 and 200 F, heat loss from a 2-in. pipe at a temperature difference of 159.4 F is found to be 2.615 Btu/h · ft² · F. Total annual heat loss from the entire line = 2.615 × 159.4 × 0.622 (linear ft factor) × 165 (linear ft) × 4000 (h) = 171 million Btu.

HEAT FLOW CALCULATIONS

In calculating heat flow, Eqs 11 and 12 are generally used. Eq 11 is used for flat surfaces (Fig. 4), and Eq 12 is used for cylindrical surfaces (Fig. 5).

$$q_s = \frac{t_o - t_a}{(L_1/k_1) + (L_2/k_2) + R_s} \qquad (11)$$

$$q_s = \frac{t_o - t_a}{[r_s \log_e(r_1/r_o)]/k_1 + [r_s \log_e(r_s/r_1)]/k_2 + R_s} \qquad (12)$$

where

q_s = rate of heat transfer per square foot of outer surface of insulation, Btu/h · ft².

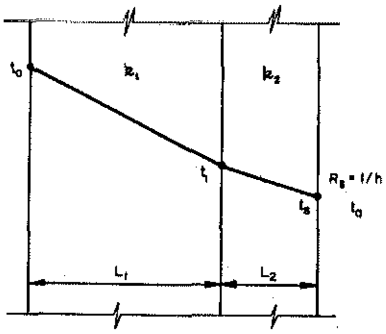


Fig. 4 Heat Flow through Flat Surfaces

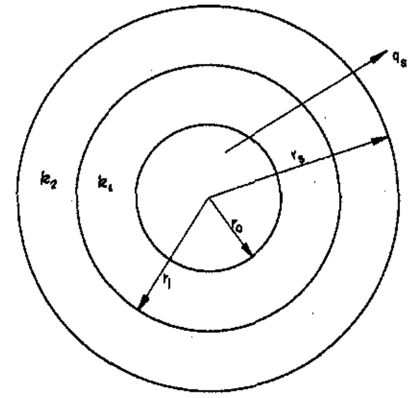


Fig. 5 Heat Flow through Cylindrical Surfaces

k = thermal conductivity of insulation at mean temperature, Btu · in./h · ft² · F.
L = thickness of insulation, in.
t_a = temperature of ambient air, F.
t_o = temperature of inner surface of insulation, F.
t_s = temperature of outer surface of insulation, F.
r_o = inner radius of insulation, in.
$r_1, r_2, \cdots$ = outer radius of intermediate layers of insulation, in.
R_s = surface resistance = $1/h$ = ft² · F · h/Btu.
h = surface conductance coefficient, Btu/h · ft² · F.
$\log_e$ = natural or Napierian logarithm.

To calculate heat flow per ft² of pipe surface, use:

$$q_o = q_s\,(r_s/r_o) \qquad (13)$$

where

q_o = rate of heat transfer per square foot of pipe surface, Btu/h · ft².

For steady state conditions, heat flow through each successive material is the same. However, the temperature drop through each material is proportional to its thermal resistance. The terms which appear in the denominators of Eqs 11 and 12 represent the resistances to heat flow.

The heat transferred is inversely proportional to the sum of the resistances ($R_1 + R_2 + \cdots + R_s$) of the system. The various temperature drops in the system are proportional to the resistances.

The assumptions used for calculations of heat loss are usually:

t_o = temperature at inner surface of insulation equal to the temperature of fluid in the pipe or container.
t_a = still air ambient temperature = 80 F.
r_o = inner radius of insulation = outside radius of iron pipe.
r_s = outer radius of insulation = $r_o + L$.

Example 8: Compute 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 mean temperature of the mineral fiber block is 700 F, mean temperature of the insulating cement is 200 F, and R_s = 0.60.

From Table 3B, k_1 = 0.62 and k_2 = 0.80. Then:

$$q_s = \frac{1100 - 80}{(4.5/0.62) + (0.5/0.80) + 0.60} = \frac{1020}{8.48}$$

$$= 120.2 \text{ Btu/h} \cdot \text{ft}^2$$

As a check, from Fig. 6, at 120.2 Btu/h · ft², R_s = 0.56. The mean temperature of the mineral fiber block is:

$$(4.5/0.62 = 7.26/2 = 3.63)$$

$$1100 - (3.63/8.48)(1020) = 1100 - 437 = 663 \text{ F}$$

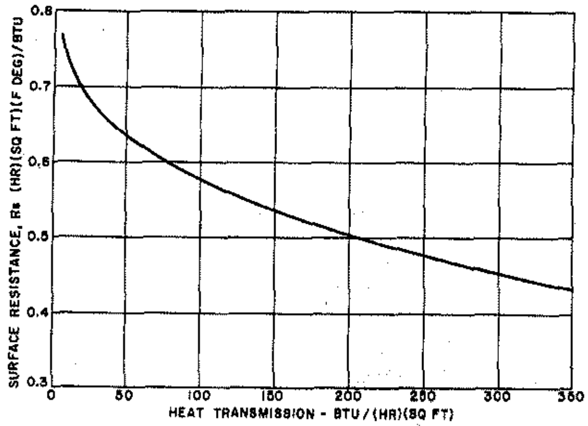


Fig. 6 Heat Transmission vs. Surface Resistance for Flat and Cylindrical Surfaces
(Surface Emittance 0.85 to 0.90 in Still Air)

The mean temperature of the insulating cement is:

$$1100 - (7.57/8.48)\,(1020) = 1100 - 911 = 189 \text{ F}$$

From Table 3B, at 663 F, $k_1 = 0.60$, and at 189 F, $k_2 = 0.79$. Recalculating q_s with these adjusted values:

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

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

From Fig. 6, at 117.4 Btu/h · ft², $R_s = 0.56$.

The mean temperature of the mineral fiber block is:

$$1100 - (3.75/8.69)\,(1020) = 1100 - 440 = 660 \text{ F}$$

The mean temperature of the insulating cement is:

$$1100 - (7.81/8.69)\,(1020) = 1100 - 917 = 183 \text{ F}$$

From Table 3B, at 661 F, $k_1 = 0.60$, and at 183 F, $k_2 = 0.79$.

Since R_s, k_1, and k_2 do not change at these values, $q_s = 117.4$ Btu/h · ft².

Example 9: Compute heat loss per ft² 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. iron pipe, insulated with a nominal 3 in. of diatomaceous silica as the inner layer and a nominal 2 in. of calcium silicate as the outer layer.

Solution: From Table 15, $r_o = 3.31$ in. A nominal 3-in. thick diatomaceous silica insulation to fit a nominal 6-in. iron 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.; $r_s = 8.41$ in.

Assume that the mean temperature of the diatomaceous silica is 600 F, the mean temperature of the calcium silicate is 250 F, and $R_s = 0.50$.

From Table 3B, $k_1 = 0.66$ and $k_2 = 0.42$:

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

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

From Fig. 6, at 76.0 Btu/h · ft², $R_s = 0.60$.

The mean temperature of the diatomaceous silica is:

$$1200 - (4.13/14.83)\,(1120) = 1200 - 312 = 888 \text{ F}$$

The mean temperature of the calcium silicate is:

$$1200 - (11.24/14.83)\,(1120) = 1200 - 849 = 351 \text{ F}$$

From Table 3B, $k_1 = 0.72$ and $k_2 = 0.46$. 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 Fig. 6, at 83.8 Btu/h · ft², $R_s = 0.59$.
Mean temperature of the diatomaceous silica is:

$$1200 - (3.78/13.36)\,(1120) = 1200 - 317 = 883 \text{ F}$$

Mean temperature of the calcium silicate is:

$$1200 - (10.17/13.36)\,(1120) = 1200 - 853 = 347 \text{ F}$$

From Table 3B, $k_1 = 0.72$ and $k_2 = 0.46$. Recalculating:

$$q_2 = \frac{1120}{(5.45/0.72) + (2.39/0.46) + 0.59} = 83.8 \text{ Btu/h} \cdot \text{ft}^2$$

Since R_s, k_1, and k_2 will not change at 83.8 Btu/h · ft², this is the final q_s.

The heat flow per square foot of the inner surface of the insulation will be:

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

HEAT FLOW CALCULATIONS INVOLVING BURIED PIPE LINES

In calculating heat flow from or to buried pipe lines, it is necessary to make an assumption as to the thermal properties of the earth. Because most soil or earth contains moisture, it is technically incorrect to report thermal conductivity. Table 17 gives the *apparent* thermal conductivity values of various soils. These values may be used as a guide when making heat flow calculations involving buried lines. See Ref 10 for discussion of thermal properties of soil. Ref 11 gives methods for calculating the heat flow that takes place between one or more buried cylinders and the surroundings.

THERMAL CHARACTERISTICS AND RESPONSE FACTORS FOR FLOORS, WALLS, AND ROOFS

Current methods for estimating the heat transferred through floors, walls, and roofs of buildings are largely based on a steady state or steady periodic heat flow concept (Equivalent Temperature Difference Concept). The engineering application of these concepts is not complicated and has served well for many years in the process of design and selection of heating and cooling equipment for buildings. However, competitive practices of the building industry sometimes require more than the selection or design of a single heating or cooling system. Consultants are requested to present a detailed comparison of alternative heating and cooling systems for a given building, including initial costs as well as short- and long-term operating and maintenance costs. The degree of sophistication required for costs may make it necessary to calculate the heating and cooling load for estimating energy requirements in hourly increments for a year's time for given buildings at known geographic locations. Because of the number of calculations involved, computer processing becomes necessary. The hour-by-hour heating and cooling load calculations, when based upon a steady heat flow or steady periodic heat flow concept, do not account for the heat storage effects of the building structure, especially with regard to net heat gain to the air-conditioned spaces.

A heat transfer calculation to better account for randomly fluctuating hourly outdoor climatic conditions and indoor energy use schedules, such as lighting, is necessary. A technique called the *response factor method* evaluates the heat conducted through multilayer building elements under transient (nonsteady and nonsteady periodic) exposure conditions. According to this method, the heat flux Btu/h · ft² at a given time t at the outer as well as the inner surfaces of building elements exposed to the outdoors (expressed $q_{o,t}$ and $q_{i,t}$ respectively) can be calculated as follows:

$$q_{o,t} = \sum_{j=o}^{\infty} T_{o,t-j}X_j - \sum_{j=o}^{\infty} T_{i,t-j}Y_j \qquad (14a)$$

$$q_{i,t} = \sum_{j=o}^{\infty} T_{o,t-j}Y_j - \sum_{j=0}^{\infty} T_{i,t-j}Z_j \qquad (14b)$$

In these expressions, $T_{o,t-j}$ and $T_{i,t-j}$ are outdoor and indoor temperatures [F] (or outside surface and inside surface temperatures depending upon the heat conduction system) at time t-j h. The response factors are three sets of numbers expressed as X_j, Y_j, and Z_j (for j = 1,2, ∞) in above equations and have units of Btu/h · ft² · F, the same as the unit for overall heat transfer coefficient U. Application of the response factor relations to a steady state heat conduction situation *where*

$$q_{o,t} = q_{i,t} = U(T_o - T_i)$$

$$T_o = T_{o,t} \quad \text{for all } t$$

$$T_i = T_{i,t} \quad \text{for all } t,$$

would result in:

$$\sum_{j=o}^{\infty} X_j = \sum_{j=o}^{\infty} Y_j = \sum_{j=o}^{\infty} Z_j = U \qquad (15)$$

Wall Response Factors

The tabulation at the end of this section illustrates response factors *calculated* for a typical wall. In this particular wall, the response factors for $j > 28$ can be obtained by a geometric progression using the common ratio R such that:

$$(X_{j+1}/X_j) = (Y_{j+1}/Y_j) = (Z_{j+1}/Z_j) = R$$

In typical wall heat transfer calculations, the summation terms in Eqs 14A and 14B may be truncated at j = 48. In other words, if the value of heat flux at time t is needed, it is necessary to have the hourly temperature history covering the previous 48-h period as well as the values of X_j, Y_j, and Z_j for j = 0, 2,···47. By making use of the hourly heat flux history in addition to the temperature history, the maximum number of j could be decreased considerably. This aspect is discussed in detail in Chapter 2. The temperature and heat flux data need not be steady or steady periodic at all.

Unlike the overall heat transfer coefficient, or U-value, calculation of the response factor requires complex mathematical treatment. Computer programs are available at both the National Research Council of Canada and the National Bureau of Standards to calculate response factors from known data, such as the number of composite layers, and for each layer, the thermal conductivity, thermal diffusivity, and thickness. (In the case of an air cavity or air space, only the thermal resistance value is required.) The NBS program can also be used to calculate response factors for constructions of cylindrical and spherical shape.

As is the case when applying U-values, many building elements are so constructed that parallel heat paths of different thermal characteristics result. If there is appreciable lateral heat transfer between paths, for example, when metal skins are used, theoretical calculation of response factors is not yet possible. For such constructions, experimental determination of transient heat transfer characteristics is necessary to determine the response factors. ASHRAE has sponsored experimental research (RP-102).

Tabulation of Illustrative Wall Response Factors

I	Thickness L(I) ft	Thermal Conductivity k(I) Btu/h·ft²·F	Density ϱ(I) lb/ft³	Specific Heat c(I) Btu/lb F	Resistance of Air Layer Res (I) ft·F·h/Btu	Wall Composition
1					0.3333	Outside surface
2	0.3333	0.77	125	0.22		4-in. face brick
3					0.842	0.75-in. air space
4	0.1667	0.025	5.7	0.3		2-in. insulation
5	0.0313	0.24	78	0.26		0.375-in. gypsum bd
6	0.042	0.27	90	0.2		0.50-in. plaster
7					0.833	Inside surface

Overall heat transfer coefficient U = 0.1060 Btu/h·ft²·F

i	X	Y	Z
0	1.9828631184	0.0000694414	0.7658454069
1	−0.5332548902	0.0032610373	−0.3626101180
2	−0.2897180964	0.0108381158	−0.1594774346
3	−0.2226418777	0.0143821960	−0.0722106733
4	−0.1751782415	0.0141359305	−0.0330527494
5	−0.1381393441	0.0124128118	−0.0153907015
6	−0.1089916981	0.0103599746	−0.0073676305
7	−0.0860172059	0.0084293880	−0.0036792673
8	−0.0678956034	0.0067667191	−0.0019496245
9	−0.0535962455	0.0053921814	−0.0011124022
10	−0.0423104538	0.0042793546	−0.0006875056
11	−0.0334020144	0.0033884423	−0.0004575496
12	−0.0263696421	0.0026795634	−0.0003231437
13	−0.0208180261	0.0021174509	−0.0002380978
14	−0.0164352751	0.0016725725	−0.0001803688
15	−0.0129752460	0.0013208578	−0.0001389992
16	−0.0102436541	0.0010429664	−0.0001082184
17	−0.0080871331	0.0008234788	−0.0000847576
18	−0.0063846118	0.0006501542	−0.0000666111
19	−0.0050405105	0.0005132985	−0.0000524525
20	−0.0039793727	0.0004052451	−0.0000413496
21	−0.0031416279	0.0003199354	−0.0000326175
22	−0.0024802469	0.0002525834	−0.0000257387
23	−0.0019581009	0.0001994098	−0.0000203148
24	−0.0015458781	0.0001574300	−0.0000160357
25	−0.0012204372	0.0001242877	−0.0000126587
26	−0.0009635087	0.0000981225	−0.0000099933
27	−0.0007606692	0.0000774656	−0.0000078893
28	−0.0006005318	0.0000611574	−0.0000062283

Common ratio for $\frac{X_{j+1}}{X_j} = \frac{Y_{j+1}}{Y_j} = \frac{Z_{j+1}}{Z_j} = R$ for $j > 28$.

REFERENCES

[1]F. B. Rowley, A. B. Algren, and J. L. Blackshaw: ASHVE Research Report No. 869—Surface conductances as affected by air velocity, temperature and character of surface (ASHVE TRANSACTIONS, Vol. 36, 1930, p. 444). (Also see University of Minnesota, *Engineering Experiment Station Bulletin*, No. 12, 1937).

[2]G. V. Parmelee and R. G. Huebscher: *Forced Convection Heat Transfer from Flat Surfaces* (ASHVE Research Bulletin No. 3, p. 40, also published in ASHVE TRANSACTIONS, Vol. 53, 1947, p. 245).

[3]G. V. Parmelee and W. W. Aubele: ASHVE Research Report No. 1399—Heat flow through unshaded glass: Design data for load calculations (ASHVE TRANSACTIONS, Vol. 56, 1958, p. 371).

[4]H. J. Sabine, M. B. Lacher, D. R. Flynn, and T. L. Quindry: *Acoustical and Thermal Performance of Exterior Residential Walls,*

Doors, and Windows (National Bureau of Standards *Building Science Series* 77).

[5]F. A. Joy: Improving attic space insulating values (ASHAE TRANSACTIONS, Vol. 64, 1958, p. 251).

[6]F. C. Houghten, S. I. Taimuty, Carl Gutberlet, and C. J. Brown: ASHVE Research Report No. 1213—Heat loss through basement walls and floors (ASHVE TRANSACTIONS, Vol. 48, 1942, p. 369).

[7]R. S. Dill, W. C. Robinson, and H. E. Robinson: *Measurements of Heat Losses from Slab Floors* (National Bureau of Standards, Building Materials and Structures Report BMS 103).

[8]G. V. Parmelee: *Heat Transmission through Glass* (ASHVE Research Bulletin No. 1, July 1947).

[9]Clifford Strock: *Handbook of Air Conditioning, Heating and Ventilating* (The Industrial Press, New York, NY, 1959, p. 4-167, 170).

[10]M. S. Kersten: *Thermal Properties of Soils* (University of Minnesota, Engineering Experiment Station Bulletin, No. 28, June 1949).

[11]H. S. Carslaw and J. C. Jaeger: *Conduction of Heat in Soilds* (Oxford University Press, Amen House, London, England, 1959, p. 449).

[12]W. C. Lewis: *Thermal Conductivity of Wood-base Fiber and Particle Panel Materials* (U.S. Forest Service, Forest Products Laboratory, *Research Paper* FPL 77, June 1967).

[13]Clifford Strock: *Handbook of Air Conditioning, Heating and Ventilating* (The Industrial Press, New York, NY, 1959, p. 4-105).

[14]J. I. Yellott: Thermal and mechanical effects of solar radiation on steel doors (ASHRAE TRANSACTIONS, Vol. 71, 1965, Part II, p. 42).

[15]Thermal Insulation: Acoustical materials; five tests; building constructions (*ASTM Standards*, Part 14, November 1970).

[16]National Bureau of Standards Building Science Series-77 (Calibrated Hot Box).

[17]J.K. Latta and G.G. Boileau: Heat losses from house basements (*Canadian Building*, Vol. 19, No. 10, October 1969, p. 39).

[18]F.C. Houghten, S.I. Taimuty, C. Gutberlet, and C.J. Brown: Heat loss through basement walls and floors (ASHVE TRANSACTIONS, Vol. 48, 1942, p. 369).

BIBLIOGRAPHY

ASHVE Research Reports:

No. 852—F. B. Rowley, A. B. Algren, and J. L. Blackshaw: Effects of air velocities on surface coefficients (ASHVE TRANSACTIONS, Vol. 36, 1930, p. 123).

No. 895—F. C. Houghten and Paul McDermott: Wind velocities gradients near a surface and their effect on film conductance (ASHVE TRANSACTIONS, Vol. 37, 1931, p. 301).

914—F. B. Rowley and W. A. Eckley: Surface coefficients as affected by direction of wind (ASHVE TRANSACTIONS, Vol. 38, 1932, p. 33).

No. 915—F. C. Houghten and Carl Gutberlet: Conductivity of concerete (ASHVE TRANSACTIONS, Vol. 38, 1932, p. 47).

No. 964—F. B. Rowley: The heat conductivity of wood at climatic temperature differences (ASHVE TRANSACTIONS, Vol. 39, 1933, p. 329).

No. 966—F. B. Rowley: Insulating value of bright metallic surfaces (ASHVE TRANSACTIONS, Vol. 40, 1934, p. 413).

No. 1026—F. B. Rowley, A. B. Algren, and Clifford Carlson: Thermal properties of concrete construction (ASHVE TRANSACTIONS, Vol. 42, 1936, p. 33).

No. 1048—F. B. Rowley, A. B. Algren, and Robert Lander: Thermal properties of concrete construction (ASHVE TRANSACTIONS, Vol. 43, 1937, p. 33).

No. 1351—G. V. Parmelee and W. W. Aubele: Overall coefficients for flat glass determined under natural weather conditions (ASHVE TRANSACTIONS, Vol. 55, 1949, p. 39).

G. B. Wilkes and C. M. F. Peterson: Radiation and convection across air spaces in frame construction (ASHVE TRANSACTIONS, Vol. 43, 1937, p. 351).

L. W. Schad: Insulating effect of successive air space bounded by bright metallic surfaces (ASHVE TRANSACTIONS, Vol. 37, 1931, p. 285).

J. D. MacLean: Thermal conductivity of wood (ASHVE TRANSACTIONS, Vol. 47, 1941, p. 323).

G. B. Wilkes and C. O. Wood: The specific heat of thermal insulating materials (ASHVE TRANSACTIONS, Vol. 48, 1942, p. 493).

D. B. Anderson: Heat loss studies in four identical buildings to determine the effect of insulation (ASHVE TRANSACTIONS, Vol. 48, 1942, p. 471).

Standard Method of Test for Thermal Conductivity by Means of the Guarded Hot Plate, sponsored by ASHVE, ASTM, ASRE, and NRC, and approved as a tentative code by ASHVE and ASTM in 1942 (ASTM designation C-177-45, approved, 1945).

G. B. Wilkes and C. M. F. Peterson: Radiation and convection from surfaces in various positions (ASHVE TRANSACTIONS, Vol. 44, 1938, p. 513).

B. F. Raber and F. W. Hutchinson: Radiation corrections for basic constants used in the design of all types of heating systems (ASHVE TRANSACTIONS, Vol. 51, 1945, p. 213).

H. E. Robinson, F. J. Powlitch, and R. S. Dill: *The Thermal Insulating Value of Airspaces* (Housing and Home Finance Agency, Housing Research Paper No. 32, U.S. Government Printing Office, 1954).

C. G. Wilkes, F. G. Hechler, and E. R. Queer: Thermal test coefficients of aluminum insulation for buildings (ASHVE TRANSACTIONS, Vol. 46, 1940, p. 109).

T. D. Phillips: *Effect of Ceiling Insulation upon Summer Comfort* (National Bureau of Standards Report BMS 52, July 1, 1940).

L. V. Teesdale: *Thermal Insulation Made of Wood-Base Materials, Its Application and Use in Houses* (U.S. Forest Products Laboratory Report No. R1740, October 1949).

F. B. Rowley and A. B. Algren: *Heat Transmission through Building Materials* (University of Minnesota Engineering Experiment Station Bulletin, No. 8).

P. D. Close: *Building Insulation* (American Technical Society, Chicago, IL, 1951, 4th ed.).

F. C. Houghten and Carl Gutberlet: Heat emission from iron and copper pipe (ASHVE TRANSACTIONS, Vol. 39, 1938, p. 97).

R. H. Heilman: Surface heat transmission (Sec. 1, *Mechanical Engineering*, May 1929, p. 355).

S. Crocker: *Piping Handbook* (McGraw-Hill Book Co., New York, NY, 1945, 4th ed.).

T. S. Nickerson and G. M. Dusinberre: Heat transfer through thick insulation on cylindrical enclosures (*ASME Transactions*, Vol. 70, 1948, p. 903).

F. B. Rowley, R. C. Jordan, and R. M. Lander: Thermal conductivity of insulating materials at low mean temperatures (REFRIGERATING ENGINEERING, December 1945, p. 541).

F. B. Rowley, R. C. Jordan, and R. M. Lander: Low mean temperature thermal conductivity studies (REFRIGERATING ENGINEERING, January 1947, p. 35).

J. D. Verschoor: Thermal conductivity of commercial insulations at low temperatures (REFRIGERATING ENGINEERING, September 1954, p. 35).

G. B. Wilkes: Thermal conductivity expansion and specific heat of insulators at extremely low temperatures (REFRIGERATING ENGINEERING, July 1946, p. 37).

Simplified Practice Recommendation for Thermal Conductance Factors for Preformed Above-Deck Roof Insulation (No. R257-55, U.S. Department of Commerce, Washington, DC, 1955).

W. C. Lewis: *Thermal Insulation from Wood for Buildings—Effect of Moisture and its Control* (U.S. Forest Service, Forest Products Laboratory, Research Paper, FPL 86, 1968).

D. G. Stephenson and G. P. Mitalas: Cooling load calculation by thermal response factor method (ASHRAE TRANSACTIONS, Vol. 73, 1967, Part I, p. III. 1.1).

D. G. Stephenson and G. P. Mitalas: Room thermal response factors (ASHRAE TRANSACTIONS, Vol. 73, 1967, Part I, p. III.2.1).

L. A. Pipes: Matrix analysis of heat transfer problems (*Franklin Institute Journal*, Vol. 263, No. 3, March 1957, p. 195).

R. W. Muncey: The thermal response of a building to sudden changes of temperature and heat flow (*Australian Journal of Applied Science*, Vol. 14, No. 2, June 1963, p. 123).

W. R. Brisken: Heat load calculation by thermal response (ASHAE TRANSACTIONS, Vol. 62, 1956, p. 391).

D. G. Stephenson: Calculation of cooling load by digital computer (ASHRAE JOURNAL, April 1968, p. 41).

G. P. Mitalas and J. G. Arsenaeult: Fortran IV Program to Calculate Heat Flux Response Factors for a Multilayer Lab, (National Research Council of Canada, Division of Building Research, Computer Program No. 26, June 1967).

T. Kusuda: Thermal response factors for multilayer structures of various heat conduction systems (ASHRAE TRANSACTIONS, Vol. 75, 1969, Part I, p. 246).

C. O. Pedersen and E. D. Mouen: Application of system identification technniques to the determination of thermal response factors from experimentation data (ASHRAE TRANSACTIONS, Vol. 79, Part II, 1973, p. 127).

C. D. Pedersen and E. D. Mouen: *The Thermal Response Factor Method and Building Elements Containing Air Cavities* (Second Symposium on the Use of Computers for Environmental Engineering Related to Buildings, Paris, France, June 13-15, 1974).

Table 1 Surface Conductances and Resistances for Air[a,b,c]

All conductance values expressed in Btu/h · ft² · F.

A surface cannot take credit for both an air space resistance value and a surface resistance value. No credit for an air space value can be taken for any surface facing an air space of less than 0.5 in.

Position of Surface	Direction of Heat Flow	Surface Emittance: Non-reflective ε = 0.90		Reflective ε = 0.20		Reflective ε = 0.05	
		h_i	R	h_i	R	h_i	R
STILL AIR							
Horizontal	Upward	1.63	*0.61*	0.91	*1.10*	0.76	*1.32*
Sloping—45 deg	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 deg	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	h_o	R	h_o	R
15-mph Wind (for winter)	Any	6.00	0.17				
7.5-mph Wind (for summer)	Any	4.00	0.25				

[a]For ventilated attics or spaces above ceilings under summer conditions (heat flow down) see Table 6.

[b]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 deg F and for surface temperature of 70 F.

[c]See Fig. 1 for additional data.

Table 2 Thermal Resistances of Plane[a] Air Spaces[d,e]*

SECTION A

All resistance values expressed in ft² · F · h/Btu

Values apply only to air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no leakage of air to or from the space. These conditions are not normally present in standard building construction. When accurate values are required, use overall *U*-factors determined for your particular construction through calibrated hot box (BSS-77) 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. See the Caution section, under Overall Coefficients and Their Practical Use.

Position of Air Space	Direction of Heat Flow	Air Space Mean Temp,[b] (F)	Air Space Temp Diff,[b] (deg F)	0.5-in. Air Space[d] Value of $E^{b,c}$ 0.03	0.05	0.2	0.5	0.82	0.75-in. Air Space[d] Value of $E^{b,c}$ 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

Table 2 Thermal Resistances of Plane[a] Air Spaces[d,e]* (Concluded)

SECTION A

Position of Air Space	Direction of Heat Flow	Air Space Mean Temp,[b] (F)	Air Space Temp Diff,[b] (deg F)	1.5-in. Air Space[d] Value of $E^{b,c}$ 0.03	0.05	0.2	0.5	0.82	3.5-in. Air Space[d] Value of $E^{b,c}$ 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

SECTION B. Reflectivity and Emittance Values of Various Surfaces and Effective Emittances of Air Spaces

Surface	Reflectivity in Percent	Average *Emittance* ε	Effective *Emittance E* of Air Space: One surface emittance ε; the other 0.90	Both surfaces emittances ε
Aluminum foil, bright....	92 to 97	0.05	0.05	0.03
Aluminum sheet	80 to 95	0.12	0.12	0.06
Aluminum coated paper, polished............	75 to 84	0.20	0.20	0.11
Steel, galvanized, bright...	70 to 80	0.25	0.24	0.15
Aluminum paint	30 to 70	0.50	0.47	0.35
Building materials: wood, paper, masonry, nonmetallic paints.....	5 to 15	0.90	0.82	0.82
Regular glass	5 to 15	0.84	0.77	0.72

[a]See Chapter 20, section on Factors Affecting Heat Transfer across Air Spaces. Thermal resistance values were determined from the relation, $R = 1/C$, where $C = h_c + Eh_r$, h_c is the conduction-convection coefficient, Eh_r is the radiation coefficient $\cong 0.00686E\,[(t_m + 460)/100]^3$, and t_m is the mean temperature of the air space. Values for h_c were determined from research data (National Bureau of Standards), such as those presented in HRP No. 32.* For interpolation from Table 2 to air space thicknesses 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 thickness in inches, and h_c is assumed to represent heat transfer by conduction alone through air.

[b]Interpolation is permissible for other values of mean temperature, temperature differences, and effective emittance *E*. Interpolation and moderate extrapolation for air spaces greater than 3.5 in. are also permissible.

[c]Effective emittance of the space *E* is given by $1/E = 1/e_1 + 1/e_2 - 1$, *where* e_1 and e_2 are the emittances of the surfaces of the air space. (See section B of Table 1.)

[d]Credit for an air space resistance value cannot be taken more than once and only for the boundary conditions established.

[e]Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

See also Chapter 2, Tables 3 and 4, and Chapter 39.

*Based on National Bureau of Standards data presented in Housing Research Paper No. 32, Housing and Home Finance Agency, 1954, U. S. Government Printing Office, Washington, DC, 20402.

Table 3A Thermal Properties of Typical Building and Insulating Materials—(Design Values)[a]

(For Industrial Insulation Design Values, see Table 3B). These constants are expressed in Btu per (hour) (square foot) (degree Fahrenheit temperature difference). Conductivities *(k)* are per inch thickness, and conductances *(C)* are for thickness or construction stated, not per inch thickness. **All values are for a mean temperature of 75 F, except as noted by an asterisk (*) which have been reported at 45 F.** The SI units for Resistance (last two columns) were calculated by taking the values from the two Resistance columns under Customary Unit, and multiplying by the factor 1/k (r/in.) and 1/C (R) for the appropriate conversion factor in Table 18.

Description	Customary Unit						SI Unit	
	Density (lb/ft³)	Conductivity (*k*)	Conductance (*C*)	Resistance[b] (*R*) Per inch thickness (1/*k*)	Resistance[b] (*R*) For thickness listed (1/*C*)	Specific Heat, Btu/(lb) (deg F)	Resistance[b] (*R*) (m·K)/W	Resistance[b] (*R*) (m²·K)/W
BUILDING BOARD								
Boards, Panels, Subflooring, Sheathing Woodboard Panel Products								
Asbestos-cement board	120	4.0	—	*0.25*	—	0.24	1.73	
Asbestos-cement board 0.125 in.	120	—	33.00	—	*0.03*			*0.005*
Asbestos-cement board 0.25 in.	120	—	16.50	—	*0.06*			*0.01*
Gypsum or plaster board 0.375 in.	50	—	3.10	—	*0.32*	0.26		*0.06*
Gypsum or plaster board 0.5 in.	50	—	2.22	—	*0.45*			*0.08*
Gypsum or plaster board 0.625 in.	50	—	1.78	—	*0.56*			*0.10*
Plywood (Douglas Fir)[c]	34	0.80	—	*1.25*	—	0.29	8.66	
Plywood (Douglas Fir) 0.25 in.	34	—	3.20	—	*0.31*			*0.05*
Plywood (Douglas Fir) 0.375 in.	34	—	2.13	—	*0.47*			*0.08*
Plywood (Douglas Fir) 0.5 in.	34	—	1.60	—	*0.62*			*0.11*
Plywood (Douglas Fir) 0.625 in.	34	—	1.29	—	*0.77*			*0.19*
Plywood or wood panels 0.75 in.	34	—	1.07	—	*0.93*	0.29		*0.16*
Vegetable Fiber Board								
Sheathing, regular density 0.5 in.	18	—	0.76	—	*1.32*	0.31		*0.23*
0.78125 in.	18	—	0.49	—	*2.06*			*0.36*
Sheathing intermediate density 0.5 in.	22	—	0.82	—	*1.22*	0.31		*0.21*
Nail-base sheathing 0.5 in.	25	—	0.88	—	*1.14*	0.31		*0.20*
Shingle backer 0.375 in.	18	—	1.06	—	*0.94*	0.31		*0.17*
Shingle backer 0.3125 in.	18	—	1.28	—	*0.78*			*0.14*
Sound deadening board 0.5 in.	15	—	0.74	—	*1.35*	0.30		*0.24*
Tile and lay-in panels, plain or acoustic	18	0.40	—	*2.50*	—	0.14	17.33	
0.5 in.	18	—	0.80	—	*1.25*			*0.22*
0.75 in.	18	—	0.53	—	*1.89*			*0.33*
Laminated paperboard	30	0.50	—	*2.00*	—	0.33	13.86	
Homogeneous board from repulped paper	30	0.50	—	*2.00*	—	0.28	13.86	
Hardboard								
Medium density	50	0.73	—	*1.37*	—	0.31	9.49	
High density, service temp. service underlay	55	0.82	—	*1.22*	—	0.32	8.46	
High density, std. tempered	63	1.00	—	*1.00*	—	0.32	6.93	
Particleboard								
Low density	37	0.54	—	*1.85*	—	0.31	12.82	
Medium density	50	0.94	—	*1.06*	—	0.31	7.35	
High density	62.5	1.18	—	*0.85*	—	0.31	5.89	
Underlayment 0.625 in.	40	—	1.22	—	*0.82*	0.29		*0.14*
Wood subfloor 0.75 in.		—	1.06	—	*0.94*	0.33		*0.17*
BUILDING MEMBRANE								
Vapor—permeable felt	—	—	16.70	—	*0.06*			*0.01*
Vapor—seal, 2 layers of mopped 15-lb felt	—	—	8.35	—	*0.12*			*0.02*
Vapor—seal, plastic film	—	—	—	—	Negl.			
FINISH FLOORING MATERIALS								
Carpet and fibrous pad	—	—	0.48	—	*2.08*	0.34		*0.37*
Carpet and rubber pad	—	—	0.81	—	*1.23*	0.33		*0.22*
Cork tile 0.125 in.	—	—	3.60	—	*0.28*	0.48		*0.05*
Terrazzo 1 in.	—	—	12.50	—	*0.08*	0.19		*0.01*
Tile—asphalt, linoleum, vinyl, rubber	—	—	20.00	—	*0.05*	0.30		*0.01*
vinyl asbestos						0.24		
ceramic						0.19		
Wood, hardwood finish 0.75 in.			1.47		*0.68*			0.12
INSULATING MATERIALS								
Blanket and Batt[d]								
Mineral Fiber, fibrous form processed from rock, slag, or glass								
approx.[e] 3–3.5 in.	0.3–2.0	—	0.091	—	*11*[d]			*1.94*
approx.[e] 5.50–6.5	0.3–2.0	—	0.053	—	*19*[d]			*3.35*
approx.[e] 6–7 in.	0.3–2.0		0.045		*22*[d]			*3.87*
approx.[e] 8.5–9 in.	0.3–2.0		0.033		*30*[d]			*5.28*
approx. 12 in.	0.3–2.0	—	0.026		*38*[d]			*6.69*

Table 3A Thermal Properties of Typical Building and Insulating Materials—(Design Values)[a]

Description	Density (lb/ft³)	Conductivity (k)	Conductance (C)	Customary Unit Resistance[b] (R) Per inch thickness (1/k)	Customary Unit Resistance[b] (R) For thickness listed (1/C)	Specific Heat, Btu/(lb)(deg F)	SI Unit Resistance[b] (R) (m·K)/W	SI Unit Resistance[b] (R) (m²·K)/W
BOARD AND SLABS								
Cellular glass	8.5	0.35	—	*2.86*	—	0.18	*19.81*	
Glass fiber, organic bonded	4-9	0.25	—	*4.00*	—	0.23	*27.72*	
Expanded perlite, organic bonded	1.0	0.36	—	*2.78*	—	0.30	*19.26*	
Expanded rubber (rigid)	4.5	0.22	—	*4.55*	—	0.40	*31.53*	
Expanded polystyrene extruded								
Cut cell surface	1.8	0.25	—	*4.00*	—	0.29	*27.72*	
Smooth skin surface	1.8-3.5	0.20	—	*5.00*	—	0.29	*34.65*	
Expanded polystyrene, molded beads	1.0	0.20	—	—	—	—	*26.3*	*3.8*
	1.25	0.25	—	—	—	—	*27.8*	*4.0*
	1.5	0.24	—	—	—	—	*29.1*	*4.2*
	1.75	0.24	—	—	—	—	*29.1*	*4.2*
	2.0	0.23	—	—	—	—	*29.8*	*4.3*
Cellular polyurethane[f] (R-11 exp.)(unfaced)	1.5	0.16	—	*6.25*	—	0.38	*43.82*	
(Thickness 1 in. or greater)	2.5							
(Thickness 1 in. or greater—high resistance to gas permeation facing)	1.5	0.14						
Foil-faced, glass fiber-reinforced cellular								
Polyisocyanurate (R-11 exp.)[n]	2	0.14	—	*7.04*	—	0.22	*48.79*	
Nominal 0.5 in.		—	0.278	—	*3.6*			*0.63*
Nominal 1.0 in.		—	0.139	—	*7.2*			*1.27*
Nominal 2.0 in.		—	0.069	—	*14.4*			*2.53*
Mineral fiber with resin binder	15	0.29	—	*3.45*	—	0.17	23.91	
Mineral fiberboard, wet felted								
Core or roof insulation	16-17	0.34	—	*2.94*	—		20.38	
Acoustical tile	18	0.35	—	*2.86*	—	0.19	19.82	
Acoustical tile	21	0.37	—	*2.70*	—		18.71	
Mineral fiberboard, wet molded								
Acoustical tiles[g]	23	0.42	—	*2.38*	—	0.14	16.49	
Wood or cane fiberboard								
Acoustical tiles[g] 0.5 in.	—	—	0.80	—	*1.25*	0.31		0.22
Acoustical tiles[g] 0.75 in.	—	—	0.53	—	*1.89*			0.33
Interior finish (plank, tile)	15	0.35	—	*2.86*	—	0.32	19.82	
Cement fiber slabs (shredded wood with Portland cement binder	25-27	0.50-0.53	—	*2.0-1.89*	—	—	*13.87*	
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	22	0.57	—	*1.75*	—	0.31	*12.16*	
LOOSE FILL								
Cellulosic insulation (milled paper or wood pulp)	2.3-3.2	0.27-0.32	—	*3.13-3.70*	—	0.33	*21.69-25.64*	
Sawdust or shavings	8.0-15.0	0.45	—	*2.22*	—	0.33	*15.39*	
Wood fiber, softwoods	2.0-3.5	0.30	—	*3.33*	—	0.33	*23.08*	
Perlite, expanded	5.0-8.0	0.37	—	*2.70*	—	0.26	*18.71*	
	2.0-4.1	0.27-0.31	3.7-3.3					
	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)								
approx.[e] 3.75-5 in.	0.6-2.0	—	—		11	0.17		*1.94*
approx.[e] 6.5-8.75 in.	0.6-2.0	—	—		19			*3.35*
approx.[e] 7.5-10 in.	0.6-2.0	—	—		22			*3.87*
approx.[e] 10.25-13.75 in.	0.6-2.0	—	—		30			*5.28*
Vermiculite, exfoliated	7.0-8.2	0.47	—	*2.13*	—	3.20	*14.76*	
	4.0-6.0	0.44	—	*2.27*	—		*15.73*	
ROOF INSULATION[h]								
Preformed, for use above deck								
Different roof insulations are available in different thicknesses to provide the design C values listed.[h] Consult individual manufacturers for actual thickness of their material.			0.36 to 0.05		2.7 *to* 20		—	*0.49 to 3.52*
MASONRY MATERIALS								
CONCRETES								
Cement mortar	116	5.0	—	*0.20*	—		*1.39*	
Gypsum-fiber concrete 87.5% gypsum, 12.5% wood chips	51	1.66	—	*0.60*	—	0.21	*4.16*	

Table 3A Thermal Properties of Typical Building and Insulating Materials—(Design Values)[a]

Description	Density (lb/ft³)	Conductivity (k)	Conductance (C)	Customary Unit Resistance[b] (R) Per inch thickness (1/k)	Customary Unit Resistance[b] (R) For thickness listed (1/C)	Specific Heat, Btu/(lb) (deg F)	SI Unit Resistance[b] (R) (m·K)/W	SI Unit Resistance[b] (R) (m²·K)/W
Lightweight aggregates including expanded shale, clay or slate; expanded slags; cinders; pumice; vermiculite; also cellular concretes	120	5.2	—	0.19	—		1.32	
	100	3.6	—	0.28	—		1.94	
	80	2.5	—	0.40	—		2.77	
	60	1.7	—	0.59	—		4.09	
	40	1.15	—	0.86	—		5.96	
	30	0.90	—	1.11	—		7.69	
	20	0.70		1.43			9.91	
Perlite, expanded	40	0.93		1.08			7.48	
	30	0.71		1.41			9.77	
	20	0.50		2.00		0.32	13.86	
Sand and gravel or stone aggregate (oven dried)	140	9.0	—	0.11		0.22	0.76	
Sand and gravel or stone aggregate (not dried)	140	12.0	—	0.08			0.55	
Stucco	116	5.0	—	0.20			1.39	
MASONRY UNITS								
Brick, common[i]	120	5.0	—	0.20	—	0.19	1.39	
Brick, face[j]	130	9.0	—	0.11	—		0.76	
Clay tile, hollow:								
1 cell deep ... 3 in.	—	—	1.25	—	0.80	0.21		0.14
1 cell deep ... 4 in.	—	—	0.90	—	1.11			0.20
2 cells deep ... 6 in.	—	—	0.66	—	1.52			0.27
2 cells deep ... 8 in.	—	—	0.54	—	1.85			0.33
2 cells deep ... 10 in.	—	—	0.45	—	2.22			0.39
3 cells deep ... 12 in.	—	—	0.40	—	2.50			0.44
Concrete blocks, three oval core:								
Sand and gravel aggregate ... 4 in.	—	—	1.40	—	0.71	0.22		0.13
... 8 in.	—	—	0.90	—	1.11			0.20
... 12 in.	—	—	0.78	—	1.28			0.23
Cinder aggregate ... 3 in.	—	—	1.16	—	0.86	0.21		0.15
... 4 in.	—	—	0.90	—	1.11			0.20
... 8 in.	—	—	0.58	—	1.72			0.30
... 12 in.	—	—	0.53	—	1.89			0.33
Lightweight aggregate ... 3 in.	—	—	0.79	—	1.27	0.21		0.22
(expanded shale, clay, slate ... 4 in.	—	—	0.67	—	1.50			0.26
or slag; pumice) ... 8 in.	—	—	0.50	—	2.00			0.35
... 12 in.	—	—	0.44	—	2.27			0.40
Concrete blocks, rectangular core.*[j]								
Sand and gravel aggregate								
2 core, 8 in. 36 lb.[k]*	—	—	0.96	—	1.04	0.22		0.18
Same with filled cores[j]*	—	—	0.52	—	1.93	0.22		0.34
Lightweight aggregate (expanded shale, clay, slate or slag, pumice):								
3 core, 6 in. 19 lb.[k]*	—	—	0.61	—	1.65	0.21		0.29
Same with filled cores[l]*	—	—	0.33	—	2.99			0.53
2 core, 8 in. 24 lb.[k]*	—	—	0.46	—	2.18			0.38
Same with filled cores[l]*	—	—	0.20	—	5.03			0.89
3 core, 12 in. 38 lb.[k]*	—	—	0.40	—	2.48			0.44
Same with filled cores[l]*	—	—	0.17	—	5.82			1.02
Stone, lime or sand	—	12.50	—	0.08	—	0.19	0.55	
Gypsum partition tile:								
3 × 12 × 30 in. solid	—	—	0.79	—	1.26	0.19		0.22
3 × 12 × 30 in. 4-cell	—	—	0.74	—	1.35			0.24
4 × 12 × 30 in. 3-cell	—	—	0.60	—	1.67			0.29
METALS (See Chapter 39, Table 3)								
PLASTERING MATERIALS								
Cement plaster, sand aggregate	116	5.0	—	0.20	—	0.20	1.39	
Sand aggregate ... 0.375 in.	—	—	13.3	—	0.08	0.20		0.01
Sand aggregate ... 0.75 in.	—	—	6.66	—	0.15	0.20		0.03
Gypsum plaster:								
Lightweight aggregate ... 0.5 in.	45	—	3.12	—	0.32			0.06
Lightweight aggregate ... 0.625 in.	45	—	2.67	—	0.39			0.07
Lightweight agg. on metal lath ... 0.75 in.	—	—	2.13	—	0.47			0.08
Perlite aggregate	45	1.5	—	0.67	—	0.32	4.64	
Sand aggregate	105	5.6	—	0.18	—	0.20	1.25	
Sand aggregate ... 0.5 in.	105	—	11.10	—	0.09			0.02
Sand aggregate ... 0.625 in.	105	—	9.10	—	0.11			0.02
Sand aggregate on metal lath ... 0.75 in.	—	—	7.70	—	0.13			0.02
Vermiculite aggregate	45	1.7	—	0.59	—		4.09	

Table 3A Thermal Properties of Typical Building and Insulating Materials—(Design Values)[a]

Description	Density (lb/ft³)	Conductivity (k)	Conductance (C)	Customary Unit Resistance[b] (R) Per inch thickness (1/k)	Customary Unit Resistance[b] (R) For thickness listed (1/C)	Specific Heat, Btu/(lb) (deg F)	SI Unit Resistance[b] (R) (m·K)/W	SI Unit Resistance[b] (R) (m²·K)/W
ROOFING								
Asbestos-cement shingles	120	—	4.76	—	*0.21*	0.24		*0.04*
Asphalt roll roofing	70	—	6.50	—	*0.15*	0.36		*0.03*
Asphalt shingles	70	—	2.27	—	*0.44*	0.30		0.08
Built-up roofing .... 0.375 in.	70	—	3.00	—	*0.33*	0.35		*0.06*
Slate .... 0.5 in.	—	—	20.00	—	*0.05*	0.30		*0.01*
Wood shingles, plain and plastic film faced	—	—	1.06	—	*0.94*	0.31		*0.17*
SIDING MATERIALS (ON FLAT SURFACE)								
Shingles								
Asbestos-cement	120	—	4.75	—	*0.21*			*0.04*
Wood, 16 in., 7.5 exposure	—	—	1.15	—	*0.87*	0.31		*0.15*
Wood, double, 16-in., 12-in. exposure	—	—	0.84	—	*1.19*	0.28		*0.21*
Wood, plus insul. backer board, 0.3125 in.	—	—	0.71	—	*1.40*	0.31		*0.25*
Siding								
Asbestos-cement, 0.25 in., lapped	—	—	4.76	—	*0.21*	0.24		*0.04*
Asphalt roll siding	—	—	6.50	—	*0.15*	0.35		*0.03*
Asphalt insulating siding (0.5 in. bed.)	—	—	0.69	—	*1.46*	0.35		*0.26*
Hardboard siding, 0.4375 in.	40	1.49	—	*0.67*		0.28	*4.65*	
Wood, drop, 1 × 8 in.	—	—	1.27	—	*0.79*	0.28		*0.14*
Wood, bevel, 0.5 × 8 in., lapped	—	—	1.23	—	*0.81*	0.28		*0.14*
Wood, bevel, 0.75 × 10 in., lapped	—	—	0.95	—	*1.05*	0.28		*0.18*
Wood, plywood, 0.375 in., lapped	—	—	1.59	—	*0.59*	0.29		*0.10*
Aluminum or Steel[m], over sheathing								
Hollow-backed	—	—	1.61	—	*0.61*	0.29		*0.11*
Insulating-board backed nominal 0.375 in.	—	—	0.55	—	*1.82*	0.32		*0.32*
Insulating-board backed nominal 0.375 in., foil backed			0.34		2.96			0.52
Architectural glass	—	—	10.00	—	*0.10*	0.20		*0.02*
WOODS[o,p]								
Maple, oak, and similar hardwoods	45	1.10	—	*0.91*	—	0.30	*6.31*	—
Fir, pine, etc.	32	0.80	—	*1.25*	—	0.33	*8.66*	—
.... 0.75 in.	32	—	1.06	—	*0.94*		—	*0.17*
.... 1.5 in.		—	0.53	—	*1.88*		—	*0.33*
.... 2.5 in.		—	0.32	—	*3.12*		—	*0.55*
.... 3.5 in.		—	0.23	—	*4.38*		—	*0.77*
.... 5.5 in.		—	0.14	—	*7.14*		—	*1.26*
.... 7.25 in.		—	–.11	—	*9.09*		—	*1.60*
.... 9.25 in.		—	0.09	—	*11.11*		—	*1.96*
.... 11.25 in.		—	0.07	—	*14.28*		—	*2.15*

Notes for Table 3A

[a]Representative values for dry materials were selected by ASHRAE TC 4.4, Thermal Insulation and Moisture Retarders (Total Thermal Performance Design Criteria). They are intended as design (not specification) values for materials in normal use. Insulation materials in actual service may have thermal values which vary from design values depending on their in-situ properties such as density and moisture content. For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

[b]Resistance values are the reciprocals of *C* before rounding off *C* to two decimal places.

[c]Also see Insulating Materials, Board.

[d]Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an air space, see Tables 1 and 2 for the insulating value of air space for the appropriate effective emittance and temperature conditions of the space.

[e]Conductivity varies with fiber diameter. (See Chapter 21, Thermal Conductivity section, and Fig. 1) Insulation is produced by different densities; therefore, there is a wide variation in thickness for the same *R*-value among manufacturers. No effort should be made to relate any specific *R*-value to any specific thickness. Commercial thicknesses generally available range from 2 to 8.5.

[f]Values are for aged, unfaced, board stock. For change in conductivity with age of expanded urethane, see Chapter 20, Factors Affecting Thermal Conductivity.

[g]Insulating values of acoustical tile vary, depending on density of the board and on type, size, and depth of perforations.

[h]ASTM C-855-77 recognizes the specification of roof insulation on the basis of the *C*-values shown. Roof insulation is made in thicknesses to meet these values.

[i]Face brick and common brick do not always have these specific densities. When density is different from that shown, there will be a change in thermal conductivity.

[j]Data on rectangular core concrete blocks differ from the above data on oval core blocks, due to core configuration, different mean temperatures, and possibly differences in unit weights. Weight data on the oval core blocks tested are not available.

[k]Weights of units approximately 7.625 in. high and 15.75 in. long. These weights are given as a means of describing the blocks tested, but conductance values are all for 1 ft^2 of area.

[l]Vermiculite, perlite, or mineral wool insulation. Where insulation is used, vapor barriers or other precautions must be considered to keep insulation dry.

[m]Values for metal siding applied over flat surfaces vary widely, depending on amount of ventilation of air space beneath the siding; whether air space is reflective or nonreflective; and on thickness, type, and application of insulating backing-board used. Values given are averages for use as design guides, and were obtained from several guarded hotbox tests (ASTM C236) or calibrated hotbox (BSS 77) on hollow-backed types and types made using backing-boards of wood fiber, foamed plastic, and glass fiber. Departures of ±50% or more from the values given may occur.

[n]Time-aged values for board stock with gas-barrier quality (0.001 in. thickness or greater) aluminum foil facers on two major surfaces.

[o]Forest Products Laboratory Wood Handbook, U.S. Dept. of Agriculture #72, 1974, Tables 3 and 4.

[p]L. Adams: Supporting cryogenic equipment with wood (*Chemical Engineering*, May 17, 1971).

Table 3B Thermal Conductivity (k) of Industrial Insulation (Design Values)[a] (For Mean Temperatures Indicated)
Expressed in Btu per (hour)(square foot)(degree Fahrenheit temperature difference per in.)

Form / Material Composition	Accepted Max Temp for Use, F*	Typical Density (lb/ft³)	−100	−75	−50	−25	0	25	50	75	100	200	300	500	700	900
			Typical Conductivity k at Mean Temp F													
BLANKETS & FELTS																
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		
Mineral fiber, glass Blanket, flexible, fine-fiber organic bonded	350	less than				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			
	850	3	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.35	0.55			
Laminated & felted Without binder	1200	7.5											0.35	0.45	0.60	
VEGETABLE & ANIMAL FIBER																
Hair Felt or Hair Felt plus Jute	180	10						0.26	0.28	0.29	0.30					
BLOCKS, BOARDS & PIPE INSULATION																
ASBESTOS																
Laminated asbestos paper	700	30									0.40	0.45	0.50	0.60		
Corrugated & laminated asbestos Paper																
4-ply	300	11–13								0.54	0.57	0.68				
6-ply	300	15–17								0.49	0.51	0.59				
8-ply	300	18–20								0.47	0.49	0.57				
MOLDED AMOSITE & BINDER	1500	15–18									0.32	0.37	0.42	0.52	0.62	0.72
85% MAGNESIA	600	11–12									0.35	0.38	0.42			
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	8.5	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.35	0.36	0.42	0.49	0.70	1.03	
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		
MINERAL FIBER																
Resin binder		15			0.23	0.24	0.25	0.26	0.28	0.29						
RIGID POLYSTYRENE																
Extruded, Refrigerant 12 exp, smooth skin surface	170	2.2	0.16	0.16	0.17	0.16	0.17	0.18	0.19	0.20						
Extruded cut cell surface	170	1.8	0.17	0.18	0.19	0.20	0.21	0.23	0.24	0.25	0.27					
Molded beads	170	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 POLYISOCYANDRATE**																
Cellular, foil-faced glass fiber reinforced, Refrigerant 11 exp	250	2						0.12	0.13	0.14	0.15					
POLYURETHANE***																
Refrigerant 11 exp (unfaced)	210	1.5–2.5	0.16	0.17	0.18	0.18	0.18	0.17	0.16	0.16	0.17					
RUBBER, Rigid Foamed	150	4.5						0.20	0.21	0.22	0.23					
VEGETABLE & 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 as selected by ASHRAE TC 4.4, *Thermal Insulation and Moisture Retarders (Total Thermal Performance Design Criteria).* They are intended as design (not specification) values for materials of building construction for normal use. Insulation materials in actual service may have thermal values which vary from design values depending on their in-situ properties such as density and moisture content. For thermal resistance of a particular product, use the value supplied by the manufacturer or by unbiased tests.

*These temperatures are generally accepted as maximum. When operating temperature approaches these limits follow the manufacturer's recommendations.

**Time-aged values for board stock with gas-barrier quality (0.001 in. or greater) aluminum foil facers on two major surfaces.

***Values are for aged, unfaced, board stock. For change in conductivity with age of refrigerant-blown expanded urethane see section on Thermal Conductivity, Chapter 20.

Note: Some polyurethane foams are formed by means which produce a stable product (with respect to k), but most are blown with refrigerant and will change with time.

Table 3C Insulation Materials Manufactured In-situ

Expressed in Btu per (hour) (square foot) (degree Fahrenheit temperature per in.)

Form Material Composition	Accepted Max Temp for Use, F*	Typical Density (lb/ft^3)	Typical Conductivity k at Mean Temp F −100	−75	−50	−25	0	25	50	75	100	200	300	500	700	900
FOAMED IN PLACE																
Polyurethane	110	1.5-2.5								0.16–0.18						
Ureaformaldehyde	100	0.7-1.6								0.22–0.28						
Phenol formaldehyde																
SPRAYED ON SUBSTRATE																
Cellulosic fiber base	120	2-6								0.24–0.30						
Cementitious/fiber and perlite or vermiculite base	1000	24-36								0.52–0.77						
Mineral fiber base	2000	12-14								0.30						

*These temperatures are generally accepted as maximum. When operating temperature approaches these limits follow the manufacturer's recommendations.

Notes for Table 3C

The material listed above are fabricated in-situ and are especially sensitive to installation and fabrication technique. They are subject to variations in density, dimensional stability, and moisture content. Thermal data listed are not to be used as absolute values and are for guidance only. Degradations for installed performance of up to 50% of listed values are possible. CAUTION: For all materials manufactured in the field, follow the manufacturer's precautions and recommendations.

Table 3D Abbreviated Reference of Previously Listed Insulating Materials

This table is included as a guide for determining the thermal performance of existing constructions. Most of the materials below are no longer commercially available. The table was abstracted from Heating, Ventilating, Air Conditioning Guide, 1939, pp. 95, 97, 98.

Expressed in Btu per (hour)(square foot)(degree Fahrenheit temperature difference per in.)

Material	Description	Density, lb/ft^3	Mean temp, F	k or C	$1/k$ or $1/C$	Ref (see below)
INSULATION—BLANKET OR FLEXIBLE TYPES						
Fiber	Typical	—	—	0.27*	3.70	—
	Chemically treated wood fibers held between layers of strong paper**	3.62	70	0.25	4.00	3
	Eel grass between strong paper**	4.60	90	0.26	3.85	1
	" " " " "	3.40	90	0.25	4.00	1
	Flax fibers between strong paper**	4.90	90	0.28	3.57	1
	Chemically treated hog hair between kraft paper	5.76	71	0.26	3.85	3
	Chemically treated hog hair between kraft paper and asbestos paper**	7.70	71	0.28	3.57	3
	Hair felt between layers of paper**	11.00	75	0.25	4.00	3
	Kapok between burlap or paper**	1.00	90	0.24	4.17	1
	Jute fiber**	6.70	75	0.25	4.00	3
	Ground paper between two layers, each 3/8-in. thick made up of two layers of kraft paper (sample 3/4-in. thick)	12.1	75	0.40†	2.50	4
INSULATION—SEMI-RIGID TYPE						
Fiber	Felted cattle hair**	13.00	90	0.26	3.84	1
	" " "	11.00	90	0.26	3.84	1
	Flax**	12.10	70	0.30	3.33	3
	Flax and rye**	13.60	90	0.32	3.12	1
	Felted hair and asbestos**	7.80	90	0.28	3.57	1

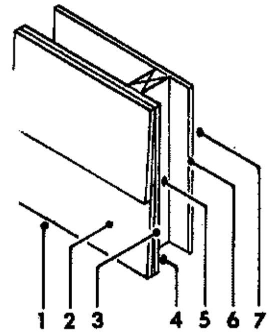
Table 3D Abbreviated Reference of Previously Listed Insulating Materials (Concluded)

	75% hair and 25% jute**	6.30	90	0.27	3.70	1
	50% hair and 50% jute**	6.10	90	0.26	3.85	1
	Jute**	6.70	75	0.25	4.00	3
	Felted jute and asbestos**	10.00	90	0.37	2.70	1
	Compressed peat moss	11.00	70	0.26	3.84	3
INSULATION—LOOSE FILL OR BAT TYPE						
Fiber	Made from ceiba fibers**	1.90	75	0.23	4.35	3
	" " " "	1.60	75	0.24	4.17	3
	Fibrous material made from dolomite and silica	1.50	75	0.27	3.70	3
	Fibrous material made from slag	9.40	103	0.27	3.70	1
Glass wool	Fibrous material 25 to 30 microns in diameter, made from virgin bottle glass	1.50	75	0.27	3.70	3
Granular	Made from combined silicate of lime and alumina	4.20	72	0.24	4.17	3
	Made from expanded aluminum-magnesium silicate	6.32	86	0.29	3.45	3
Gypsum	Cellular dry	30.00	90	1.00	1.00	1
	" "	24.00	90	0.77	1.30	1
	" "	18.00	90	0.59	1.69	1
	" "	12.00	90	0.44	2.27	1
	Flaked, dry and fluffy**	34.00	90	0.60	1.67	1
	" " " "	26.00	90	0.52	1.92	1
	" " " "	24.00	75	0.48*	2.08	3
	" " " "	19.80	90	0.35	2.86	1
	" " " "	18.00	75	0.34	2.94	3
Mineral wool	All forms typical	—	—	0.27*	3.70	—
Regranulated cork	About 3/16-in. particles	8.10	90	0.31	3.22	1
Rock wool	Fibrous material made from rock	21.00	90	0.30	3.33	1
	" " " " "	18.00	90	0.29	3.45	1
	" " " " "	14.00	90	0.28	3.57	1
	" " " " "	10.00	90	0.27*	3.70	1
	Rock wool with a binding agent	14.50	77	0.33	3.03	1
	Rock wool with flax, straw pulp, and binder	14.50	75	0.38	2.63	3
	Rock wool with vegetable fibers	11.50	72	0.31	3.22	3
Sawdust	Various	12.00	90	0.41	2.44	1
Shavings	Various from planer	8.80	90	0.41	2.44	1
	From maple, beech and birch (coarse)	13.20	90	0.36	2.78	1
	Redwood bark	3.00	90	0.31	3.22	1
	Redwood bark	5.00	75	0.26	3.84	3
INSULATION—RIGID						
Corkboard	Typical	—	—	0.30*	3.33	—
	No added binder	14.00	90	0.34	2.94	1
	" " "	10.60	90	0.30	3.33	1
	" " "	7.00	90	0.27	3.70	1
	" " "	5.40	90	0.25	4.00	1
	Asphaltic binder	14.50	90	0.32	3.12	1
Fiber	Typical	—	—	0.33*	3.03	—
	Chemically treated hog hair covered with film of asphalt	10.00	75	0.28	3.57	3
	Made from corn stalks	15.00	71	0.33	3.03	3
	" " exploded wood fibers	17.90	78	0.32	3.12	4
	" " hard wood fibers	15.20	70	0.32	3.12	3
	Insulating plaster 9/10-in. thick applied to 3/8-in. plaster board base	54.00	75	1.07†	0.93	3
	Made from licorice roots	16.10	81	0.34	2.94	3
	" " 85% magnesia and 15% asbestos	19.30	86	0.51	1.96	1
	" " shredded wood and cement	24.20	72	0.46	2.17	3
	" " sugar cane fiber	13.50	70	0.33	3.03	3
	Sugar cane fiber insulation blocks encased in asphalt membrane	13.80	70	0.30	3.33	3
	Made from wheat straw	17.00	68	0.33	3.03	3
	" " wood fiber	15.90	72	0.33	3.03	3
	" " " "	15.00	70	0.33	3.03	3
	" " " "	—	52	0.33	3.03	—
	" " " "	8.50	72	0.29	3.45	3
	" " " "	15.20	—	0.33	3.03	3
	" " " "	16.90	90	0.34	2.94	1
BUILDING BOARDS						
Asbestos	Compressed cement and asbestos sheets	123.00	86	2.70	0.37	1
	Corrugated asbestos board	20.40	110	0.48	2.08	2

[1]U.S. Bureau of Standards, tests based on samples submitted by manufacturers.
[2]A.C. Willard, L.C. Lichty, and L.A. Harding, tests conducted at the University of Illinois.
[3]J.C. Peebles, tests conducted at Armour Institute of Technology, based on samples submitted by manufacturers.
[4]F.B. Rowley, tests conducted at the University of Minnesota.
*Recommended conductivities and conductances for computing heat transmission coefficients.
**Not compressed.
†For thickness stated or used on construction, not per 1-in. thickness.

Table 4A Coefficients of Transmission (*U*) of Frame Walls[a]

These coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on an outside wind velocity of 15 mph



Replace Air Space with 3.5-in. R-11 Blanket Insulation (New Item 4)

Construction	1 Resistance (R) Between Framing	1 At Framing	2 Between Framing	2 At Framing
1. Outside surface (15 mph wind)	0.17	0.17	0.17	0.17
2. Siding, wood, 0.5 in.× 8 in. lapped (average)	0.81	0.81	0.81	0.81
3. Sheathing, 0.5-in. vegetable fiber board	1.32	1.32	1.32	1.32
4. Nonreflective air space, 3.5 in. (50 F mean; 10 deg F temperature difference)	1.01	—	11.00	—
5. Nominal 2-in. × 4-in. wood stud	—	4.35	—	4.35
6. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45	0.45
7. Inside surface (still air)	0.68	0.68	0.68	0.68
Total Thermal Resistance (R)	R_i=4.44	R_s=7.78	R_i=14.43	R_s=7.78

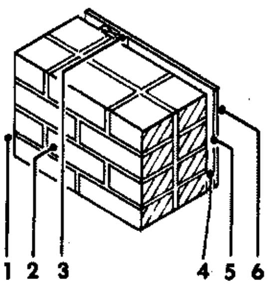
Construction No. 1: U_i = 1/4.44=0.225; U_s=1/7.81 =0.128. With 15% framing (typical of 2-in. × 4-in. studs @ 16-in. o.c.), U_{av} = 0.8 (0.225) + 0.15 (0.128) = 0.199 (See Eq 9)

Construction No. 2: U_i = 1/14.43 = 0.069; U_s = 0.128. With framing unchanged, U_{av} = 0.8(0.069) + 0.2(0.128) = 0.081

[a] See text section Calculating Overall Coefficients for basis of calculations.

Table 4B Coefficients of Transmission (*U*) of Solid Masonry Walls[a]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on an outside wind velocity of 15 mph



Replace Furring Strips and Air Space with 1-in. Expanded Polystyrene Extruded, Smooth Skin Surface, 2.2 lb/ft³ (New Item 4)

Construction	1 Resistance (*R*) Between Furring	1 At Furring	2
1. Outside surface (15 mph wind)	0.17	0.17	0.17
2. Common brick, 8 in.	1.60	1.60	1.60
3. Nominal 1-in. ×3-in. vertical furring	—	0.94	—
4. Nonreflective air space, 0.75 in. (50 F mean; 10 deg F temperature difference)	1.01	—	5.00
5. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45
6. Inside surface (still air)	0.68	0.68	0.68
Total Thermal Resistance (R)	R_i = 3.91	R_s = 3.84	R_i = 7.90 = R_s

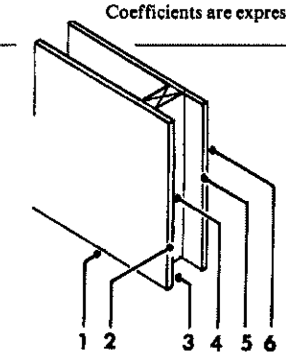
Construction No. 1: U_i = 1/3.91=0.256; U_s=1/3.84=0.260. With 20% framing (typical of 1-in. × 3-in. vertical furring on masonry @ 16-in. o.c.) U_{av} = 0.8 (0.256) + 0.2 (0.260) = 0.257

Construction No. 2: U_i = U_s = U_{av} = 1/7.90 = 0.127

[a] See text section Calculating Overall Coefficients for basis of calculations.

Table 4C Coefficients of Transmission (*U*) of Frame Partitions or Interior Walls[a]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on still air (no wind) conditions on both sides



Replace Air Space with 3.5-in. R-11 Blanket Insulation (New Item 3)

Construction	1 Resistance (R) Between Framing	1 At Framing	2 Between Framing	2 At Framing
1. Inside surface (still air)	0.68	0.68	0.68	0.68
2. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45	0.45
3. Nonreflective air space, 3.5 in. (50 F mean; 10 deg F temperature difference)	1.01	—	11.00	—
4. Nominal 2-in. × 4-in. wood stud	—	4.38	—	4.38
5. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45	0.45
6. Inside surface (still air)	0.68	0.68	0.68	0.68
Total Thermal Resistance (R)	R_i= 3.27	R_s= 6.64	R_i=13.26	R_s= 6.64

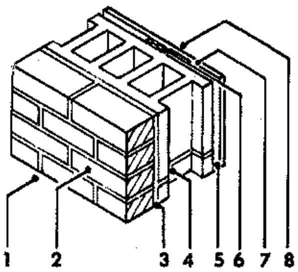
Construction No. 1: U_i= 1/3.27 = 0.306; U_s= 1/6.64 = 0.151. With 12% framing (typical of 2-in. × 4-in. studs @ 24-in. o.c.), U_{av}= 0.9 (0.306) + 0.12 (0.151) = 0.293

Construction No. 2: U_i = 1/13.26 = 0.075_6 U_s = 1/6.64 = 0.151. With framing unchanged, U_{av} = 0.9(0.075) + 0.1(0.151) = 0.083

[a] See text section Calculating Overall Coefficients for basis of calculations.

Table 4D Coefficients of Transmission (*U*) of Masonry Walls[a]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on an outside wind velocity of 15 mph



Replace Cinder Aggregate Block with 6-in. Light-weight Aggregate Block with Cores Filled (New Item 4)

Construction	1 Resistance (R) Between Furring	1 At Furring	2 Between Furring	2 At Furring
1. Outside surface (15 mph wind)	0.17	0.17	0.17	0.17
2. Face brick, 4 in.	0.44	0.44	0.44	0.44
3. Cement mortar, 0.5 in.	0.10	0.10	0.10	0.10
4. Concrete block, cinder aggregate, 8 in.	1.72	1.72	2.99	2.99
5. Reflective air space, 0.75 in. (50 F mean; 30 deg F temperature difference) E = 0.05	2.77	—	2.77	—
6. Nominal 1-in. × 3-in. vertical furring	—	0.94	—	0.94
7. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45	0.45
8. Inside surface (still air)	0.68	0.68	0.68	0.68
Total Thermal Resistance (R)	R_i = 6.33	R_s = 4.50	R_i = 7.60	R_s = 5.77

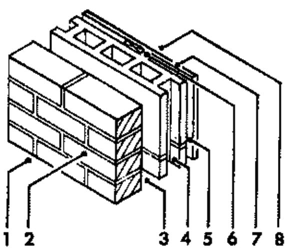
Construction No. 1: $U_i = 1/6.33 = 0.158$; $U_s = 1/4.50 = 0.222$. With 20% framing (typical of 1-in. × 3-in. vertical furring on masonry @ 16-in. o.c.), $U_{av} = 0.8\,(0.158) + 0.2\,(0.222) = 0.171$

Construction No. 2: $U_i = 1/7.60 = 0.132_6$ $U_s = 1/5.77 = 0.173$. With framing unchanged, $U_{av} = 0.8(0.132) + 0.2(0.173) = 0.140$

[a] See text section Calculating Overall Coefficients for basis of calculations.

Table 4E Coefficients of Transmission *(U)* of Masonry Cavity Walls[a]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on an outside wind velocity of 15 mph



Replace Furring Strips and Gypsum Wallboard with 0.625-in. Plaster (Sand Aggregate) Applied Directly to Concrete Block-Fill 2.5-in. Air Space with Vermiculite Insulation, 7-8.2 lb/ft³ (New Items 3 and 7)

Construction	1 Resistance (*R*) Between Furring	1 At Furring	2
1. Outside surface (15 mph wind)	0.17	0.17	0.17
2. Common brick, 4 in.	0.80	0.80	0.80
3. Nonreflective air space, 2.5 in. (30 F mean; 10 deg F temperature difference)	1.10*	1.10*	5.32**
4. Concrete block, three-oval core, stone and gravel aggregate, 4 in.	0.71	0.71	0.71
5. Nonreflective air space 0.75 in. (50 F mean; 10 deg F temperature difference)	1.01	—	—
6. Nominal 1-in. × 3-in. vertical furring	—	0.94	—
7. Gypsum wallboard, 0.5 in.	0.45	0.45	0.11
8. Inside surface (still air)	0.68	0.68	0.68
Total Thermal Resistance (R)	R_i = 4.92	R_s = 4.85	$R_i = R_s$ = 7.79

Construction No. 1: $U_i = 1/4.92 = 0.203$; $U_s = 1/4.85 = 0.206$. With 20% framing (typical of 1-in. × 3-in. vertical furring on masonry @16-in. (o.c.), $U_{av} = 0.8(0.203) + 0.2(0.206) = 0.204$

Construction No. 2: $U_i = U_s = U_{av} = 1.79 = 0.128$

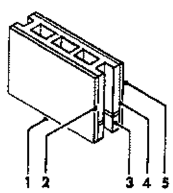
[a] See text section Calculating Overall Coefficients for basis of calculations.

* Interpolated value from Table 2.

** Calculated value from Table 3.

Table 4F Coefficients of Transmission *(U)* of Masonry Partitions[a]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on still air (no wind) conditions on both sides



Replace Concrete Block with 4-in. Gypsum Tile (New Item 3)

Construction	1	2
1. Inside surface (still air)	0.68	0.68
2. Plaster, lightweight aggregate, 0.625 in.	0.39	0.39
3. Concrete block, cinder aggregate, 4 in.	1.11	1.67
4. Plaster, lightweight aggregate, 0.625 in.	0.39	0.39
5. Inside surface (still air)	0.68	0.68
Total Thermal Resistance(R)	3.25	3.81

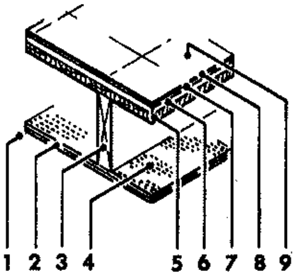
Construction No. 1: $U = 1/3.25 = 0.308$

Construction No. 2: $U - 1/3.81 - 0.262$

[a] See text section Calculating Overall Coefficients for basis of calculations.

Table 4G Coefficients of Transmission (*U*) of Frame Construction Ceilings and Floors[a]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference between the air on the two sides), and are based on still air (no wind) on both sides



Assume Unheated Attic Space above Heated Room with Heat Flow Up—Remove Tile, Felt, Plywood, Subfloor and Air Space—Replace with R-19 Blanket Insulation (New Item 4)

Heated Room Below Unheated Space	1		2	
	Resistance (R)			
Construction (Heat Flow Up)	**Between Floor Joists**	**At Floor Joists**	**Between Floor Joists**	**At Floor Joists**
1. Bottom surface (still air)	0.61	0.61	0.61	0.61
2. Metal lath and lightweight aggregate, plaster, 0.75 in.	0.47	0.47	0.47	0.47
3. Nominal 2-in. × 8-in. floor joist	—	9.06	—	9.06
4. Nonreflective airspace, 7.25-in. (50 F mean; 10 deg F temperature difference)	0.93*	—	19.00	—
5. Wood subfloor, 0.75 in.	0.94	0.94	—	—
6. Plywood, 0.625 in.	0.77	0.77	—	—
7. Felt building membrane	0.06	0.06	—	—
8. Tile	0.05	0.05	—	—
9. Top surface (still air)	0.61	0.61	0.61	0.61
Total Thermal Resistance (R)	R_i= 4.44	R_s= 12.57	R_i= 20.69	R_s=10.75

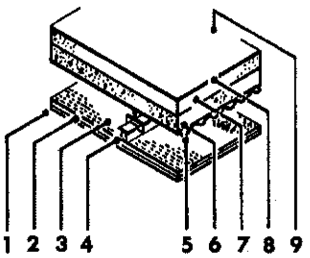
Construction No. 1: U_i= 1/4.45= 0.225; U_s= 1/12.58= 0.079. With 10% framing (typical of 2-in. joists @ 16-in. o.c.), U_{av} = 0.9 (0.225) + 0.1 (0.079)= 0.210

Construction No. 2: U_i = 1/20.69 = 0.048; U_s = 1/10.75 = 0.093. With framing unchanged, U_{av} = 0.9 (0.048) + 0.1 (0.093) = 0.053

[a]See text section Calculating Overall Coefficients for basis of calculations.
*Use largest air space (3.5 in.) value shown in Table 2.

Table 4H Coefficients of Transmission (*U*) of Flat Masonry Roofs with Built-up Roofing, with and without Suspended Ceilings[a,b] (Winter Conditions, Upward Flow)

These Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based upon an outside wind velocity of 15 mph



Add Rigid Roof Deck Insulation, C = 0.24 (R = 1/C = 4.17) (New Item 7)

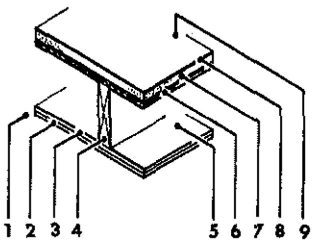
Construction (Heat Flow Up)	**1**	**2**
1. Inside surface (still air)	0.61	0.61
1. Metal lath and lightweight aggregate plaster, 0.75 in.	0.47	0.47
3. Nonreflective air space, greater than 3.5 in. (50 F mean; 10 deg F temperature difference)	0.93*	0.93*
4. Metal ceiling suspension system with metal hanger rods	0**	0**
5. Corrugated metal deck	0	0
6. Concrete slab, lightweight aggregate, 2 in. (30 lb/ft^3)	2.22	2.22
7. Rigid roof deck insulation (none)	—	4.17
8. Built-up roofing, 0.375 in.	0.33	0.33
9. Outside surface (15 mph wind)	0.17	0.17
Total Thermal Resistance (R)	4.73	8.90

Construction No. 1: U_{av} = 1/4.73 = 0.211
Construction No. 2: U_{av} = 1/8.90= 0.112

[a]See text section Calculating Overall Coefficients for basis of calculations.
[b]To adjust *U* values for the effect of added insulation between framing members, see Table 5 or 6.
*Use largest air space (3.5 in.) value shown in Table 2.
**Area of hanger rods is negligible in relation to ceiling area.

Table 4I Coefficients of Transmission (*U*) of Wood Construction Flat Roofs and Ceilings[a] (Winter Conditions, Upward Flow)

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based upon an outside wind velocity of 15 mph



Replace Roof Deck Insulation and Partially Fill the 7.25-in. Air Space with 6-in. R-19 Blanket Insulation and 1.25-in. Air Space (New Items 5 and 7)

Construction (Heat Flow Up)	1 Resistance (R) Between Joists	1 At Joists	2 Between Joists	2 At Joists
1. Inside surface (still air)	0.61	0.61	0.61	0.61
2. Acoustical tile, fiberboard, 0.5 in.	1.25	1.25	1.25	1.25
3. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45	0.45
4. Nominal 2-in. × 8-in. ceiling joists	—	9.06	—	9.06
5. Nonreflective air space, 7.25 in. (50 F mean; 10 deg F temperature difference)	0.93*	—	1.05**	—
6. Plywood deck, 0.625 in.	0.78	0.78	0.78	0.78
7. Rigid roof deck insulation, c = 0.72, ($R = 1/C$)	1.39	1.39	19.00	—
8. Built-up roof	0.33	0.33	0.33	0.33
9. Outside surface (15 mph wind)	0.17	0.17	0.17	0.17
Total Thermal Resistance (R)	R_i=5.91	R_s=14.04	R_i=23.64	R_s=12.65

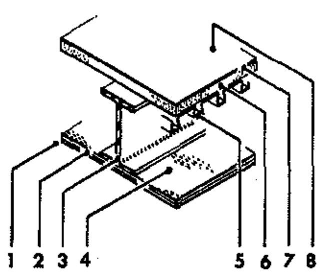
Construction No. 1: $U_i = 1/5.91 = 0.169$; $U_s = 1/14.04 = 0.071$. With 10% framing (typical of 2-in. joists @ 16-in. o.c.), $U_{av} = 0.9\,(0.169) + 0.1\,(0.071) = 0.159$

Construction No. 2: $U_i = 1/23.64 = 0.042$; $U_s = 1/12.65 = 0.079$. With framing unchanged, $U_{av} = 0.9\,(0.042) + 0.1\,(0.079) = 0.046$

[a] See text section Calculating Overall Coefficients for basis of calculations.
*Use largest air space (3.5 in.) value shown in Table 2.
**Interpolated value (0 F mean; 10 deg F temperature difference).

Table 4J Coefficients of Transmission (*U*) of Metal Construction Flat Roofs and Ceilings[a] (Winter Conditions, Upward Flow)

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on upon outside wind velocity of 15 mph



Replace Rigid Roof Deck Insulation ($C = 0.24$) and Sand Aggregate Plaster with Rigid Roof Deck Insulation, $C = 0.36$ and Lightweight Aggregate Plaster 0.75 in. on Metal Lath (New Items 2 and 6)

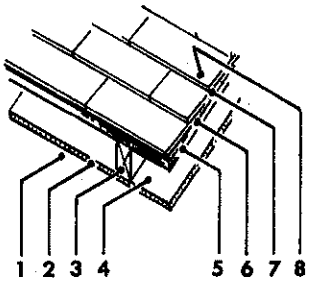
Construction (Heat Flow Up)	1	2
1. Inside surface (still air)	0.61	0.61
2. Metal lath and sand aggregate plaster, 0.75 in	0.13	0.47
3. Structural beam	0.00*	0.00*
4. Nonreflective air space (50 F mean; 10 deg F temperature difference) thickness	0.93**	0.93**
5. Metal deck	0.00*	0.00*
6. Rigid roof deck insulation, $C = 0.24$ ($R = 1/c$)	4.17	2.78
7. Built-up roofing, 0.375 in.	0.33	0.33
8. Outside surface (15 mph wind)	0.17	0.17
Total Thermal Resistance (R)	6.34	5.29

Construction No. 1: $U = 1/6.34 = 0.158$
Construction No. 2: $U = 1/5.29 = 0.189$

[a] See text section Calculating Overall Coefficients for basis of calculations.
*If structural beams and metal deck are to be considered, the technique shown in *Examples 1 and 2*, and Fig. 3 may be used to estimate total *R*. Full scale testing of a suitable portion of the construction is, however, preferable.
**Use largest air space (3.5 in.) value shown in Table 2.

Table 4K Coefficients of Transmission (U) of Pitched Roofs[a,b]

Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides), and are based on an outside wind velocity of 15 mph for heat flow upward and 7.5 mph forheat flow downward



Find U_{av} for same Construction 2 with Heat Flow Down (Summer Conditions)	1		2	
Construction 1 (Heat Flow Up) (Reflective Air Space)	**Between Rafters**	**At Rafters**	**Between Rafters**	**At Rafters**
1. Inside surface (still air)	0.62	0.62	0.76	0.76
2. Gypsum wallboard 0.5 in., foil backed	0.45	0.45	0.45	0.45
3. Nominal 2-in. × 4-in. ceiling rafter	—	4.35	—	4.35
4. 45 deg slope reflective air space, 3.5 in. (50 F mean, 30 deg F temperature difference) E = 0.05	2.17	—	4.33	—
5. Plywood sheathing,0.625 in.	0.77	0.77	0.77	0.77
6. Permeable felt building membrane	0.06	0.06	0.06	0.06
7. Asphalt shingle roofing	0.44	0.44	0.44	0.44
8. Outside surface (15 mph wind)	0.17	0.17	0.25**	0.25**
Total Thermal Resistance (R)	R_i=4.68	R_s=6.86	R_i=7.06	R_s=7.08

Construction No. 1: U_i=1/4.69= 0.213; U_s = 1/6.90 = 0.145. With 10% framing (typical of 2-in. rafters @16-in. o.c.), U_{av}= 0.9 (0.213) + 0.1 (0.145) = 0.206

Construction No. 2: U_i=1/7.07 = 0.141; U_s = 1/7.12 = 0.140. With framing unchanged, U_{av}= 0.9 (0.141) + 0.1 (0.140) = 0.141

Find U_{av} for same Construction 2 with Heat Flow Down (Summer Conditions)	3		4	
Construction 1 (Heat Flow Up) (Non-Reflective Air Space)	**Between Rafters**	**At Rafters**	**Between Rafters**	**At Rafters**
1. Inside surface (still air)	0.62	0.62	0.76	0.76
2. Gypsum wallboard, 0.5 in.	0.45	0.45	0.45	0.45
3. Nominal 2-in. × 4-in. ceiling rafter	—	4.35	—	4.35
4. 45 deg slope, nonreflective air space, 3.5 in. (50 F mean, 10 deg F temperature difference)	0.96	—	0.90*	—
5. Plywood sheathing, 0.625 in.	0.77	0.77	0.77	0.77
6. Permeable felt building membrane	0.06	0.06	0.06	0.06
7. Asphalt shingle roofing	0.44	0.44	0.44	0.44
8. Outside surface (15-mph wind)	0.17	0.17	0.25**	0.25**
Total Thermal Resistance (R)	R_i=3.47	R_s=6.86	R_i=3.63	R_s=7.08

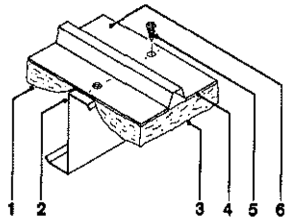
Construction No. 3: U_i= 1/3.48 = 0.287; U_s = 1/6.90 = 0.145. With 10% framing (typical of 2-in. rafters @ 16-in. o.c.), U_{av}= 0.9 (0.287)+ 0.1 (0.145) = 0.273

Construction No. 4: U_i= 1/3.64 = 0.275; U_s = 1/7.12 = 0.140. With framing unchanged, U_{av}= 0.9 (0.275) + 0.1 (0.140) = 0.262

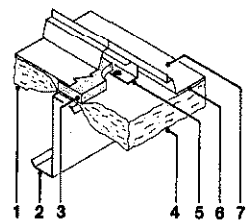
[a] See text section Calculating Overall Coefficients for basis of calculations.
[b] Pitch of roof—45 deg.
*Air space value at 90 F mean, 10 F dif. temperature difference.
**7.5-mph wind.

Table 4L Tested Coefficients of Transmission (*U*) for Pre-Engineered Metal Buildings

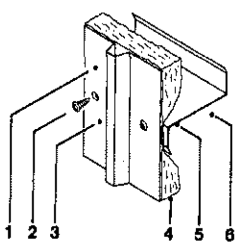
Coefficients are expressed in Btu per (hour) (square foot) (degree Fahrenheit difference in temperature between the air on the two sides)



Construction Details	Blanket insulation thickness, in.[a] 2	3	4
Construction 1 **Roof Section** **Winter Conditions, Upward Flow**			
1. Inside surface (still air)	0.61	0.61	0.61
2. Structural support (purlin)			
3. Blanket insulation		Tested R^b (= 1/*C*) =	
4. Corrugated metal panel	4.22	6.37	7.91
5. Panel fastener			
6. Outside surface (15 mph wind)	0.17	0.17	0.17
Thermal resistance (*R*)	5.00	7.15	7.97
U(= 1/*R*)	0.20	0.14	0.13



Construction Details	2	3	4
Construction 2 **Roof Section** **Winter Conditions, Upward Flow**			
1. Inside surface (still air)	0.61	0.61	0.61
2. Structural support (purlin)			
3. Spacer block		Tested R^b (= 1/*C*) =	
4. Blanket insulation	7.52	9.90	11.36
5. Panel fastener clip			
6. Corrugated metal panel			
7. Outside surface (15 mph wind)	0.17	0.17	0.17
Thermal resistance (*R*)	8.30	10.68	12.14
U(= 1/*R*)	0.12	0.09	0.08



Construction Details	2	3	4
Construction 1 **Wall Section** **Winter Conditions, Outward Flow**			
1. Outside surface (15 mph wind)	0.17	0.17	0.17
2. Panel fastener			
3. Corrugated metal panel		Tested R^b (= 1/*C*) =	
4. Blanket insulation	5.08	5.78	7.94
5. Structural support (girt)			
6. Inside surface (still air)	0.68	0.68	0.68
Thermal resistance (*R*)	5.93	6.63	8.79
U(=1/*R*)	0.17	0.15	0.11

[a]Blanket insulation is 0.6 lb/ft^3 density (k = 0.31 @ 75 F) with an integral vapor retarder.
[b]Tested *R* value is determined by testing for *C* value of the roof or wall assembly in a guarded hot box in accordance with ASTM C-236.

Table 5A Determination of *U*-Value Resulting from Addition of Insulation to the Total Area[e] of any Given Building Section

Given Building Section Property[a,b]		Added $R^{c,d,e}$ R = 4	R = 6	R = 8	R = 12	R = 16	R = 20	R = 24
U	*R*	*U*	*U*	*U*	*U*	*U*	*U*	*U*
1.00	1.00	0.20	0.14	0.11	0.08	0.06	0.05	0.04
0.90	1.11	0.20	0.14	0.11	0.08	0.06	0.05	0.04
0.80	1.25	0.19	0.14	0.11	0.08	0.06	0.05	0.04
0.70	1.43	0.18	0.13	0.11	0.07	0.06	0.05	0.04
0.60	1.67	0.18	0.13	0.10	0.07	0.06	0.05	0.04
0.50	2.00	0.17	0.13	0.10	0.07	0.06	0.05	0.04
0.40	2.50	0.15	0.12	0.10	0.07	0.05	0.04	0.04
0.30	3.33	0.14	0.11	0.09	0.07	0.05	0.04	0.04
0.20	5.00	0.11	0.09	0.08	0.06	0.05	0.04	0.03
0.10	10.00	0.07	0.06	0.06	0.05	0.04	0.03	0.03
0.08	12.50	0.06	0.05	0.05	0.04	0.04	0.03	0.03

[a]For *U*- or *R*-values not shown in the table, interpolate as necessary.
[b]Enter column 1 with *U* or *R* of the design building section.
[c]Under appropriate column heading for added *R*, find *U*-value of resulting design section.
[d]If the insulation occupies previously considered air space, an adjustment must be made in the given building section *R*-value.
[e]If insulation is applied between framing members, use Eq 9 to determine average *U*-value.

Table 5B Determination of *U*-Value Resulting from Addition of Insulation to Uninsulated Roof Deck

U-Value of Roof without Roof-Deck Insulation[a]	Conductance *C* of Roof-Deck Insulation 0.12	0.15	0.19	0.24	0.36	0.72
	U	*U*	*U*	*U*	*U*	*U*
0.10	0.05	0.06	0.07	0.07	0.08	0.09
0.15	0.07	0.08	0.08	0.09	0.11	0.12
0.20	0.08	0.09	0.10	0.11	0.13	0.16
0.25	0.08	0.09	0.11	0.12	0.15	0.19
0.30	0.09	0.10	0.12	0.13	0.16	0.21
0.35	0.09	0.11	0.12	0.14	0.18	0.24
0.40	0.09	0.11	0.13	0.15	0.19	0.26
0.50	0.10	0.12	0.14	0.16	0.21	0.30
0.60	0.10	0.12	0.14	0.17	0.23	0.33
0.70	0.10	0.12	0.15	0.18	0.24	0.35

[a]Interpolation or mild extrapolation may be used.

Table 6 Effective Resistance of Ventilated Attics[a]—(Summer Condition)[5]

PART A. NONREFLECTIVE SURFACES

Ventilation Air Temp., F	Sol-Air[d] Temp., F	No Ventilation		Natural Ventilation		Power Ventilation[e]					
		Ventilation Rate, cfm/ft²									
		0		0.1[b]		0.5		1.0		1.5	
		1/U Ceiling Resistance, R[c]									
		10	20	10	20	10	20	10	20	10	20
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
PART B. REFLECTIVE SURFACES[f]											
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]The term *effective resistance is* used when there is attic ventilation. A value for no ventilation is also included. The effective resistance of the attic may be added to the resistance (1/U) of the ceiling (Table 4G) to obtain the effective resistance of the combination based on sol-air (Chapter 26) and room temperature. These values apply to wood frame construction with a roof deck and roofing having a conductance of 1.0 Btu/h · ft² · F.

[b]When attic ventilation meets the requirements of Table 3 in Chapter 22, 0.1 cfm/ft² may be assumed as the natural summer ventilation rate for design purposes.

[c]*Resistance* is 1 h · ft² · F/Btu. Determine ceiling resistance from Tables 4G and 5A, and adjust for framing by Eq 9. Do not add the effect of a reflective surface facing the attic to the ceiling resistance from Table 4G, as it is accounted for in Table 6, Part B.

[d]Roof surface temperature rather than sol-air temperature (see Chapter 26) may be used if 0.25 is subtracted from the attic resistance shown.

[e]Based on air discharging outward from attic.

[f]Surfaces with effective emittance *E* of 0.05 between ceiling joists facing the attic space.

Table 7 Estimated Heat Lost from Building by Infiltration[a]

The tabulated factors, when multiplied by room or building volume (ft³), will result in estimated heat loss (Btu/h) due to infiltration and does not include the heat needed to warm ventilating air

Room or Building Type	No. of Walls with Windows	Temp. Difference, deg F 25	50	75	100	Room or Building Type	No. of Walls with Windows	Temp. Difference, deg F 25	50	75	100
	None	0.23	0.45	0.68	0.90	B	Any	1.35	2.70	4.05	5.40
	1	0.34	0.68	1.02	1.36	C	Any	0.90-1.35	1.80-270	2.70-4.05	3.60-5.40
A	2	0.68	1.35	2.02	2.70	D	Any	0.45-0.68	0.90-1.35	1.35-2.02	1.80-2.70
	3 or 4	0.90	1.80	2.70	3.60	E	Any	0.68-1.35	1.35-2.70	2.03-4.05	2.70-5.40

A = Offices, apartments, hotels, multistory buildings in general.
B = Entrance halls or vestibules.
C = Industrial buildings.
D = Houses, all types, all rooms except vestibules.
E = Public or institutional buildings.

[a]See Chapter 25, section entitled Calculating Heat Loss Due to Infiltration.

Table 8 Overall Coefficients of Heat Transmission (*U*-Factor) of Windows, Sliding Patio Doors, and Skylights for Use in Peak Load Determination and Mechanical Equipment Sizing Only and Not in Any Analysis of Annual Energy Usage, W/m² · °C (Btu/h · ft² · F)

Part A. Exterior[a] Vertical Panels

	No Storm Sash				Glass Outdoor Storm Sash 25-mm (1-in.) Air Space[b]			
	No Shade		Indoor Shade		No Shade		Indoor Shade	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Flat Glass[c]								
Single Glass,	6.2(1.10)	5.9(1.04)	4.7(0.83)	4.6(0.81)	2.3(0.50)	2.8(0.50)	2.5(0.44)	2.8(0.49)
Insulating Glass; Double[c]								
5-mm (3/16-in.) air space[f]	3.5(0.62)	3.7(0.65)	3.0(0.52)	3.3(0.58)	2.1(0.37)	2.3(0.40)	1.7(0.29)	2.1(0.37)
6-mm (1/4-in.) air space[f]	3.3(0.59)	3.5(0.61)	2.7(0.48)	3.1(0.55)	2.0(0.35)	2.2(0.39)	1.6(0.28)	2.0(0.36)
13-mm (1/2-in.) air space[g]	2.8(0.49)	3.2(0.56)	2.4(0.42)	3.0(0.52)	1.8(0.32)	2.2(0.39)	1.4(0.25)	2.1(0.30)
13-mm (1/2-in.) air space low emittance coating[h]								
e = 0.60	2.4(0.43)	2.9(0.51)	2.2(0.38)	2.7(0.48)	1.7(0.30)	2.0(0.36)	1.4(0.24)	2.0(0.35)
e = 0.40	2.2(0.38)	2.6(0.48)	2.0(0.36)	2.5(0.43)	1.5(0.27)	1.9(0.39)	1.3(0.22)	1.8(0.32)
e = 0.20	1.8(0.32)	2.2(0.38)	1.7(0.30)	2.1(0.37)	1.4(0.24)	1.7(0.30)	1.1(0.20)	1.6(0.28)
Insulating Glass; Triple								
6-mm (1/4-in.) air space[f]	2.2(0.39)	2.5(0.44)	1.8(0.31)	2.3(0.40)	1.5(0.27)	1.8(0.32)	1.3(0.22)	1.7(0.30)
13-mm (1/2-in. air space[i]	1.8(0.31)	2.2(0.39)	1.5(0.26)	2.0(0.36)	1.3(0.23)	1.8(0.31)	1.1(0.19)	1.7(0.29)

	Glass Indoor Storm Sash 25-mm (1-in.) Air Space[b]				Acrylic Indoor Storm Sash 25-mm (1-in.) Air Space[b]			
	No Shade		Indoor Shade		No Shade		Indoor Shade	
	Winter*	Summer**	Winter*	Summer**	Winter*	Summer**	Winter*	Summer**
Flat Glass[c]								
Single Glass,	2.8(0.50)	2.8(0.50)	2.5(0.44)	2.8(0.49)	2.7(0.48)	2.7(0.48)	2.4(0.42)	2.7(0.47)
Insulating Glass; Double[c]								
5-mm (3/16-in.) air space[f]	2.1(0.37)	2.3(0.40)	1.7(0.29)	2.0(0.36)	2.0(0.35)	2.2(0.39)	1.6(0.28)	2.0(0.35)
6-mm (1/4-in.) air space[f]	2.0(0.35)	2.2(0.39)	1.6(0.28)	2.0(0.36)	(1.9(0.34)	2.2(0.38)	1.5(0.27)	1.9(0.34)
13-mm (1/2-in.) air space[g]	1.8(0.31)	2.2(0.38)	1.4(0.25)	2.0(0.35)	1.7(0.30)	2.1(0.37)	1.4(0.24)	1.9(0.33)
13-mm (1/2-in.) air space, Low emittance costing[h]								
e = 0.60	1.7(0.29)	2.0(0.36)	1.4(0.24)	1.9(0.33)	1.6(0.28)	2.0(0.35)	1.3(0.23)	1.8(0.32)
e = 0.40	1.5(0.27)	1.9(0.33)	1.3(0.22)	1.8(0.31)	1.5(0.26)	1.8(0.32)	1.3(0.22)	1.7(0.30)
e = 0.20	1.4(0.25)	1.7(0.29)	1.1(0.20)	1.5(0.26)	1.4(0.24)	1.6(0.28)	1.1(0.20)	1.5(0.27)
Insulating Glass; Triple[e]								
6-mm (1/4-in.) air space[f]	1.5(0.27)	1.8(0.32)	1.3(0.22)	1.7(0.30)	1.5(0.26)	1.8(0.31)	1.3(0.22)	1.7(0.29)
13-mm (1/2-in.) air space[i]	1.3(0.23)	1.7(0.30)	1.1(0.19)	1.6(0.28)	1.3(0.22)	1.7(0.29)	1.0(0.18)	1.6(0.28)

Part B. Exterior[a] Horizontal Panels (Skylights)

Description	Winter[i]	Summer[j]
Flat Glass[e]		
Single Glass	7.0 (1.23)	4.7 (0.83)
Insulating Glass; Double[c]		
5-mm (3/16-in.) air space[d]	4.0 (0.70)	3.2 (0.57)
6-mm (1/4-in.) air space[d]	3.7 (0.65)	3.1 (0.54)
13-mm (1/2-in.) air space[e]	3.4 (0.59)	2.8 (0.49)
13-mm (1/2-in.) air space, low emittance coating[f]		
e = 0.20	2.7 (0.48)	2.0 (0.36)
e = 0.40	3.0 (0.52)	2.4 (0.42)
e = 0.60	3.2 (0.56)	2.6 (0.46)
Plastic Domes[k]		
Single Walled	6.5 (1.15)	4.5 (0.80)
Double Walled	4.0 (0.70)	2.6 (0.46)

Part C. Adjusting Factors for Various Windows and Sliding Patio Door Types (Multiply *U*-Values in Parts A and B by These Factors)

Description	Single Glass	Double or Triple Glass	Storm Windows
Windows			
All Glass[h]	1.00	1.00	1.00
Wood Sash; 80% Glass	0.90	0.95	0.90
Wood Sash; 60% Glass	0.80	0.85	0.80
Metal Sash; 80% Glass	1.00	1.20[m]	1.20[m]
Sliding Patio Doors			
Wood Frame	0.95	1.00	—
Metal Frame	1.00	1.10[m]	—

[a] See Part C for adjustments for various windows and sliding patio doors.
[b] Emissivity of uncoated glass surface = 0.84.
[c] Double and triple refer to number of lights of glass.
[d] 3-mm (1/8-in.) glass.
[e] 6-mm (1/4-in.) glass.
[f] Coating on either glass surface facing air space; all other glass surfaces uncoated.
[g] Window design: 6-mm (1/4 in.) glass, 3-mm (1/8 in.) glass, 6-mm (1/4 in.) glass.
[h] Refers to windows with negligible opaque areas.
[i] For heat flow up.
[j] For heat flow down.
[k] Based on area of opening, not total surface area.
[m] Values will be less than these when metal sash and frame incorporate thermal breaks. In some thermal break designs *U* values will be equal to or less than those for the glass. Window manufacturers should be consulted for specific data.
*24 km/h (15 mph outdoor air velocity; −18°C (0 F) outdoor air; 21°C (70 F) inside air temp. natural convection.
*12 km/h (7.5 mph) outdoor air velocity; 32°C (89 F) outdoor air; 21°C (75 F) inside air natural convection; solar radiation 782 W/m² (248.3 Btuh/ft²).
The reciprocal of the above *U*-factors is the thermal resistance, *R* for each type of glazing. If tightly drawn drapes (heavy close weave), closed Venetian blinds, or closely fitted roller shades are used internally, the additional *R* is approximately 0.05 m² · °C/W (0.29 ft² · F Btuh). If minature louvered solar screens are used in close proximity to the outer fenestration surface, the additional *R* is approximately 0.04 m² · °C/W (0.24 ft² · F/Btuh).

Example: Find the winter *U*-factor for uncoated double insulating glass [13-mm (0.5-in.) air space] when (1) external miniature louvered sun screens are used; and (2) tightly woven drapes are added.

Solution: Winter R for 13-mm (0.5-in.) air space double insulating glass = 1/2.8 = .36 (2.04); added resistance for the miniature louvered sun screen =0.04 (0.24); so total R = 0.40 (2.28) and *U*-factor = 2.5 W/m² · °C (0.44 Btuh/ft² · deg F). Adding the tightly woven drape R = 0.05 (0.29), total R = .45 (2.57), so U = 2.2 W/m² · °C (.39 Btuh/ft² · deg F).

Table 9A Coefficients of Transmission (*U*) for Wood Doors,[a] Btu/h · ft² · F

Door Thickness, in.[d]	Description	Winter[b] No Storm Door	Winter[b] Wood Storm Door[e]	Winter[b] Metal Storm Door[f]	Summer[c] No Storm Door
1-3/8	Hollow core flush door	0.47	0.30	0.32	0.45
1-3/8	Solid core flush door	0.39	0.26	0.28	0.38
1-3/8	Panel door with 7/16-in. panels	0.57	0.33	0.37	0.54
1-3/4	Hollow core flush door	0.46	0.29	0.32	0.44
	with single glazing[g]	0.56	0.33	0.36	0.54
1-3/4	Solid core flush door	0.33	0.28	0.25	0.32
	With single glazing[g]	0.46	0.29	0.32	0.44
	With insulating glass[g]	0.37	0.25	0.27	0.36
1-3/4	Panel door with 7/16-in. panels[h]	0.54	0.32	0.36	0.52
	With single glazing[i]	0.67	0.36	0.41	0.63
	With insulating glass[i]	0.50	0.31	0.34	0.48
1-3/4	Panel door with 1-1/8-in. panels[h]	0.39	0.26	0.28	0.38
	With single glazing[i]	0.61	0.34	0.38	0.58
	With insulating glass[i]	0.44	0.28	0.31	0.42
2-1/4	Solid core flush door	0.27	0.20	0.21	0.26
	With single glazing[g]	0.41	0.27	0.29	0.40
	With insulating glass[g]	0.33	0.23	0.25	0.32

[a] Values for doors are based on nominal 3′8″ × 6′8″ door size. Interpolation and moderate extrapolation are permitted for glazing areas and door thicknesses other than those specified.
[b] 15 mph outdoor air velocity; 0 F outdoor air; 70 F inside air temp natural convection.
[c] 7.5 mph outdoor air velocity; 89 F outdoor air; 75 F inside air natural convection.
[d] Nominal thickness.
[e] *Values for wood storm door are approximately 50% glass area.*
[f] Values for metal storm door are for any percent of glass area.
[g] 17% exposed glass area; insulating glass contains 0.25 inch air space.
[h] 55% panel area.
[i] 33% glass area; 22% panel area; insulating glass contains 0.25 inch air space.

Table 9B Coefficients of Transmission (*U*) for Steel Doors
Btu/h · ft² · F

Thickness	Steel Door[14]			No Storm Door
1.75 in.				
A[a]	0.59	—	—	0.58
B[b]	0.40	—	—	0.39
C[c]	0.47	—	—	0.46

[a] A = Mineral fiber core (2 lb/ft³).
[b] B = Solid urethane foam core with thermal break.
[c] C = Solid Polystyrene core with thermal break.

Table 10 Conversion Table for Wall Coefficient *U* for Various Wind Velocities

U for 15 mph[a]	*U* for 0 to 30 mph Wind Velocities 0	5	10	20	25	30	*U* for 15 mph[a]	*U* for 0 to 30 mph Wind Velocities 0	5	10	20	25	30
0.050	0.049	0.050	0.050	0.050	0.050	0.050	0.290	0.257	0.278	0.286	0.293	0.295	0.296
0.060	0.059	0.059	0.060	0.060	0.060	0.060	0.310	0.273	0.296	0.305	0.313	0.315	0.317
0.070	0.068	0.069	0.070	0.070	0.070	0.070	0.330	0.288	0.314	0.324	0.333	0.336	0.338
0.080	0.078	0.079	0.080	0.080	0.080	0.080	0.350	0.303	0.332	0.344	0.354	0.357	0.359
0.090	0.087	0.089	0.090	0.090	0.091	0.091	0.370	0.318	0.350	0.363	0.375	0.378	0.380
0.100	0.096	0.099	0.100	0.100	0.101	0.101	0.390	0.333	0.368	0.382	0.395	0.399	0.401
0.110	0.105	0.108	0.109	0.110	0.111	0.111	0.410	0.347	0.385	0.402	0.416	0.420	0.422
0.130	0.123	0.127	0.129	0.131	0.131	0.131	0.430	0.362	0.403	0.421	0.436	0.441	0.444
0.150	0.141	0.147	0.149	0.151	0.151	0.152	0.450	0.376	0.420	0.439	0.457	0.462	0.465
0.170	0.158	0.166	0.169	0.171	0.172	0.172	0.500	0.410	0.464	0.487	0.509	0.514	0.518
0.190	0.175	0.184	0.188	0.191	0.192	0.193	0.600	0.474	0.548	0.581	0.612	0.620	0.626
0.210	0.192	0.203	0.208	0.212	0.213	0.213	0.700	0.535	0.631	0.675	0.716	0.728	0.736
0.230	0.209	0.222	0.227	0.232	0.233	0.234	0.800	0.592	0.711	0.766	0.821	0.836	0.847
0.250	0.226	0.241	0.247	0.252	0.253	0.254	0.900	0.645	0.789	0.858	0.927	0.946	0.960
0.270	0.241	0.259	0.266	0.273	0.274	0.275	1.000	0.695	0.865	0.949	1.034	1.058	1.075

[a] *U* in first column is from previous tables or as calculated for 15 mph wind velocity.

Table 11 Heat Losses from Horizontal Bare Steel Pipes and Flat Surfaces[a]

In Btu per (Square foot of pipe surface)(hour)(degree Fahrenheit temperature difference between pipe and air)

Pipe Size (in.)	Linear Foot Factor[b]	Temperature Difference Degree Fahrenheit between Pipe Surface and Surrounding Air (Air at 80 F)																			
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
0.5	0.220	2.12	2.48	2.80	3.10	3.42	3.74	4.07	4.47	4.86	5.28	5.72	6.19	6.69	7.22	7.79	8.39	9.03	9.70	10.42	11.18
0.75	0.275	2.08	2.43	2.74	3.04	3.35	3.67	4.00	4.40	4.79	5.21	5.65	6.12	6.61	7.15	7.71	8.31	8.95	9.62	10.34	11.09
1	0.344	2.04	2.38	2.69	2.99	3.30	3.61	3.94	4.33	4.72	5.14	5.58	6.05	6.54	7.07	7.64	8.23	8.87	9.55	10.26	11.02
1.25	0.435	2.00	2.34	2.64	2.93	3.24	3.55	3.88	4.27	4.66	5.07	5.51	5.97	6.47	7.00	7.56	8.16	8.79	9.47	10.18	10.94
1.5	0.497	1.98	2.31	2.61	2.90	3.20	3.52	3.84	4.23	4.62	5.03	5.47	5.93	6.43	6.96	7.52	8.12	8.75	9.43	10.14	10.89
2	0.622	1.95	2.27	2.56	2.85	3.15	3.46	3.78	4.17	4.56	4.97	5.41	5.87	6.37	6.89	7.45	8.05	8.68	9.36	10.07	10.82
2.5	0.753	1.92	2.23	2.52	2.81	3.11	3.42	3.74	4.12	4.51	4.92	5.36	5.82	6.31	6.84	7.40	7.99	8.63	9.30	10.01	10.77
3	0.916	1.89	2.20	2.49	2.77	3.07	3.37	3.69	4.08	4.46	4.87	5.31	5.77	6.26	6.79	7.35	7.94	8.57	9.25	9.96	10.71
3.5	1.047	1.87	2.18	2.46	2.74	3.04	3.34	3.66	4.05	4.43	4.84	5.27	5.73	6.23	6.75	7.31	7.91	8.54	9.21	9.92	10.67
4	1.178	1.85	2.16	2.44	2.72	3.01	3.32	3.64	4.02	4.40	4.81	5.25	5.71	6.20	6.72	7.28	7.87	8.51	9.18	9.89	10.64
4.5	1.309	1.84	2.14	2.42	2.70	2.99	3.30	3.61	4.00	4.38	4.79	5.22	5.68	6.17	6.69	7.25	7.85	8.48	9.15	9.86	10.61
5	1.456	1.83	2.13	2.40	2.68	2.97	3.28	3.59	3.97	4.35	4.76	5.20	5.65	6.15	6.68	7.23	7.82	8.45	9.12	9.83	10.58
6	1.734	1.80	2.10	2.37	2.65	2.94	3.24	3.55	3.94	4.32	4.72	5.16	5.61	6.10	6.63	7.19	7.78	8.41	9.08	9.79	10.54
7	1.996	1.79	2.08	2.35	2.63	2.91	3.21	3.53	3.91	4.29	4.69	5.13	5.58	6.07	6.60	7.15	7.75	8.38	9.05	9.76	10.51
8	2.258	1.77	2.06	2.33	2.60	2.89	3.19	3.50	3.88	4.26	4.67	5.10	5.56	6.05	6.57	7.12	7.72	8.35	9.02	9.73	10.48
9	2.520	1.76	2.05	2.31	2.59	2.87	3.17	3.48	3.86	4.24	4.65	5.08	5.53	6.02	6.54	7.10	7.69	8.32	8.99	9.70	10.45
10	2.814	1.75	2.03	2.30	2.57	2.85	3.15	3.46	3.84	4.22	4.62	5.05	5.51	6.00	6.52	7.08	7.67	8.30	8.97	9.68	10.43
12	3.338	1.73	2.01	2.27	2.54	2.83	3.12	3.43	3.81	4.19	4.59	5.02	5.48	5.96	6.48	7.04	7.63	8.26	8.93	9.64	10.39
14	3.665	1.72	2.00	2.26	2.53	2.81	3.11	3.41	3.79	4.17	4.57	5.00	5.46	5.94	6.47	7.02	7.61	8.24	8.91	9.62	10.37
16	4.189	1.70	1.98	2.24	2.51	2.79	3.08	3.39	3.77	4.14	4.55	4.98	5.43	5.92	6.44	6.99	7.59	8.21	8.88	9.59	10.34
18	4.717	1.69	1.96	2.22	2.49	2.77	3.07	3.37	3.75	4.12	4.53	4.96	5.41	5.90	6.42	6.97	7.56	8.19	8.86	9.57	10.32
20	5.236	1.68	1.95	2.21	2.47	2.75	3.05	3.36	3.73	4.11	4.51	4.94	5.39	5.88	6.40	6.95	7.54	8.17	8.84	9.55	10.29
24	6.283	1.66	1.93	2.19	2.45	2.73	3.02	3.33	3.70	4.07	4.48	4.90	5.36	5.84	6.36	6.92	7.51	8.14	8.80	9.51	10.26
Vertical Surface		1.84	2.14	2.42	2.70	3.00	3.30	3.62	4.00	4.38	4.79	5.22	5.68	6.17	6.70	7.26	7.85	8.48	9.15	9.86	10.62
Horizontal Surface Facing Upward		2.03	2.37	2.67	2.97	3.28	3.59	3.92	4.31	4.70	5.12	5.56	6.02	6.52	7.05	7.61	8.21	8.85	9.52	10.24	10.99
Horizontal Surface Facing Downward		1.61	1.86	2.11	2.36	2.64	2.93	3.23	3.60	3.97	4.37	4.80	5.25	5.73	6.25	6.80	7.39	8.02	8.69	9.39	10.14

[a]Values are for Flat Surfaces 4 ft^2 or more in area.

[b]To secure losses per linear ft, multiply ft^2 losses in table by this factor. Losses per ft^2 of pipe surface for pipes larger than 24 in. can be considered the same as losses for 24-in. pipe.

Table 12 Heat Losses from Bare Tarnished Copper Tube[a]

Nominal Diameter of Tube (in.)	Temperature of Tube, F							
	120	150	180	210	240	270	300	330
	Temperature Difference, Tube to Air, Deg F							
	50	80	110	140	170	200	230	260
	Heat Loss per Linear Foot of Tube, Btu/h							
0.25	8	14	21	29	37	46	56	66
0.375	10	18	28	37	48	60	72	85
0.5	13	22	33	45	59	72	88	104
0.625	15	26	39	53	68	85	102	121
0.75	17	30	45	61	79	97	117	139
1	21	37	55	75	97	120	146	173
1.25	25	45	66	90	117	145	175	207
1.5	29	52	77	105	135	167	203	241
2	37	66	97	132	171	212	257	305
2.5	44	78	117	160	206	255	310	367
3	51	92	136	186	240	297	360	428
3.5	59	104	156	212	274	340	412	490
4	66	118	174	238	307	381	462	550
5	80	142	212	288	373	464	561	669
6	93	166	246	336	432	541	656	776
8	120	215	317	435	562	699	848	1010
10	146	260	387	527	681	848	1031	1227
12	172	304	447	621	802	999	1214	1446

[a]Extracted from Ref 9. Used by permission.

Table 13 External Surface per Linear Foot of Copper Tubing

Outside diameter 0.125 in. greater than nominal size

Tube Size (in.)	Surface Area (ft^2)	Tube Size (in.)	Surface Area (ft^2)	Tube Size (in.)	Surface Area (ft^2)
0.5	0.164	2	0.556	5	1.342
0.75	0.229	2.5	0.687	6	1.604
1	0.295	3	0.818	8	2.128
1.25	0.360	3.5	0.949	...	....
1.5	0.426	4	1.080	...	....

Table 14 Area of Flanged Fittings, Square Feet[a]

Nominal Pipe Size (in.)	Flanged Coupling Standard	Flanged Coupling Extra Heavy	90 Deg Ell Standard	90 Deg Ell Extra Heavy	Long Radius Ell Standard	Long Radius Ell Extra Heavy	Tee Standard	Tee Extra Heavy	Cross Standard	Cross Extra Heavy
1	0.320	0.438	0.795	1.015	0.892	1.083	1.235	1.575	1.622	2.07
1.25	0.383	0.510	0.957	1.098	1.084	1.340	1.481	1.925	1.943	2.53
1.5	0.477	0.727	1.174	1.332	1.337	1.874	1.815	2.68	2.38	3.54
2	0.672	0.848	1.65	2.01	1.84	2.16	2.54	3.09	3.32	4.06
2.5	0.841	1.107	2.09	2.57	2.32	2.76	3.21	4.05	4.19	5.17
3	0.945	1.484	2.38	3.49	2.68	3.74	3.66	5.33	4.77	6.95
3.5	1.122	1.644	2.98	3.96	3.28	4.28	4.48	6.04	5.83	7.89
4	1.344	1.914	3.53	4.64	3.96	4.99	5.41	7.07	7.03	9.24
4.5	1.474	2.04	3.95	5.02	4.43	5.46	6.07	7.72	7.87	10.07
5	1.622	2.18	4.44	5.47	5.00	6.02	6.81	8.52	8.82	10.97
6	1.82	2.78	5.13	6.99	5.99	7.76	7.84	10.64	10.08	13.75
8	2.41	3.77	6.98	9.76	8.56	11.09	10.55	14.74	13.44	18.97
10	3.43	5.20	10.18	13.58	12.35	15.60	15.41	20.41	19.58	26.26
12	4.41	6.71	13.08	17.73	16.35	18.76	19.67	26.65	24.87	34.11

[a]Including areas of accompanying flanges bolted to the fitting.

Table 15 Approximate Wall Thickness (L) of Insulation for Pipes[15]

Pipe: Nominal Size in.	Pipe: Outer Diameter in.	Pipe: Outer Diameter mm	Insulation, Nominal Thickness 1 in. (25 mm): Approximate Wall Thickness in.	mm	1.5 in. (38 mm): in.	mm	2 in. (51 mm): in.	mm	2.5 in. (64 mm): in.	mm	3 in. (76 mm): in.	mm	3.5 in. (89 mm): in.	mm	4 in. (102 mm): in.	mm
0.5	0.84	21	1.01	26	1.57	40	2.07	53	2.88	73	3.38	86	3.88	99	4.38	111
0.75	1.05	27	0.90	23	1.46	37	1.96	50	2.78	71	3.28	83	3.78	96	4.28	109
1	1.32	33	1.08	27	1.58	40	2.12	54	2.64	67	3.14	80	3.64	92	4.14	105
1.25	1.66	42	0.91	23	1.66	42	1.94	49	2.47	63	2.97	75	3.47	88	3.97	101
1.5	1.90	48	1.04	26	1.54	39	2.35	60	2.85	72	3.35	85	3.85	98	4.42	112
2	2.38	60	1.04	26	1.58	40	2.10	53	2.60	66	3.10	79	3.60	91	4.17	106
2.5	2.88	73	1.04	26	1.86	47	2.36	60	2.86	73	3.36	85	3.92	100	4.42	112
3	3.50	89	1.02	26	1.54	39	2.04	52	2.54	65	3.04	77	3.61	92	4.11	104
3.5	4.00	102	1.30	33	1.80	46	2.30	58	2.80	71	3.36	85	3.86	98	4.36	111
4	4.50	114	1.04	26	1.54	39	2.04	52	2.54	65	3.11	79	3.61	92	4.11	104
4.5	5.00	127	1.30	33	1.80	46	2.30	58	2.86	73	3.36	85	3.86	98	4.48	114
5	5.56	141	0.99	25	1.49	38	1.99	51	2.56	65	3.06	78	3.56	90	4.18	106
6	6.62	168	0.96	24	1.46	37	2.02	51	2.52	64	3.02	77	3.65	93	4.15	105
7	7.62	194	—	—	1.52	39	2.02	51	2.52	64	3.15	80	3.65	93	4.15	105
8	8.62	219	—	—	1.52	39	2.02	51	2.65	67	3.15	80	3.65	93	4.15	105
9	9.62	244	—	—	1.52	39	2.15	55	2.65	67	3.15	80	3.65	93	4.15	105
10	10.75	273	—	—	1.58	40	2.08	53	2.58	66	3.08	78	3.58	91	4.08	104
11	11.75	298	—	—	1.58	40	2.08	53	2.58	66	3.08	78	3.58	91	4.08	104
12	12.75	324	—	—	1.58	40	2.08	53	2.58	66	3.08	78	3.58	91	4.08	104
14[a]	14.00	356	—	—	1.46	37	1.96	50	2.46	62	2.96	75	3.46	88	3.96	101

[a]Larger sizes through 36 in., same as for 14 in.

Table 16 Approximate Wall Thickness of Insulation for Tubes[15]

Tube: Nominal Size in.	Tube: Outer Diameter in.	Tube: Outer Diameter mm	Insulation, Nominal Thickness 1 in. (25 mm): Approximate Wall Thickness in.	mm	1.5 in. (38 mm): in.	mm	2 in. (51 mm): in.	mm	2.5 in. (64 mm): in.	mm	3 in. (76 mm): in.	mm	3.5 in. (89 mm): in.	mm	4 in. (102 mm): in.	mm
0.375	0.50	13	0.93	24	1.49	38	1.99	51	2.52	64	3.05	77	—	—	—	—
0.5	0.62	16	1.12	28	1.43	36	1.93	49	2.46	62	2.99	76	—	—	—	—
0.75	0.88	22	1.00	25	1.56	40	2.06	52	2.86	73	3.36	85	3.87	98	4.37	111
1	1.12	28	0.87	22	1.43	36	1.93	49	2.74	70	3.24	82	3.74	95	4.24	108
1.25	1.38	35	1.06	27	1.56	40	2.08	53	2.62	67	3.12	79	3.62	92	4.12	105
1.5	1.62	41	0.93	24	1.43	36	1.96	50	2.49	63	2.99	76	3.49	89	3.99	101
2	2.12	54	0.92	23	1.42	36	2.23	57	2.73	69	3.23	82	3.73	95	4.30	109
2.5	2.62	67	0.92	23	1.45	37	1.98	50	2.48	63	2.98	76	3.48	88	4.04	103
3	3.12	79	0.92	23	1.73	44	2.23	57	2.73	69	3.23	82	3.80	97	4.30	109
3.5	3.62	92	0.95	24	1.48	38	1.98	50	2.48	63	2.98	76	3.54	90	4.04	103
4	4.12	105	1.23	31	1.73	44	2.23	57	2.73	69	3.30	84	3.80	97	4.30	109
5	5.12	130	1.23	31	1.73	44	2.23	57	2.80	71	3.30	84	3.80	97	4.42	112
6	6.12	155	1.21	31	1.71	43	2.28	58	2.78	71	3.28	83	3.90	99	4.40	112

Table 17 Apparent Thermal Conductivity (*k*) Values of Soils in Approximate Order of Decreasing Values[a]

Mean Temperature −40 F

Soil Designation	Mechanical Analysis % by Weight: Gravel	Sand	Silt	Clay	Moisture Content, %: 4			10		20	
	Over 2.0 mm	0.5 to 2.00 mm	0.005 to 0.05 mm	Under 0.005 mm	Dry Density, lb/ft³: 100	110	120	90	110	90	100
Fine Crushed Quartz	0.0	100.0	0.0	0.0	12.0	16.0					
Crushed Quartz	15.5	79.0	5.5		11.5	16.0	22.0				
Graded Ottawa Sand	0.0	99.9	0.1		10.0	14.0					
Fairbanks Sand	27.5	70.0	2.5		8.5±	10.5	13.5		15.0		
Lowell Sand	0.0	100.0	0.0	0.0	8.5	11.0			13.5		
Chena River Gravel	80.0	19.4	0.6			9.0±	13.0				
Crushed Feldspar	25.5	70.3	4.2		6.0	7.5	9.5				
Crushed Granite	16.2	77.0	6.8		5.5	7.5	10.0				
Dakota Sandy Loam	10.9	57.9	21.2	10.0		6.5	9.5		13±		
Crushed Trap Rock	27.0	63.0	10.0		5.0	6.0	7.0				
Ramsey Sandy Loam	0.4	53.6	27.5	18.5	4.5	6.5			10.0		
Northway Fine Sand	0.0	97.0	3.0	0.0	4.5	5.5			8.5		
Northway Sand	3.0	97.0	0.0	0.0	4.5	6.0			7.5±		
Healy Clay	0.0	1.9	20.1	78.0	4.0±			5.5	9.0±	8.0	10.0
Fairbanks Silt Loam	0.0	7.6	80.9	11.5				5.0	9.0±	7.5	10.0
Fairbanks Silty Clay Loam	0.0	9.2	63.8	27.0				5.0	9.0±	7.5	9.5
Northway Silt Loam	1.0	21.0	64.4	13.6				4.0±	7.0±	6.0±	7.0±

[a] *k* = Btu per (square foot)(hour)(Fahrenheit degree per inch).

Table 18 Conversion Factors to SI Metric Units

(See Chapter 37 for a more complete list of factors.)

Physical Quantity	Symbol	To Convert from	To	Multiply by
Length	x	in.	m	2.540 000* E-02
		ft	m	3.048 000* E-01
Area		in.²	m²	6.451 600* E-04
		ft²	m²	9.290 304* E-02
Volume		in.³	m³	1.638 706 E-05
		ft³	m³	2.831 685 E-02
Temperature		F	°C	$t_C = (t_F - 32)/1.8$
		F	K	$t_K = (t_F + 459.67)/1.8$
Pressure		in. Hg (60 F)	Pa	3.376 85 E + 03
Mass		lb	kg	4.535 924 E− 01
Mass/unit area	M	lb/ft²	kg/m²	4.882 428 E + 00
Moisture content rate		lb/ft²·week	kg/m²·s	8.072 793 E − 06
Density	ρ	lb/ft³	kg/m³	1.601 846 E + 01
Thermal conductivity	k	Btu·in./h · ft² · F	W/m · K	1.442 279 E − 01
Thermal conductance	C	Btu/h · ft² · F	W/m² · K	5.678 263 E + 00
U-value	U	Btu/h · ft² · F	W/m² · K	5.678 263 E + 00
Thermal resistance	R	h · ft² · F/Btu	m² · K/W	1.761 102 E − 01
Thermal resistivity	r/in.	h · ft² · F/Btu · in.	m·K/W	6.933 471 E + 00
Heat flow	q	Btu/h · ft²	W/m²	3.154 591 E + 00
Water vapor: permeability (23°C)	μ	grain / (h ·ft² ·in. Hg/in.)	kg/Pa·s·m	1.459 29 E − 12
Permeance (23°C)	p,P	grain / (h ·ft²·in. Hg)	kg/Pa · s · m²	5.745 25 E − 11

*Exact factor.