

The presence of water or ice in insulation has a marked effect on conductivity, because their conductivities are many times as great as that of the insulation. A serious moisture condition arises when the temperature of part of the insulation is below the dewpoint temperature of the surrounding air and, consequently, the water vapor from the air condenses in the insulation. While the effect of moisture on the conductivity of the insulation is not too serious so long as the moisture exists in the vapor phase, the conductivity is greatly increased by the presence of condensed moisture. Since moisture tends to migrate toward the colder surface, at low temperatures it will condense and may freeze. The effect of moisture on conductivity is difficult to determine accurately, because, in making a thermal conductivity test, a temperature difference across a sample is maintained and the moisture in the sample tends to migrate from the warmer to the colder side. It is possible for convection and air infiltration currents to occur in or through some insulations and cause an increase in the heat transfer across these insulations. Low-density loose-fill, and low-density fibrous types of insulations are most susceptible to increased heat transfer effect by convection and air infiltration. When convection occurs an increase of temperature drop across the insulation, the height of the insulation, or thickness or width of the insulated space, all tend to influence the amount of convection. However, the effect of convection in or through insulation can be minimized by careful design of the insulated structure.

Recent tests show that the effectiveness of fibrous batt type insulation is seriously impaired if installed vertically with air spaces on both sides, because of the air interchange through the insulation between the two spaces. However, when an impermeable membrane is applied to one surface, infiltration appears to be negligible and conductivities measured by hot plate tests are generally applicable.

Factors which may affect the conductivity of insulation by causing settling or other dimensional changes, include vibration, temperature extremes, and various mechanical forces.

Reference 8 discusses in detail the factors affecting the thermal conductivity and other thermal properties of soils. These factors include the effects of temperature, density, moisture, and soil characteristics. Four diagrams are presented in Reference 8 to aid in estimating the thermal conductivity of any soil. The specific heat of soil is also discussed. Tests were made on 19 different soils, which represented a wide textural variety, including gravel, sand, sandy loam, silt loam, and clay, as well as some crushed rocks and a fibrous peat. Moisture contents in tests varied from air-dried values to those greater than the optimum moisture content; densities varied from a loosely-poured condition to the maximum density obtainable by heavy ramming. Table 1 of Chapter 24 gives thermal conductivity values of soils in approximate order of decreasing values.

THERMAL CONDUCTANCE

The methods of calculating an overall coefficient of heat transmission require knowledge of the thermal conductivity and thickness of homogeneous elements, the thermal conductance of non-homogeneous elements, surface conductances of both sides of the construction, and the conductances of any contained air spaces. Accurate values of these items must be used to obtain satisfactory results. Procedures used for calculating thermal conductance and resistance, and definitions of heat transfer terms and symbols are given in Chapter 24. Sometimes parallel heat-flow paths of different resistances occur in the same construction. In such cases determination of the overall thermal transmittance by means of the *Guarded*

Table 1 . . . Variation in Surface Conductance Coefficient for Vertical Surfaces with Different Temperatures of Surrounding Surface

Surrounding Surface Temperature	75 F	70 F	69 F	60 F	50 F
Convection—Btu per (hr) (sq ft)	6.6	6.6	6.6	6.6	6.6
Radiation—Btu per (hr) (sq ft)	4.4	8.6	9.6	17.0	24.9
Total—Btu per (hr) (sq ft)	11.0	15.2	16.2	23.6	31.5

Hot Box method described in ASTM Designation C-236 is recommended.

Surface Conductance

The surface conductance of a wall is the combined heat transfer to or from the wall by radiation, convection, and conduction. Each of the three portions making up the total may vary, independently of the others, thus affecting the total conductance. The heat transfer by radiation between two surfaces is controlled by the character of the surfaces (emissivity), the temperature difference between them, and the solid angle through which they see each other. The heat transfer by convection and conduction is controlled by the roughness of the surface, by air movement, and temperature difference between the air and the surface.

The importance of the effect of temperature of surrounding surfaces on the surface conductance, due to the effect of radiation, is illustrated in Table 1, which applies to a vertical surface at 80 F, with ambient air at 70 F and with radiation exchange corresponding to an effective emissivity of 0.83.

In many cases, because the thermal resistance (reciprocal of conductance) of the internal parts of the wall is high compared with the surface resistance, the surface factors are of minor importance. The surface resistances of single glass windows, constitute almost the entire resistance and are therefore very important. An analysis of various factors affecting surface conductance and the difference between surface and air temperatures will be found in Reference 9. (See Chapter 14 of the 1964 GUIDE AND DATA BOOK.)

The convection part of the surface conductance is affected markedly by air movement. This is illustrated by Fig. 1 of Chapter 24. On smooth surfaces, surface length¹⁴ also significantly affects the convection part of conductance; the average value decreases as the surface length increases. Moreover, observations¹⁵ of the magnitude of low temperature radiant energy received from outdoor surroundings show that only under certain conditions may the out-of-doors be treated as a black body radiating at air temperature.

Because of these factors, the selection of surface conductance coefficients for a practical building becomes a matter of judgment. Surface conductances are shown in Table 2 of Chapter 24, and are applicable to ordinary building materials.

In special cases, where surface conductances become important factors in the overall rates of heat transfer, more selective coefficients may be required. Principles and data given in Chapter 4 may be applied in such cases.

FACTORS AFFECTING HEAT TRANSFER ACROSS AIR SPACES

The transfer of heat across an air space involves the boundary surfaces as well as the intervening air, and depends markedly on the orientation of the air space and the direction of heat flow. The coefficients given for air space conductance represent the total conductance from one surface bounding the air space to the other. The total conductance is the sum

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of a component due to radiation and a component due to convection and conduction combined. These components may vary independently of each other.

The radiation portion of the coefficient is affected by the temperature of the two boundary surfaces, and by their respective surface emissivities ϵ , the combined effect of which is expressed by means of the *effective emissivity* E of the air space. The radiation component is not affected by the thickness of the space or by its orientation or direction of heat flow. The heat transfer by convection and conduction combined is markedly affected by the orientation of the air space and the direction of heat flow, by the temperature difference across the space and in some cases by the thickness of the space. It is also affected to a small extent, by the mean temperature of its surfaces. For air spaces usually employed in building construction, the radiation and convection-conduction components may vary independently of each other.

Table 3 of Chapter 24 gives the thermal conductances and resistances of air spaces of uniform thickness and moderately smooth surfaces, based on experimental measurements conducted at the National Bureau of Standards.¹⁶ Although the conductances of air spaces vary to some extent with thickness in the range over $\frac{1}{4}$ in., average values are tabulated for $\frac{1}{4}$ in. and 4 in., for all except horizontal spaces with heat flow downward. The error involved by averaging is usually less than 10 percent, and is less than 5 percent in most cases. For more exact values, Reference 12 may be consulted.

For narrow air spaces, which may be defined as those for which the product of the cube of the thickness of the space in inches times the temperature difference (Fahrenheit degrees) across the space is less than 3 for heat flow horizontally or downward, or less than 1 for heat flow upward, the conductance is the sum of the radiative heat transfer coefficient and that for conduction alone through air, since convection is practically suppressed. The radiation component can be computed by methods outlined in Chapter 4. The conduction component can be computed using the conductivity of air at the appropriate mean temperature (see Chapter 5).

The effects of different mean temperatures, temperature differences, and effective emissivities are indicated in Table 3 of Chapter 24.

To obtain a high thermal resistance with reflective insulation used with refrigeration, multiple air layers bounded by reflective surfaces are formed and the total resistance is equal to the sum of the resistance values across each air space. Depending upon the type of reflective insulation, one or both sides may have highly reflective surfaces. Except for thick horizontal air spaces with heat flow down, little is gained thermally by the addition of a second highly reflective surface to the same air space. If an air space has only one reflective surface, it makes no appreciable difference as far as the rate of heat transfer is concerned as to the side on which the reflective surface is placed. However, it is important that condensation be prevented from forming on a reflective surface if it is the only one and is placed on the cold side of the construction. A reflective surface placed on the warm side of an air space will usually not be a condensing surface and will, therefore, maintain the thermal resistance of the air space and, in addition, will act as a water vapor barrier if the material and its joints are of adequately low permeance.

The emissivity of a surface is the measure of its ability to emit radiant energy, and for the same temperature and wave length, is equal to the absorptivity (ratio of the radiant energy absorbed by a surface to the total radiant energy falling on it). The ratio of the energy reflected by the surface to that falling on it is known as reflectivity, and for an opaque surface is equal to one minus the emissivity. The emissivity

varies with the type, color, and condition of the surface and with the wave length of the radiation.

For reflective insulation used with heating, air conditioning, and refrigeration applications, the emissivity value for long wave-length (infra-red) radiation is important, and not the value for the shorter wave lengths of the visible spectrum. Visible brightness is not a true measure of the reflectivity for thermal radiation, because there is no definite relation between the reflectivity for light and for long wave-length radiation. Typical reflectivity and emissivity values for reflective surfaces and building materials and the corresponding emissivity factors for air spaces are given in Table 2 of Chapter 24.

Changes in the condition of a reflective surface which may reduce its reflectivity and increase its emissivity include those caused by chemical action, dust accumulations, and the presence of condensation or frost. Chemical changes include oxidation, corrosion, or tarnishing caused by air, moisture, wet plaster, or the chemical treatment of wood spacing strips or other adjoining structural members. Surface emissivity values should be obtained by tests.

PART II: WATER VAPOR BARRIERS

Water vapor barriers are those materials which retard the transmission of water vapor with reasonable effectiveness under specified conditions. The permissible rate of water vapor transmission (permeance) of a barrier material depends upon design criteria for the structure or system being insulated.

VAPOR TRANSMISSION THROUGH MATERIALS

The principles and calculation of vapor flow through insulation and vapor barriers are treated in more detail in Chapter 23, Moisture in Building Construction.

Water vapor in air is a gas which exerts its own vapor pressure and which can move through materials under differences in its own vapor pressure independently of the air with which it is mixed. Water vapor transmission through materials under the influence of a water vapor pressure gradient is called vapor diffusion. The design equation commonly used is as follows:

$$W = \mu A \theta \frac{\Delta p}{l} \quad (1)$$

where

- W = total weight of vapor transmitted, grains.
 - μ = permeability, grains per (square foot) (hour) (inch of mercury vapor pressure difference per inch).
 - A = area of cross-section of the flow path, square feet.
 - θ = time during which the transmission occurred, hours.
 - Δp = difference of vapor pressure between ends of the flow path, inches of mercury.
 - l = length of flow path, (or thickness of specimen), inches.
- The basic units given are those now favored by the building industry.

Whenever it is convenient to deal with a material of a thickness other than the unit thickness to which μ refers, use may be made of the permeance coefficient M , where $M = \mu/l$. The designation *perm* for the unit of permeance is now widely used, and is a convenient substitute for the unit, 1 grain per (square foot) (hour) (inch of mercury vapor pressure difference). The corresponding unit of permeability is *perm-inch*, since it is the permeance of unit thickness. The corresponding flow equation is:

$$W = M A \theta \Delta p \quad (2)$$

The resistance to water vapor flow through a material is the reciprocal of its permeance and is equal to the thickness divided by its permeability. The overall resistance of an insulated section to water vapor flow is the sum of the resistances