insulating material usually involves a compromise with regard to several desirable properties, for example, as a special application, an insulating block may be required to have a low thermal conductivity combined with a low heat capacity; another application may require low thermal conductivity and a material that has considerable strength.

### Thermal Properties

The symbols, definitions, and units of terms used in steady-state heat transfer calculations are given in Chapter 24.

The ability of a material to retard the flow of heat is given by its thermal conductivity or conductance value. A low thermal conductivity or conductance value, therefore, distinguishes thermal insulation, except for reflective insulation. Reflective insulations, such as aluminum, depend not upon low thermal conductivity for their resistance to heat flow, but upon the low thermal emissivity of their surfaces and subdivision of the associated air space. To be effective in retarding heat flow by radiation, the reflective surface must face an air, or evacuated, space.

Design values of thermal conductivity, conductance, and resistance for the most commonly used insulations are shown in Tables 4 and 21 of Chapter 24. These values have been selected as typical and useful for engineering calculations. For more accurate values for a particular insulation, the user should consult the manufacturer or obtain the results of tests of the insulation under consideration.

Other thermal properties which may be important include specific heat, heat capacity, thermal diffusivity, the coefficient of thermal expansion, and resistance to temperature extremes. Heat capacity is taken as the product of specific heat and density. Thermal diffusivity is the ratio of thermal conductivity to heat capacity. Thermal diffusivity becomes important for those applications where large temperature changes need to be made in a relatively short time, since the rate of temperature change within an insulation is inversely proportional to its thermal diffusivity for a given thickness.

### Mechanical Properties

Some insulations have sufficient structural strength for use as load-bearing materials. They may on occasion be used to support load-bearing floors, form self-supporting partitions, or stiffen structural panels. For such applications, one or more of the various mechanical properties of an insulation, including strength in compression, tension, shear, impact, and flexure, may be important. These mechanical properties of an insulation vary with the basic composition, density, cell size, fiber diameter and orientation, type and amount of binder (if any), and the temperature at which measured.

### Properties Related to Moisture

The presence of water or ice in insulation can impair or destroy the insulating value, may cause deterioration of the insulation, and may eventually cause structural damage by rot, corrosion, or the expansion action of freezing water. Whether or not moisture accumulates within the insulation depends upon the operating temperatures and ambient conditions, and the location and effectiveness of vapor barriers.

The moisture resistance depends upon the basic material from which the insulation is made and upon the type of physical structure. Some insulations are hygroscopic and will gain or lose moisture in proportion to the relative humidity of the air in contact with the insulation. Fibrous and granular insulations permit the transmission of water vapor to the colder side of the structure. A vapor barrier should, therefore be used in conjunction with these materials where moisture transmission is a factor. Certain insulations having a closed cellular structure are relatively impervious to water and water vapor.

The various properties which express the influence of moisture include the following: absorption, hygroscopicity, capillarity, adsorption, and water vapor transmission rate.

### Health and Safety

The various properties of thermal insulation which are related to health and safety include the following: inability to support vermin and insects; freedom from fire hazard; freedom from dust or objectionable vapors; freedom from loose particles that may be irritating to the skin; freedom from rot, odors, and decay; and resistance to absorbing and retaining odors.

### Other Properties

Other properties of insulating materials which may be of importance, depending upon the particular application, include the following: density; resilience; resistance to settling; permanence; reuse or salvage value; ease of handling; dimensional uniformity and stability; resistance to chemical action and chemical change; ease in fabricating, applying, or finishing; size and thickness obtainable; electrical resistivity; sound absorption; vibration absorption; and air permeability.

## FACTORS AFFECTING THERMAL CONDUCTIVITY

Thermal conductivity is a property of a homogeneous material and of types of building materials, such as lumber, brick, and stone, which may be considered homogeneous. Most insulating materials, except reflective types, are of a porous nature and consist of combinations of solid matter with small voids. The thermal conductivity of insulation varies with the form and physical structure of the insulation, and with the environment and application conditions. The form and physical structure varies with the basic material and the manufacturing process. The variations include density, cell size, diameter and arrangement of fibers or particles, degree and extent of bonding materials, transparency to thermal radiation, and the type and pressure of gas within the insulation.

The environment and application conditions which can affect the thermal conductivity include temperature, moisture content and orientation of the insulation, and the direction of heat flow. Thermal conductivity values for insulation are usually given for oven-dry samples of a specified density tested by means of the *Guarded Hot Plate* (see ASTM Designation C-177) at a specified mean temperature. The accurate determination of fundamental conductivities and conductances requires considerable skill.

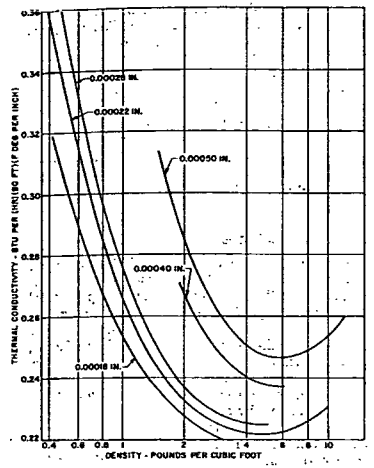
### Form and Physical Structure

The conductivity of insulation varies with density. The effect of density upon conductivity (at constant mean temperature) is illustrated in Fig. 1.[1]

A change in density due to various degrees of compaction of powder types of insulation affects the thermal conductivity. Insulating concretes made from lightweight aggregates can be made over a wide range of densities. Generally, conductivity increases with density, but the increase is often relatively small for cellular insulation in which, however, the cell size is very important. This is particularly true for plastic foams such as polystyrene and polyurethane, where the conductivity decreases as the cell size decreases.

With each type of fibrous insulation, there is a minimum conductivity value at some particular density from which the conductivity increases as the density is increased or decreased. A minimum conductivity value is also obtained when the






* *For Fibrous Glass at 75 F Mean Temperature.*

Fig. 1 .... Typical Variation of Thermal Conductivity with Fiber Diameter and Density*

fibers are spaced uniformly and are perpendicular to the direction of heat flow.

In general, a decrease of the diameter of the fibers lowers the conductivity for the same density (Fig. 1). Other factors, such as type and amount of binder, which influence the bond or contact of the fibers or particles may also affect the thermal conductivity.

At temperatures below 500 to 600 F, the greatest portion of heat transfer across most insulations is by conduction through the air or other gas in the insulation.[2-3-4] Consequently, if the gas within the insulation is replaced by another gas having a different conductivity, the conductivity of the insulation will be changed by an amount very nearly equal to the difference in conductivity of the two gases. For example, replacement with a fluorinated hydrocarbon refrigerant which has a lower conductivity than air, will lower the conductivity of the insulation by as much as 50 percent. Fluorocarbon-expanded, rigid, urethane foams utilize this principle. Commercially available urethane foams having a high proportion (greater than 90 percent) of closed cells retain the fluorocarbon within the cells for extended periods of time. As these products are initially produced, they have conductivities of approximately 0.11 Btu per (hour) (sq ft) (F deg per inch). However, the conductivity increases slowly with time as air-gases permeate into cells, diluting the fluorocarbon gas. The rate of air diffusion and subsequent increase in conductivity, is dependent on several factors, such as, environmental temperature, geometry of the insulation (thickness), and surface protection afforded the foam. This is evident in gas impermeable membrane.[5-6-7]

By decreasing the pressure within an insulation, the average distance that an enclosed gas molecule travels before striking another gas molecule (a distance known as the *mean free path*) is increased. When the *mean free path* becomes equal to the average distance a gas molecule travels before striking a solid part of the insulation, the conductivity of the insulation begins to decrease with decreasing pressure. Conversely, thermal conductivity tests on materials such as silica aerogel and fine carbon black, which have pores smaller than the mean free path of air at atmospheric pressure, have disproved the accuracy of the belief that no material containing air could have a conductivity lower than that of still air.

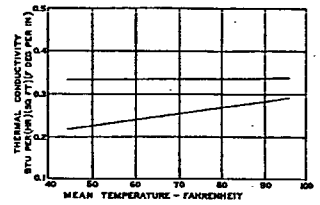



Fig. 2 .... Typical Variation of Thermal Conductivity with Mean Temperature

The transparency of a thermal insulation to thermal radiation becomes important as temperatures increase, and as temperature differences across the materials increase. For homogeneous materials, the primary mode of heat transfer is conduction, but, as temperatures and the transparency of materials increase, the heat transfer by thermal radiation and convection become a greater part of the total heat transferred. The magnitude of radiation and convection transfer depends largely on temperatures, the nature of materials involved, and geometric considerations.

### Environment and Application Conditions

The conductivity of insulating materials generally increases with temperature. Typical variations of conductivity with mean temperature are shown in Fig. 2. However, some materials, such as fluorocarbon-expanded, urethane plastics, exhibit a thermal conductivity versus mean temperature characteristic that contains inflections. See Table 4, Chapter 24. The conductivity at the mean temperature of the insulation (average of the two surfaces) may be taken as the conductivity for the material. The rate of change in conductivity with temperature varies with the type of material and its density.

Those insulating materials which permit a large percentage of heat transfer by radiation, such as a low-density fibrous material, show the greatest change in conductivity with change of temperature and change of emissivity of surrounding surfaces. The importance of radiation in conductivity determinations is recognized in the *Guarded Hot Plate Test* (ASTM Designation C-177) which requires that the surfaces of all plates shall be painted or otherwise treated to have a total emittance greater than 0.8 at operating temperature.

The effect of temperature alone on structural integrity is not ordinarily very important for most types in the low-temperature insulation field. There are more definite limitations for materials in the higher-temperature field, where decomposition, excessive linear shrinkage, softening, or some other effect of temperature alone will put a maximum limit on the temperature for which a material is suited. As extremes in temperature are approached, both high and low, the selection of a material for a specific service becomes more critical and must be based on experience and factual performance data. See Table 21, Chapter 24.