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THERMAL INSULATION OF BUILDINGS

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ABSTRACT

This circular is a brief nontechnical discussion of the principles of heat transfer as applied to thermal insulation at ordinary temperature, particularly with reference to buildings. The insulating properties of a number of general classes of insulating and building materials are given, together with estimates of the probable fuel savings resulting from the use of such materials.

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I. INTRODUCTION

This circular has been prepared to assist in answering the numerous inquiries and requests for information on the subjects of thermal insulation and insulating materials, primarily with reference to buildings. The subject will be treated very briefly, since it is not feasible to prepare a comprehensive manual of insulation methods or to discuss in detail the principles involved. Before giving the general conclusions derived from the work on insulating materials, it is desirable to explain certain principles and define certain heat terms which are not always clearly understood.

II. PRINCIPLES INVOLVED IN THE SUBJECT OF INSULATION

Thermal insulation is concerned with the problem of reducing the transfer of heat from one region to another. The physical principles involved in the subject of insulation are thus identical with those involved in the subject of heat transfer. Heat is transferred by three general methods or modes, called, respectively, conduction, convection, and radiation, which may operate either separately or in combination, depending upon the particular conditions. In any case the flow of heat invariably takes place from regions of higher temperature to regions of lower temperature.

1. CONDUCTION

In solid materials heat is transferred by a process known as conduction, the exact nature of which is not completely understood. The amount of heat conducted from one region to another is proportional to the temperature difference between the two regions in question. The ability to conduct heat varies widely among different materials, metals being, in general, far better heat conductors than nonmetallic substances. It therefore follows that nonmetallic materials are, in general, better insulators than metals. Gases, with two exceptions, are the poorest conductors of heat, but, as will be discussed later, heat transfer through gases is usually complicated by other factors besides conduction.

The numerical measure of the ability of a substance to conduct heat is called its thermal conductivity, defined in customary units as the amount of heat in B. t. u. (British thermal units) which will flow in one hour through a uniform layer of material 1 square foot in area and 1 inch in thickness, when the temperature difference between the surfaces of the layer is maintained at 1° F. A B. t. u. is the amount of heat necessary to raise the temperature of 1 pound of water 1° F. The insulating value or thermal resistivity of a material is equal to the reciprocal (one divided by) of its conductivity.

Thermal conductivity is a property of the material itself, not depending upon the size and shape of a particular piece of the material in question, providing the latter is of uniform structure. It is therefore incorrect to speak of the conductivity of a wall or other structure but only of the conductivity of the material or materials of which the structure is composed.

When dealing with a given body, such as a building wall, its insulating value as a whole is measured inversely by a property known as conductance, defined as the amount of heat flowing through the wall per unit time and per unit area when the temperature difference between the surfaces of the wall is 1°. The insulating value or thermal resistance is equal to the reciprocal of the conductance. The conductance of a wall depends upon the conductivity, size, and arrangement of the materials of which the wall is composed. If it consists of a single uniform material, its conductance is numerically equal to the conductivity of the material divided by the thickness of the wall. If the wall is composed of parallel layers of different materials, its conductance can be easily calculated from the respective thicknesses of the layers and the conductivities of the materials composing them. The insulating value of the wall is equal to the sum of the respective insulating values of the different layers. If, on the other hand, the wall does not consist simply of parallel layers, the calculation of the insulating value from the conductivity and dimensions of the wall components is much more difficult, and will not be discussed here.

2. CONVECTION

The transfer of heat in a liquid or gas is usually complicated by other factors besides conduction. Conduction is always present, but the heat transfer is ordinarily greatly increased by fluid motion called convection, set up either automatically by reason of temperature differences or by means of mechanical stirring or blowing. The former is called natural or free convection and the latter forced convection. The exchange of heat between the air in a room and the inside surface of the external wall is one of the simplest examples of natural convection. The heat loss from the outside wall surface to the outside air on a windy day is a familiar example of forced convection. The phenomenon of convection is rather complicated and can not be accurately expressed in terms of simple laws like those of conduction; but as an approximation, heat transfer by convection can be regarded as proportional to the temperature difference

3. RADIATION

The transfer of heat from one solid body to another through the intervening air or other fluid medium is still further complicated by radiation, which results in a heat transfer practically independent of the presence of the air. The process is the same as the transfer of heat from the sun to the earth through the intervening space devoid of matter. Everybody is familiar with the radiation of heat from an open fire, but it is not so generally recognized that radiation plays a very important rôle in heat transfer at ordinary temperatures. In fact, about one-half of the heat transfer from a heated room to the inside surface of the exterior walls takes place by direct radiation from interior objects and partition walls. The other half is the result of convection in the air near the exterior walls.

III. AIR SPACES AS THERMAL INSULATORS

Although air is a very poor conductor of heat, the insulating value of an ordinary air space is rather small, on account of the large transfer of heat by convection and radiation. Radiation is largely responsible for the ineffectiveness of air spaces bounded by ordinary building materials, such as are found in frame or other hollow walls. The low insulating value is often erroneously attributed to convection; but, as a matter of fact, from 50 to 80 per cent of the heat transfer across air spaces of ordinary sizes takes place by radiation. If the air spaces were bounded by bright metallic surfaces, the transfer of heat by radiation would be greatly diminished, since clean metallic surfaces are much poorer radiators than nonmetallic surfaces, such as brick, stone, glass, wood, plaster, paper, etc.

The terms conductance and resistance (insulating value), as already defined, can be applied to an air space as well as to a slab of solid material. On account of the large effects of radiation and convection, however, the insulating value of an air space is not proportional to its width (thickness), as would be the case with a slab of uniform solid material. Furthermore, the insulating value varies considerably with both mean temperature and temperature difference. For spaces more than about three-fourths inch wide the insulating value is practically constant, independent of the width. Narrower spaces have less insulating value, and below about one-half inch the insulating value is approximately proportional to the width. Under average conditions the conductance of the vertical air spaces commonly found in building walls is about 1 B. t. u. per hour, per square foot, and per temperature difference of 1° F. It will be seen later that this figure corresponds to an insulating value approximately equivalent to a one-third inch thickness of average insulating material.

IV. INSULATING MATERIALS

A thermal insulator is essentially a material having a large percentage of relatively small voids containing air. Little, if any, convection can take place within such a material, and the solid portions effectively screen off the radiation, so that the low conductivity of air is utilized to a much greater extent than in an air space. Since every known solid material has a greater thermal conductivity than air, it is evident that the conductivity of air fixes the lower limit of the conductivity of insulating materials containing air. By exhausting the air from an insulating material the conductivity can be materially reduced, and although this principle is made use of in certain types of thermos bottles and jars, it is impracticable on a large scale.

The application of the term thermal conductivity has thus far been restricted to uniform or homogeneous materials. Insulating materials are obviously not homogeneous in the microscopic sense, but in a practical sense they may be considered homogeneous, since their structure is fine-grained in comparison with the size of the specimens ordinarily dealt with. Bearing this in mind, we may use the terms thermal conductivity and insulating value in the same sense as they have been used in the case of homogeneous materials.

Investigation has shown that the differences in the respective thermal conductivities of the various light fibrous or cellular materials are not very great. The conductivities of most materials manufactured and sold primarily as insulators fall within the range 0.25 to 0.35 B. t. u. per hour, square foot, and temperature gradient of

1° F. per inch thickness. Of such insulators less than 1½ inches of the poorest material is equivalent in insulating value to 1 inch of the best. The better insulators approach fairly closely to the ideal limit, since the thermal conductivity of air is only slightly less than 0.2 B. t. u.

Commercial insulating materials can be divided into two general groups—(1) fibrous materials either in loose form or fabricated into soft flexible quilts confined between relatively thin layers of paper or textile and (2) more or less rigid boards in which the components are

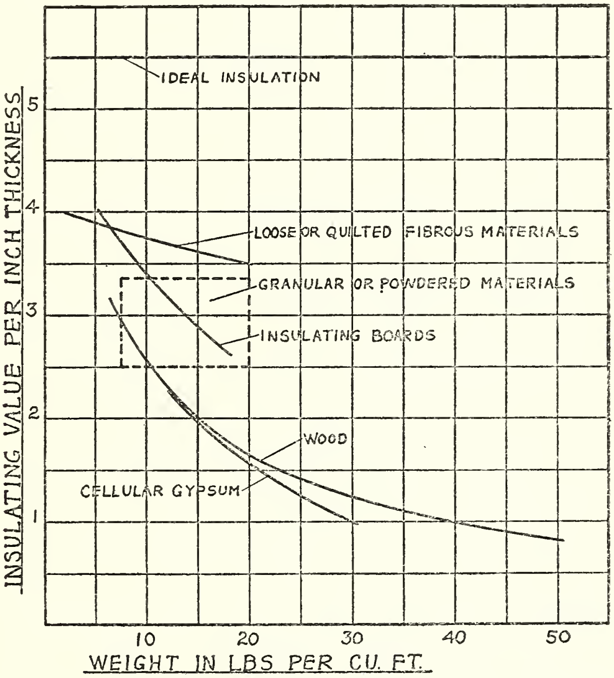

FIGURE 1.—*Relative insulating values of poor heat-conducting materials per inch thickness*

bonded together in some way. The differences in the respective insulating values of materials within each group are usually so small that the average purchaser can neglect them. In fact, the tabulation of these small differences often tends to obscure other far more important facts. In general, the lighter the material per unit total volume the better its insulating value per inch of thickness. Stiff fibrous insulating boards having considerable structural strength are somewhat poorer insulators than lighter and looser materials. Dense highly compressed wall boards made of wood or other organic fiber are not as good insulators as less compressed boards of the same general character. Heavy wall boards containing plaster in one form or another are relatively poor insulators, although they are very useful building materials, and like building paper, may be valuable in reducing infiltration of air through an otherwise porous wall.

Figure 1 is a chart showing in a general way the respective insulating values of a number of classes of poor heat-conducting materials. Insulating values, as previously defined, are plotted against the weight per unit volume of the material. The upper limit shown is the insulating value of a layer of still air 1 inch in thickness, and all other values are calculated on the basis of the same thickness. As discussed above the high insulating value of air alone can not be completely utilized in

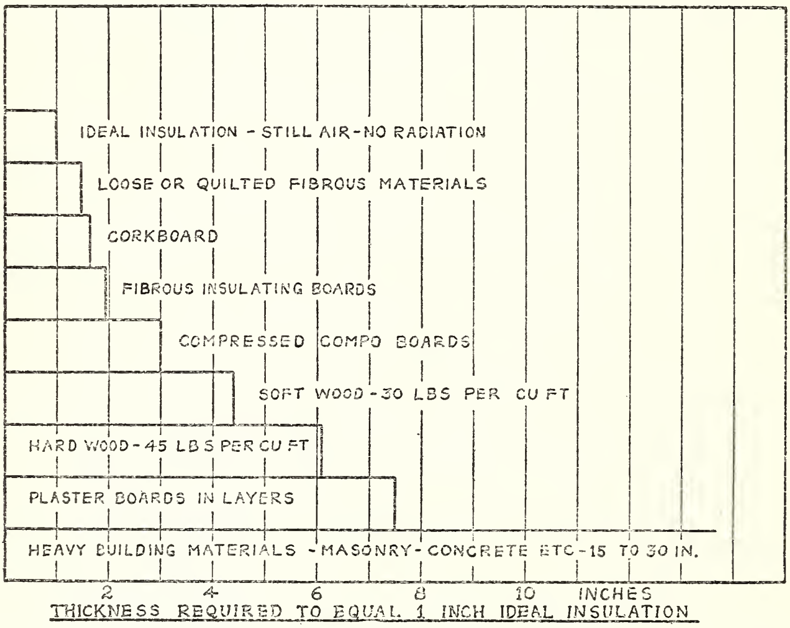

FIGURE 2.—*Thicknesses of various materials having equivalent heat-insulating values*

practice, but it represents the ideal case. It must not be supposed that the insulating values of all materials fall exactly on one or another of the lines shown in Figure 1. These lines are only approximate, but they give a general picture which is accurate enough for most purposes. One class of materials used to some extent for insulation—namely, loose powdered or granular materials, such as granulated cork, sawdust, charcoal, etc.—can not be represented by a single line in Figure 1. The insulating values of materials of this class fall within the area inclosed by the dotted lines shown in the figure.

In Figure 2 the data are presented from a somewhat different point of view where commercial materials have been divided into more restricted groups, taking into account average densities within each group. The horizontal scale gives approximately the thickness in inches required to furnish insulation equivalent to 1 inch of the best possible practical insulation, called ideal in the figure.

V. INSULATION OF BUILDINGS

From the point of view of insulation only, the most important question is the thickness of insulating material to be applied, rather than what material to select, provided the choice is restricted to the class of cellular or fibrous materials. No known material in a very thin layer can be expected to provide an appreciable amount of insulation. On the other hand, a relatively thick layer may not be economical, since relatively little additional gain is made over some layer of intermediate thickness. The selection of a material for a particular purpose must be governed largely by the requirements of that purpose in the way of structural strength, cost, fire hazard, etc. The real cost of an insulating material is obviously not the cost per square foot of commercial thickness but rather the cost per unit insulating value of the commercial thickness.

If a layer of insulating material is added to a wall, the insulating value of the wall will be increased by an amount equal to the insulating value of the layer of material added. The thicker the layer the greater will be the insulating value of the resulting wall. The percentage increase in the insulating value of the wall, however, will depend upon the original insulating value of the wall without insulation. The percentage increase in the insulating value of an actual wall containing windows will also obviously depend upon the amount of glass surface and the air leakage around windows and doors, since these factors are unaffected by the addition of insulating material.

A great many types of walls and roofs are to be found in present-day dwelling-house construction. The insulating value of one type or individual may be considerably different from that of another, but in an actual building heat losses through and around windows and doors tend to level out the effect of these differences in the properties of the walls themselves to such an extent that there are no wide variations in the amounts of fuel required to heat houses of various types of the same size in the same locality, unless air leakage around windows and doors or through very poorly constructed walls is excessive.

No particular description of insulation methods will be made in this circular, since all manufacturers furnish specifications describing the proper methods of applying their materials. With regard to roof insulation, however, it may be remarked that if the building has an attic or air space, insulation is best applied either on or in between the ceiling joists of the top story. This, of course, assumes that there is no necessity for keeping the attic warm in winter. If there is a necessity for doing this, the insulation must be applied to the roof itself.

An estimate of the probable savings in fuel resulting from insulating or weather stripping an ordinary dwelling house is given in Table 1. The first part of the table gives the fuel saving expressed in per cent of fuel which would have been required for a similar house without insulation or weather stripping. In the second part of the table the savings are expressed in per cent of fuel required for a house without insulation but with weather stripped windows. The calculations were based on data on heat transfer in building construction taken from the "Guide," published by the American Society of Heating and Ventilating Engineers. An average insulating material ($K=0.31$) is assumed, but no commercial fibrous or cellular insulating material departs far enough from this average value to make a significant difference in the approximate figures in Table 1. In taking into account the effect of windows and doors, it is assumed that the aggregate area of such openings is equal to one-fifth of the total side-wall surface, and that the heat loss through such openings is that corresponding to a 5-mile wind striking perpendicular to the wall. This corresponds roughly to average conditions over a large part of the country. Whenever insulation is involved, it is assumed that the insulation is applied to both walls and roof, and that the insulation is not substituted for some other member which is present in the uninsulated construction.

TABLE 1.—*Approximate fuel savings in dwelling houses*

[Expressed in percentage of fuel which would have been required for similar house without insulation or weather stripping]

	Saving
	Per cent
No insulation, weather stripped	15 to 20.
Same, with double (storm) windows	25 to 30.
½-inch insulation, not weather stripped	20 to 30.
½-inch insulation, weather stripped	About 40.
½-inch insulation, with double windows	About 50.
1-inch insulation, not weather stripped	30 to 40.
1-inch insulation, weather stripped	About 50.
1-inch insulation, with double windows	About 60.

[Expressed in percentage of fuel which would have been required for similar house without insulation, but with weather stripping]

	Per cent
With double windows, no insulation	10 to 15.
½-inch insulation only	25 to 35.
½-inch insulation, with double windows	40 to 45.
1-inch insulation only	35 to 45.
1-inch insulation with double windows	50 to 55.

The ranges in values correspond to the extremes in wall constructions usually encountered in average dwelling houses. As a general rule, ordinary walls of solid masonry are somewhat less effective in retarding heat loss than well-constructed frame or hollow tile walls. A somewhat greater percentage saving in fuel is therefore obtained by insulating a solid masonry wall than by applying the same insulation to a frame or hollow tile construction. Any house representing a considerable initial investment, particularly one with solid masonry walls, should be insulated, since the cost of insulation is a small proportion of the total, and the resulting additional comfort and fuel saving is considerable.

It should be borne in mind that any calculations dependent on experimental values of air leakage around windows are subject to great uncertainty on account of the variability of the factors involved. A well-built house without weather stripping may when new show less heat loss by air leakage than has been assumed in calculating the fuel savings given in Table 1. The gain resulting from weather stripping such a house would be correspondingly less. It should also be realized that infiltration of air is not necessarily disadvantageous, since a certain amount of ventilation is necessary. In the ordinary dwelling house air leakage is relied upon to furnish part of the ventilation, and it is unwise to attempt to prevent such leakage altogether. It does not appear, however, that ordinary weather stripping will reduce the air leakage to an excessively low value.

The calculations involving insulation are much more definite and certain than those involving air leakage. The application of insulation results in a certain absolute saving which is independent of heat loss through or around windows and doors. The per cent saving of fuel, however, is still dependent upon the heat loss through the uninsulated openings.

If a layer of material is placed in the middle of a wide air space, such as that between the studs in a frame wall, greater additional insulating value is obtained than if the material is placed in contact with the sheathing, or as a plaster base, as has been assumed in the calculation for Table 1. In the former case the insulating layer not only furnishes its own insulating value, but, in addition, divides the air space into two parts, each of which has about the same insulating value as the original air space. The addition of a ½-inch layer of insulation in the middle of the air space in a frame wall is therefore the equivalent of adding a little more than three-fourths inch at some other place in the wall. The process of subdivision of an air space, however, can not be carried too far, since the resultant spaces become narrow and are not so effective as insulators. The air space formed by the use of furring strips under plaster or stucco is nearly as effective as a wider air space, but narrower air spaces than this are less effective.

Aside from the saving in average fuel consumption and possible increase in comfort, the insulation of a house may allow a smaller initial investment for heating plant. In the extreme case of a structural wall of low insulating value the addition of insulation may also prevent possible condensation of moisture on the inside surfaces of the external walls. Such condensation is due to the fact that the temperature of the inside surface of a poor wall may fall below the dew point of the air in the room. Decreasing the heat transfer through the wall by the addition of insulation will increase the temperature of the inside surfaces, and thus tend to prevent condensation.

In summer, the effect of insulation is beneficial, but too much should not be expected in this respect. Increasing the total insulating value of a wall or roof will always tend to keep the building cooler during the hot part of the day, but many other factors in addition to the insulating value enter into the question in a rather complicated way. In general, thick masonry walls having large heat-storing capacities are better than relatively thin insulated walls. The insulation of roofs is probably much more effective than the insulation of walls, since the former have much greater exposure to the sun.

A great deal of misconception is prevalent regarding the use of paints as insulators. Since a paint film is relatively thin, it can offer but slight resistence to heat flow by conduction. The color of the external paint, however, has a considerable effect on the absorption of heat from the sun. Light-colored paints are more desirable, since they do not absorb as much solar heat as dark-colored paints. The reradiation of heat from the underside of a hot roof can also be reduced by coating the underside with paint containing metallic flakes in its composition, such as aluminum paint. The beneficial effects of proper painting are considerable if the roof has practically no insulating value in itself (for example, a tent), but if the roof itself has considerable insulating value the effects of painting are small.

VI. REFRIGERATOR OR COLD-STORAGE INSULATION

There is no essential difference between insulating against heat and insulating against "cold." A refrigerator is an inclosure maintained at a relatively low temperature, and it is desirable to reduce heat transfer from the outside to the inside. The same principles apply as in the case of house insulation, but the magnitudes are generally different. As a general rule, a refrigerator should be much better insulated than a house, both to save refrigeration (ice or electricity, etc.), as well as to produce a lower temperature on the inside.

While no extensive discussion of this variety of insulation will be entered into here, it may be remarked that an ordinary household refrigerator should have the equivalent of not less than 2 inches of insulation. If ice is used as the refrigerant, such a refrigerator, when operated properly, will maintain a low enough temperature for ordinary household purposes.

The question of the so-called "moisture resisting qualities" of insulating materials merits some mention at this point, since it is an important one in refrigerator or other cold storage insulation. Ordinarily it is of minor importance in house insulation. No tests have been made at the bureau to compare materials on the basis of their moisture-resisting qualities, since tests of this kind should be made on completed constructions rather than simply on the materials themselves.

To the best of our knowledge, no commercial insulating material is in any sense waterproof or moisture proof. If immersed in water or kept in air at 100 per cent humidity, one material may absorb water less rapidly than another, but this fact is of minor importance. All the materials in question are permeable to water vapor, and if the insulation is colder than the outside air and is not protected on the outside most of the water vapor which diffuses into the insulation from the outside will condense and accumulate, eventually producing a more or less saturated state and lowering the insulating value many times. In a completely saturated state there is undoubtedly very little difference between the respective thermal conductivities of various commercial materials. The only remedy for this state of affairs is adequate protection on the outside by means of airtight coatings, and, when possible, vents from the insulation to the inside should be provided. The latter allows the insulation to dry out, since the inside air is colder. As a general rule applying to insulated structures, air proof the warm side and ventilate the cold side to the colder air. In no case should the insulating materials themselves be relied upon to prevent water accumulation.

WASHINGTON, April 2, 1929.

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