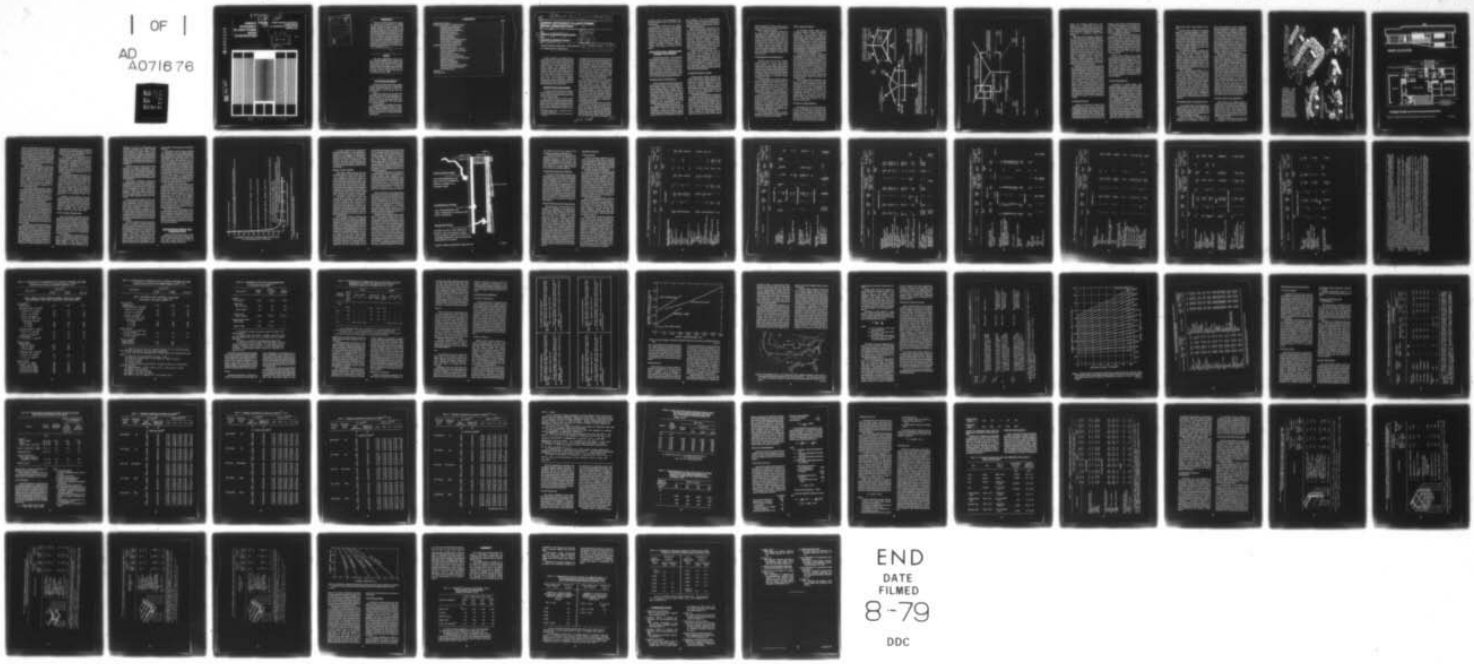
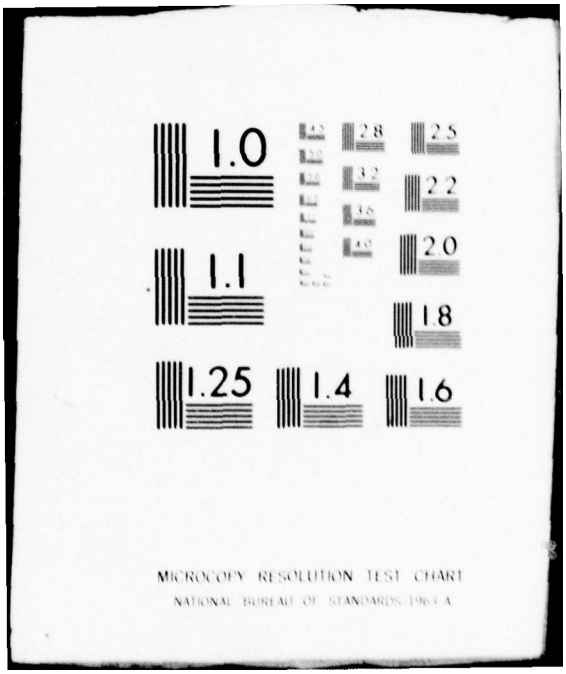
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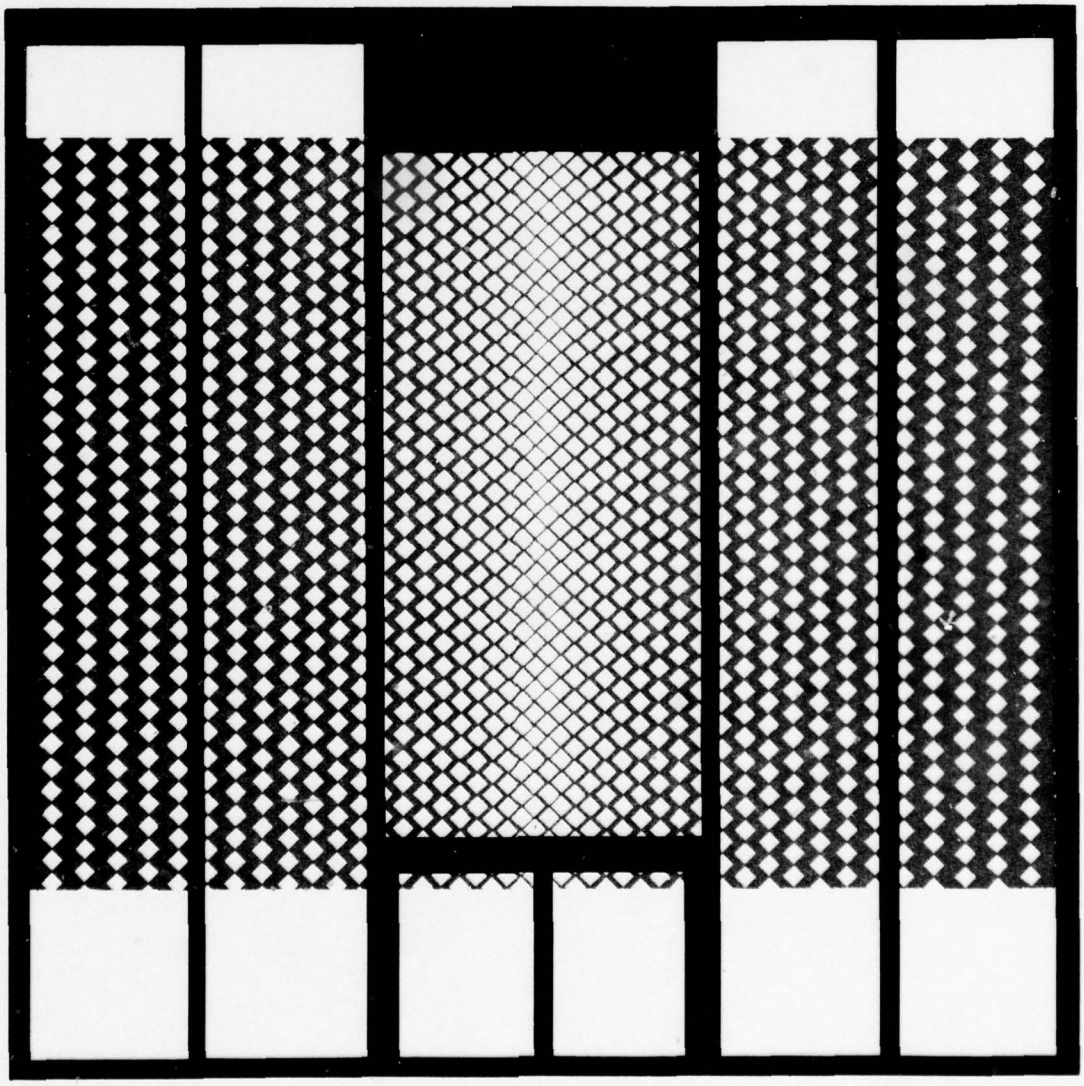
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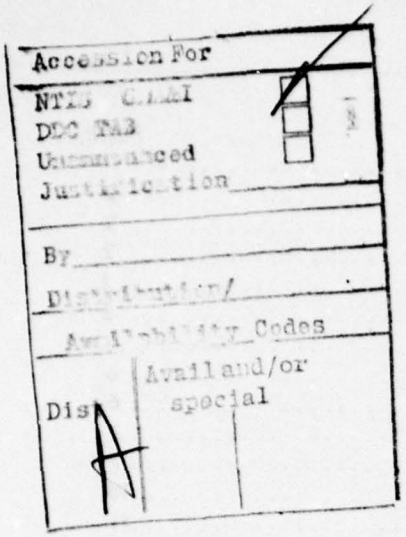
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ABSTRACT

This report presents information needed for design and construction of energy-efficient light-frame wood structures. The opening section discusses improving the thermal performance of a house by careful planning and design. A second section of the report provides technical information on the thermal properties of construction materials, and on the basic engineering design principles applicable to light-frame wood structures. Moisture condensation problems are discussed in relation to the effects of increased building insulation and more effective air leakage control.

NOTE

This paper replaces U.S. Forest Products Laboratory Report 1740, "Thermal insulation made of wood base materials—its application and use in houses" (L. V. Teasdale, 1949) and U.S. Forest Service Research Paper FPL 86, "Thermal insulation from wood for buildings: Effects of moisture and its control" (Wayne C. Lewis, 1968).

ACKNOWLEDGMENT

The following tables have been adapted with permission from the 1977 Fundamentals Volume, *ASHRAE Handbook & Product Directory:* tables 1, 2, 2A, 3, 4, 6, 6A, 11, 12, 13, 14, 15, 15A.

Drawings in figure 3 are reprinted with permission from *Solar Dwelling Design Concepts,* prepared by the AIA Research Corporation for the U.S. Department of Housing and Urban Development, May 1976 under Contract IAA H-5574.

Acknowledgment is made to the following for additional material adapted in certain tables: National Research Council of Canada; the 1977 Minimum Property Standards of the U.S. Department of Housing and Urban Development.

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ENERGY EFFICIENCY IN LIGHT-FRAME WOOD CONSTRUCTION.

By

(10) GERALD E. SHERWOOD, *Engineer*

and

GUNARD E. HANS, *Architect*

(11) 1979

(12) 62p.

Forest Products Laboratory,[1] *Forest Service*

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Recent changes in building code requirements and construction standards have made the poorly insulated house obsolete. Compared to past building practices, the modern house is more compactly planned, better insulated, and weatherstripped to minimize heat losses associated with air leakage. These steps toward energy conservation are relatively easy to accomplish in new construction, although there are practical limits to energy savings by insulation alone (*10*).[2] The interactions between climatic and occupancy factors must also be considered, as well as relationships between landscape design and construction.

OBJECTIVES AND SCOPE

This report provides information helpful for the design and construction of energy-efficient light-frame wood structures that are scaled to human needs.

The opening section of this report stresses the role of housing design and landscape planning in building energy efficient homes. Topics discussed include orientation of the home, placement and design of windows, general configuration of the house for minimal heat loss in winter, and architectural strategies for comfort through natural use of sun and shade. The role of landscaping is also discussed as a mode of natural energy conservation. Strategic placement of shading vegetation, and the use of plants or fencing to alter wind-flow patterns, can reduce heat loss in winter, or minimize need for air conditioning in the summer. In addition, human comfort is discussed as an important criterion in home construction.

The second major part of this report deals with engineering for energy efficiency. The section begins with a discussion of basic principles of heat transfer. Also discussed are performance characteristics of insulating materials, effect of alternative wall constructions on energy efficiency, calculations to determine the heat transmission of structures, and a discussion relating infiltration control and insulation to moisture condensation in the structure. Energy-efficient design is also related to current standards and building codes.

Undoubtedly, most houses will continue to be designed on the basis of code requirements or rules-of-thumb rather than a detailed engineering analysis. Nevertheless, discussion of the more detailed analytical design procedures underlying present code requirements can be useful. Such a discussion may assist the builder and designer in

[1] Maintained in Madison, Wis., in cooperation with the University of Wisconsin.

[2] Numbers in parentheses refer to literature cited at end of report.

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providing energy- and cost-efficient construction above the level of minimum code requirements.

One should realize that the overall energy efficiency of a house is also greatly influenced by the efficiency of its heating system and controls. Proper sizing of furnace or boiler, correct adjustments for the heat distribution system, and good burner maintenance are important. They can increase fuel conversion efficiency well above that encountered in most houses which have not received the needed attention in design or upkeep. Discussion of heating systems, however, falls beyond the scope of this paper.

ARCHITECTURAL DESIGN FOR ENERGY EFFICIENCY

"Architectural design" is not confined to appearance factors but is used here in its wider sense, as applicable to all design considerations. The term covers not only the arrangement of building masses, but also the relationships of a structure to its surroundings, the climate of the locale, and the sun. Human comfort requirements and occupancy patterns also influence design. These factors all affect the actual energy consumption in a home under occupied conditions.

Building Code Considerations

Minimum performance requirements for houses are defined by building codes. However, building codes can only partially influence energy usage in houses, because code requirements apply primarily only to construction specifications, and thus affect houses only under essentially unoccupied conditions. Occupant responsibilities such as ventilation and maintenance of heating equipment, which in well-insulated homes emerge as key considerations, have remained outside building code jurisdiction.

Thermal performance codes serve to reduce energy usage without sacrificing living standards. In some instances, code requirements compromise between performance desired and performance attainable using common and cost-effective construction methods. Thus the knowledgeable designer should use code requirements only as rules-of-thumb, recognizing that meeting code requirements is only the first step in energy efficient designs.

Many energy-saving improvements may be made in a home beyond meeting the minimum code requirements, and often at modest expense. Fuel costs are likely to continue rising more rapidly than the general inflation rate, making any investment in energy efficiency features attractive. However, some options may yield a higher return than others. When designers or builders seek new ways for increased energy efficiency, their decisions must be based on both construction costs and expected operating costs.

Energy efficient construction may appear costly, but seeming difficulties of amortizing it over a relatively short time period do not necessarily prove it to be a bad investment—such comparisons show only that our priorities in apportioning construction costs lie elsewhere. The amortization of a house is related to its mortgage life, and any reasonable energy efficiency measure should start paying handsome dividends well before the end of that period.

Integrated Systems Design

Current house design practices still reflect indifference to energy waste of past years, when low fuel costs permitted compensation for design deficiencies by brute force with oversized heating and cooling equipment. However, mechanical systems are operating at only part load conditions for most of the time. These systems must be correctly sized and maintained to assure their long-range efficiency.

Residential heating systems convert primary fuels to usable heat with an efficiency well below what is theoretically possible. For example, improved furnace design may result in far greater efficiencies than would improvements in construction quality. Discussion of mechanical systems falls outside the scope of this publication, but the designer must consider the relationships between heating system and home design. For instance, an outdoor air intake for the heating

plant that prevents the loss of warm room air up the chimney may be more cost-effective than many other improvements.

For increased operating efficiencies, the house and its heating plant must be designed as an integrated system. The ultimate objective is not to heat the house, but to warm its occupants. Moreover, choice of heating system involves much more than merely the output of the unit. Different types of systems—e.g., hot water, warm air, electric radiant panels—and different control systems can lead to different comfort conditions in homes of otherwise similar design, and with differing degrees of energy- and cost-efficiency.

Energy Balance Considerations

Effective use of energy from alternate sources—primarily the sun—can significantly reduce fuel usage. Performance-oriented building codes reward design which utilizes solar or other nondepletable sources. Seasonal solar benefits can be estimated accurately through computerized performance simulation. However, solar benefits can also be estimated based on simplified design methods (*1, 13, 16*)

The heat losses of a house are compensated by energy gains from three sources: (a) from the heating plant, (b) from the sun through windows, and (c) from appliances and occupants as waste heat (i.e., "internal gain"). (Heat gained from a fireplace or a wood-burning stove is included here under (c) because it assumes occupied conditions.)

To reduce fuel consumption, the heating system should operate at the lowest possible level consistent with the comfort of the occupants. Solar and internal heat gained during the day can permit cutbacks in the operation of the heating system, provided that the house design allows for a reasonable temperature distribution throughout occupied areas. South-facing windows can supply significant amounts of heat.

The energy balance design concept, therefore, considers the total magnitude and distribution of heat gains and losses.

Heat Losses and Gains

An estimated energy balance for a 24- x 48-foot reference house with southerly orientation, under conditions typical for Madison, Wis., is given in figure 1. Heat loss computations were based on construction quality suggested by "The Arkansas Story" (*11*). The window areas, however, have been allowed to remain at a 10 percent glass-to-floor area ratio typical of past design practices. Solar gain is estimated using data from National Bureau of Standards (NBS) publication BSS 96 (*4*), and internal gain schedules follow projections of NBS BSS 57 (*12*).

The 100 percent utilization of solar and internal gain assumed in figure 1 is obviously unattainable; a 67 percent level could represent a far more reasonable assumption. On the other hand, fuel usage is also likely to be lower at reduced thermostat settings, which are becoming increasingly common, than at the code-required 72° F temperature that serves as the basis for these calculations. Due to the wide range of possible variables in occupancy patterns, the estimates of potential solar and internal gain credits have also been allowed to stand at the 100 percent utilization level.

For the energy balance depicted in figure 1, the potential solar and internal gain credits can reduce the demand on the heating system to only one-third of the cumulative seasonal heat loss. Undoubtedly, the solar gain will vary greatly with different localities, and the internal gain level may be considerably reduced by choice of more energy-efficient household appliances. Nevertheless, these credits are often sufficient to make them important to more energy-efficient design.

Zoning for Energy Balance

Home planning to follow the daily path of the sun represents sound, energy-efficient zoning (fig. 2). Solar gain and internal gain sources (major household appliances) are separated to permit more even temperature distribution throughout the house during the periods when the heating plant is not operating. Internal gain sources are confined to

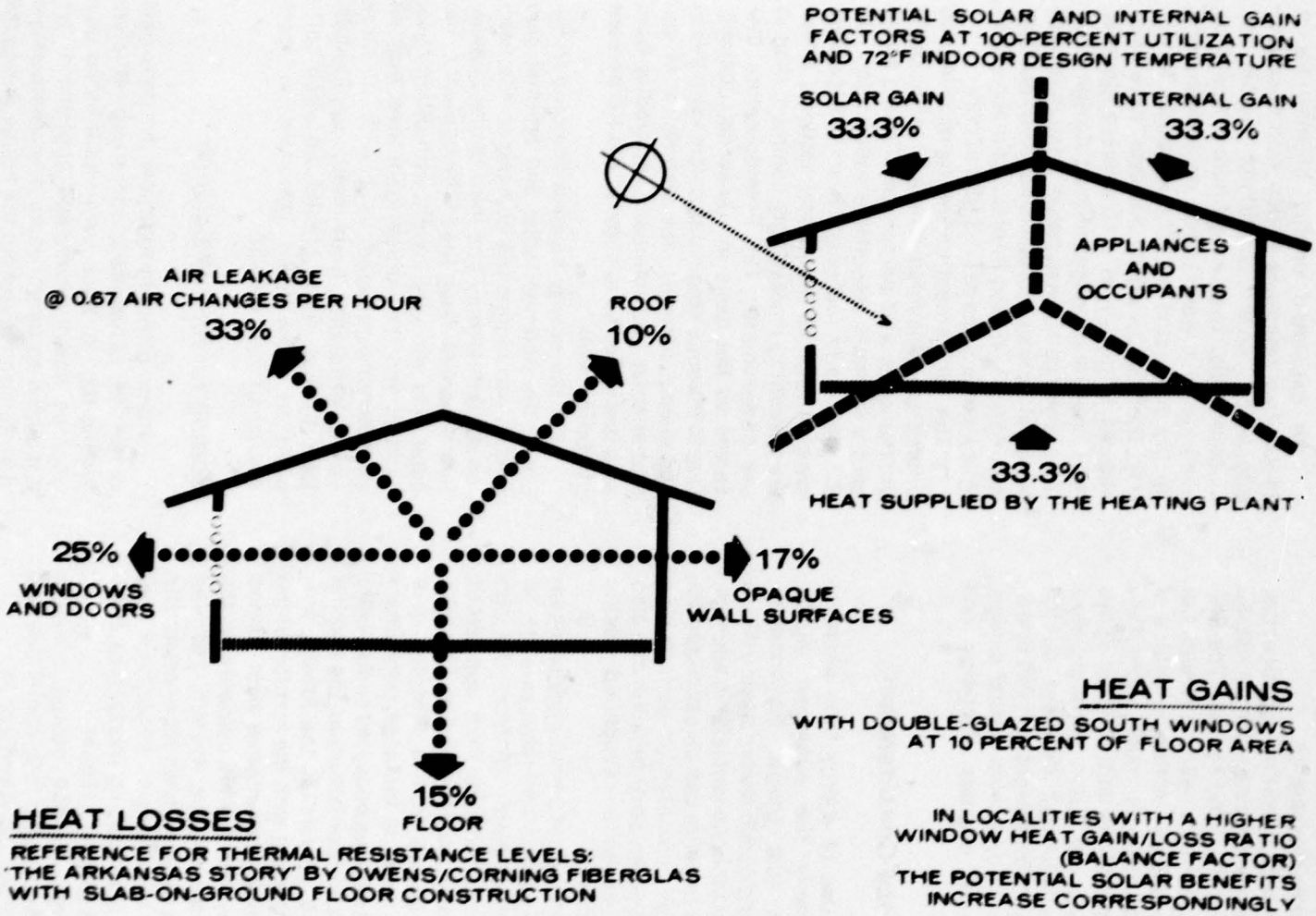


Figure 1.—Heating season energy balance for a 6 Btu/sq.ft.-degree day house at Madison, Wisconsin conditions.

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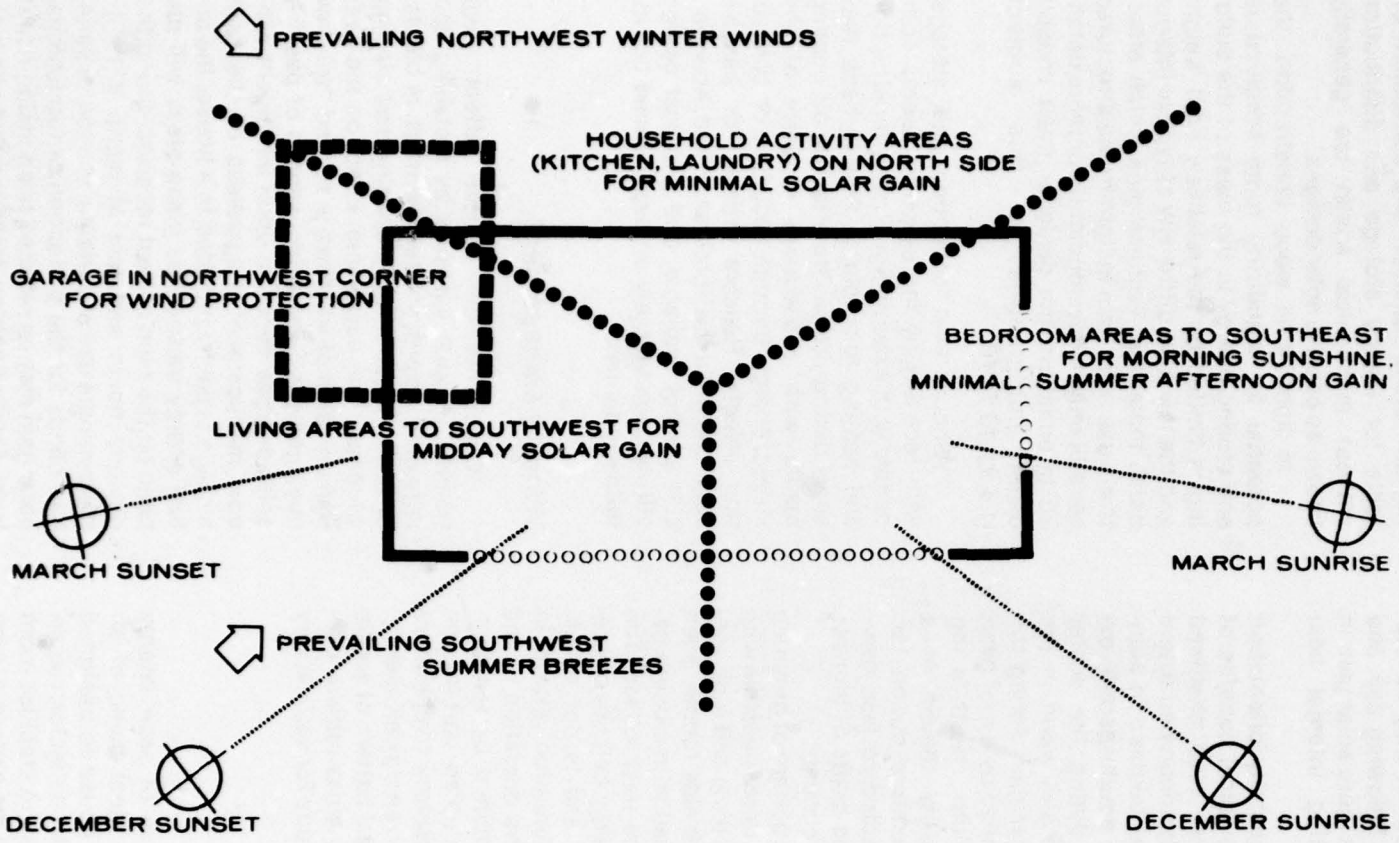


Figure 2.—Optimal home orientation for best use of internal and solar gain effects in northern latitudes.

(M 146 362)

rooms with northerly exposure for two reasons: (a) if south-facing rooms stay cooler during the night hours, they can absorb more solar heat the following day, and (b) occupants will tolerate more solar gain in rooms with no competing internal heat sources.

Bedrooms with an easterly orientation not only offer the psychological benefits of morning sunshine but are also sheltered from the sun during the afternoon hours, and therefore remain cooler at bedtime in summer. Living areas with a southwesterly exposure gain solar heat during the winter afternoon hours, and are still warm in the evening, while the summer gain during the same hours can be controlled by a roof overhang of appropriate width. North-facing areas of household activity remain at a relatively constant temperature during the entire day, and are subjected to less overheating during the daytime hours of highest activity in both winter and summer.

Departures from this pattern of orienting the living areas to the south are possible with sophisticated heating systems and high windows or skylights in north side rooms. Such openings must be provided with closure devices to control nighttime heat losses. The concept of zoning for energy balance, therefore, is entirely flexible, and is not necessarily limited to the orientation shown in figure 2. Nevertheless, the operation of the heating system is determined by temperatures in the coldest occupied part of the house, and thus a satisfactory temperature distribution is essential to energy efficiency. Deviations from the general pattern of southerly orientation for living areas require considerably more careful study for satisfactory results.

Utilizing Solar Gain

Design for direct gain of solar energy through windows is the most basic of all solar design concepts. A house so designed is essentially a lived-in solar collector, requiring adequate thermal mass to stabilize room temperatures and to store the excess energy received during periods of high solar gain. This thermal mass may be in the form of masonry interior walls, a concrete floor slab, or similar ceiling construction. Designs relying on natural radiation and convection effects for energy storage and distribution without mechanical assist are generally known as passive solar designs.

In light-frame wood construction, the potential for stabilizing room temperature and storing energy in the mass of the building is limited by the relatively light weight and the low heat diffusivity of typical interior finish materials. Technologies which effectively use solar gain in light-frame structures are still only in development. For more detailed information, the designer must consult other publications on this subject (*1,4,8,9,13,14,16*).

Window heat collection and storage, with recovery by fan systems, seems compatible with existing light-frame construction and heating technology. Pebble beds may serve during the day as effective air cooling media with subsequent recovery of the stored energy through radiation or convection effects. Reliable criteria for passive solar design in the light-frame field, however, still are not available, and practical design still is based largely on experienced but intuitive judgment.

Window Management

Occupants of houses affect heat transfer through windows by installing and adjusting drapes, shades, awnings, or blinds, or even by periodically opening and closing windows. The occupants' effect on the heat transmission of windows is termed "window management." The effectiveness of passive solar designs depends upon intelligent window management. Regardless of the heat storage capacity provided in a house, the actual energy balance for glass areas will depend on the ratio of heat received during the daytime hours and lost at night. With indiscriminate use of curtains, shades, or venetian blinds for the protection of furnishings, solar gain may be reduced to an insignificant level. Freely hanging draperies that allow air circulation across the face of the glass at night are far less effective as insulating

devices than tightly fitting shades or shutters.

Venetian blinds prevent the damaging effects of ultraviolet radiation on delicate fabrics by effectively deflecting sunlight to the ceiling. From there the scattered light can be absorbed in other surfaces. Where protection of furnishings is less important, sheer curtains may control glare, scattering sunlight for more diffuse illumination and more even energy absorption in room surfaces. With sheer curtains, reflection back through the glass is reduced.

For protection against unwanted summer sunlight, exterior shading devices are more effective than interior devices. However, solar energy is received through windows in forms other than direct or beam radiation. Depending on sky and ground conditions, substantial quantities of energy may also be received as diffuse radiation, scattered by moisture and dust in the air, or as reflected radiation received from the ground and adjacent houses.

Roof overhangs are effective only in controlling direct radiation through south windows. Windows at any other orientation require other means of shading. Deciduous trees provide shade in the summer with minimal loss of the desired winter sunlight. Broad-leaved ground cover is more effective in scattering ground reflections than a smooth lawn. The surrounding vegetation also helps to reduce summer air temperatures by evaporative cooling. For sun control, landscape design becomes an integral part of the overall design task. Advantageous positioning of trees can lead to significant improvements in the thermal performance of a house.

Windbreaks and Air Leakage Control

Use of plant material for windbreaks is a familiar concept in the prairie States. More recent studies have helped to quantify the relationships between fuel usage and wind protection, demonstrating the importance of effective air leakage control (6).

The positioning of windbreaks, such as plantings and fences, is important for creating the most desirable wind-flow patterns. Where snowfall is heavy, improperly located windbreaks can lead to undesirable drift accumulations. A pocket of calm air on the leeward side of a windbreak is known as a wind shadow. Design for wind shadow effects can lead to more effective use of outdoor living areas in mild but windy climates. A continuous enclosure on the downwind side, on the other hand, can result in a cold air trap (fig. 3). Where site conditions do not lend themselves to external wind protection, the house design must provide internal protection. For example, air-lock vestibules for entrance doors are an essential energy-efficiency feature in northern climates.

Wind control and solar design concepts are integrated in the three-bedroom ranch house plan of figure 4. This reference house design was developed as a demonstration project for a new construction system, rather than as an example in energy-efficient planning. Nevertheless, all of the previously discussed wind control concepts are clearly evident. The house is positioned on a gentle south-facing slope in rolling Wisconsin farmland, with no external protection to the northwest. The number of north- and west-facing windows is minimized. The house benefits from maximum exposure to winter sun through its 20 degree south-southwest orientation, facing the sun with the longer diagonal of the plan rather than with the shorter front wall, for added solar gain in the bedrooms. The projection of the garage both protects living room windows against late afternoon sun and casts a wind shadow for the outdoor deck. Enclosed spaces at both entrances function as air-lock vestibules.

Human Comfort Considerations

With effective air leakage control, a house may be ventilated only as needed for human comfort. The fresh air requirements in homes have not been conclusively defined. Need for odor control, which varies greatly with the living habits of the occupants, appears to be a more significant factor than depletion of the oxygen supply or accumulation of carbon dioxide.

Problems of moisture control are often misunderstood. The moisture balance in a

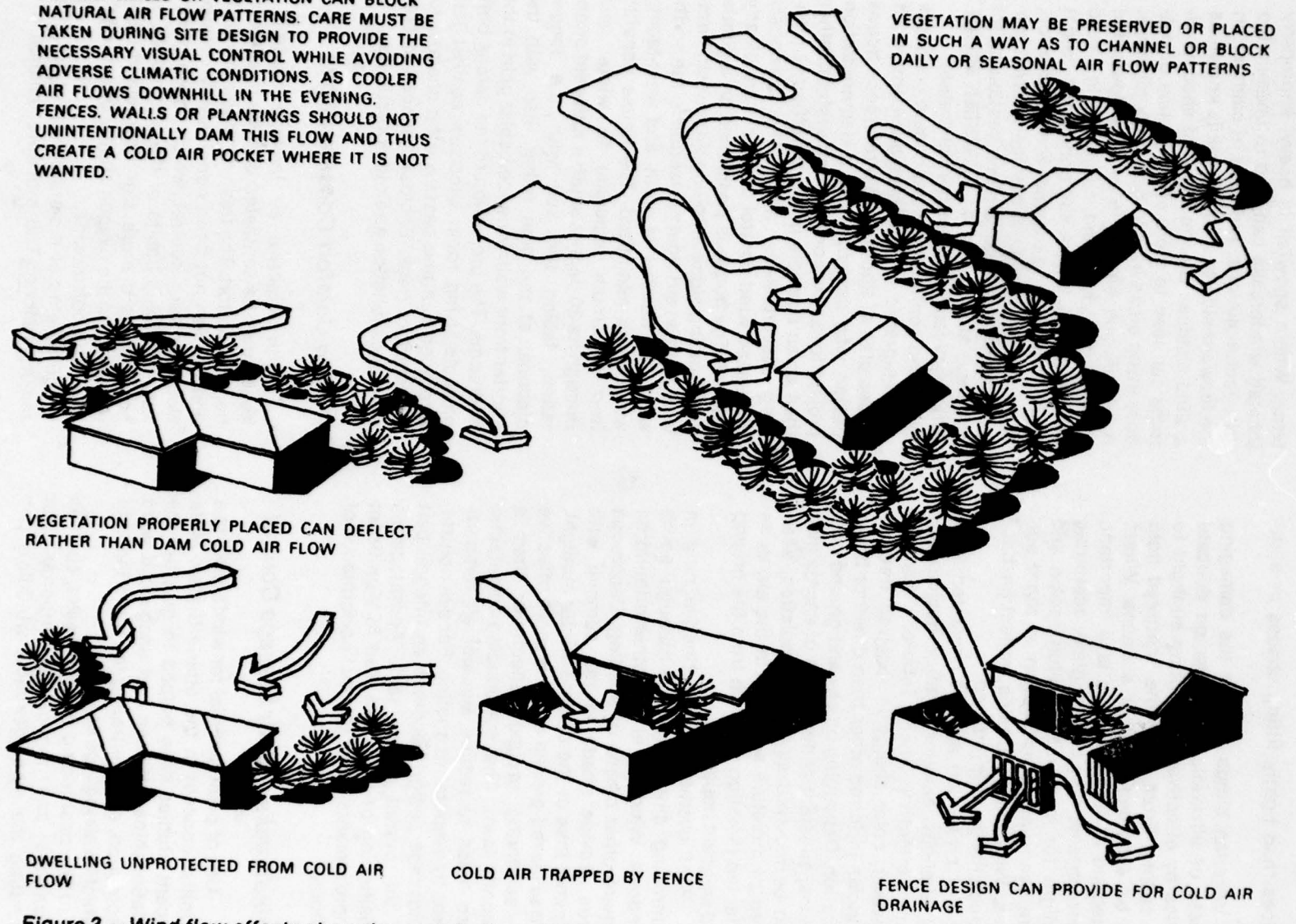
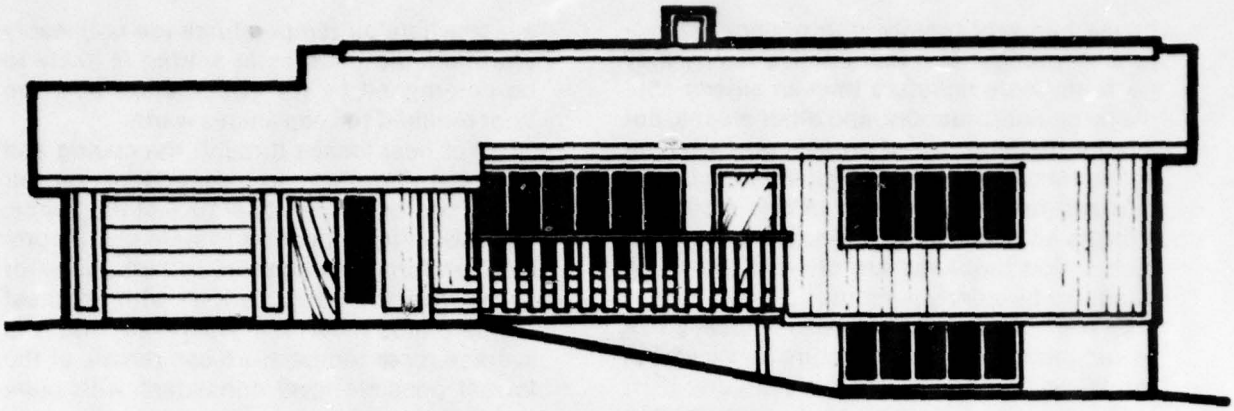
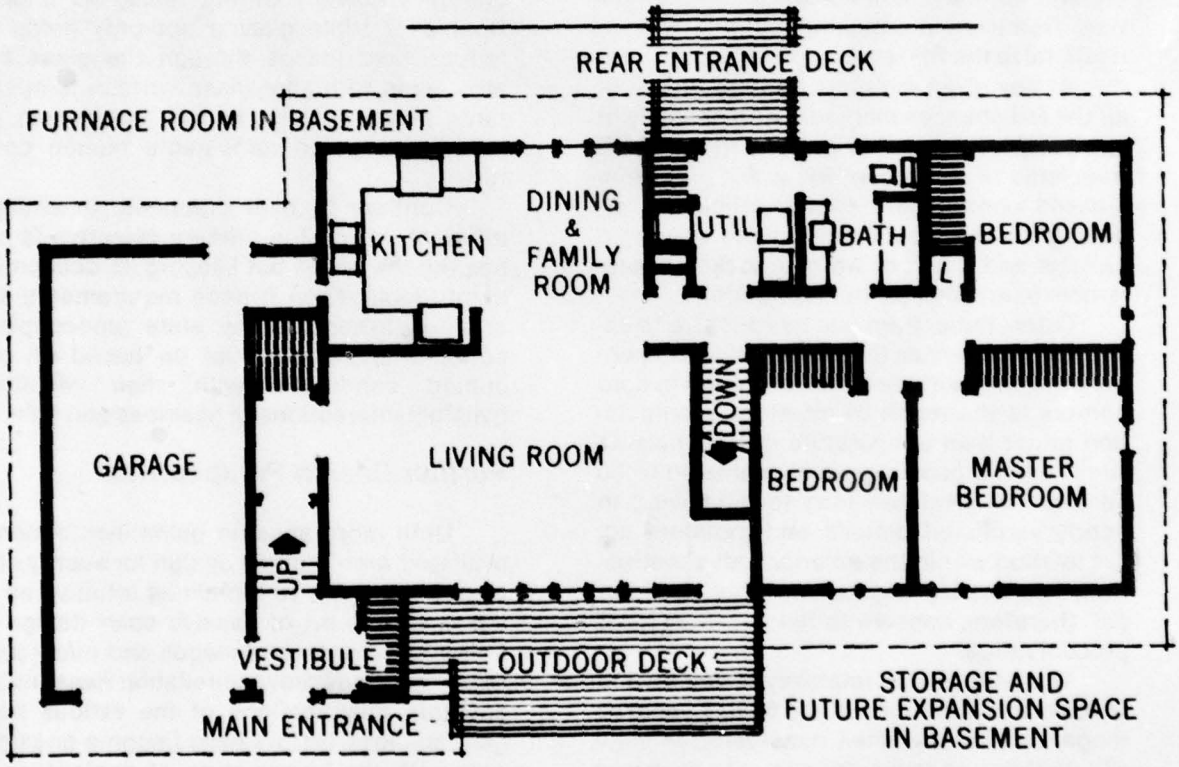


Figure 3.—Wind flow effects show the contribution of landscaping to home energy efficiency. (By courtesy of AIA Research Corp.)
(M 146 365)



FRONT ELEVATION



FLOOR PLAN

Figure 4.—Design for one type of energy-efficient, light-frame house. (M 146 366-1)

house can vary greatly with occupancy factors. A younger and more active family may generate more moisture than an elderly couple by cooking, laundry, and other means, but a more frequent use of outside doors by the active family results in a higher air exchange rate and faster dissipation of this moisture. Houses with the most serious moisture accumulation problems are often found to be occupied by elderly persons.

The human body is relatively insensitive to variations in indoor moisture levels within the 30 to 60 percent relative humidity (RH) range. Lower levels lead to dryness of skin and nasal membranes; higher levels retard normal evaporation of body moisture. Within the RH range of 30 to 60 percent, the sensation of added warmth associated with the higher moisture levels is not significant enough to warrant mechanical humidification. Reducing thermostat settings will, of itself, raise the RH level.

At any given moisture content of indoor air the RH changes markedly with changes in room temperature. A 30 percent RH at 72° F translates to 35 percent RH at 65° F. For increased comfort and energy efficiency, reducing the thermostat setting and wearing a sweater and a pair of warmer socks are preferable to mechanical humidification.

Often, houses are just as sensitive to excessive moisture as the human body. Darkening of ceiling surface at nails or walls in cold corners is the result of moisture accumulation rather than temperature differentials as such. Even a seemingly reasonable 40 to 50 percent RH level can lead to mildewing in poorly ventilated closets and moisture accumulation within the exterior wall construction. The heating season moisture level target, therefore, appears to fall in the 30 to 40 percent range.

The body is also relatively insensitive to temperature variations in the 68 to 72 degree range, particularly when considered in view of our ability to make adjustments by minor changes in clothing. With typical residential heating systems, temperatures near the floor are always lower than those at shoulder level, but such differences are often inconsequential. Nevertheless, the overall sensation of comfort is determined primarily by the skin temperature of body extremities. Thus, in a space where air temperatures are noticeably stratified, the thermostat setting is likely to be determined by the temperature near the floor required to keep ankles warm.

Yet heat losses through the ceiling and by air infiltration are dependent on air temperatures in the upper part of the space. Consequently, a heating system should provide uniform temperature distribution—or even inverse stratification with highest temperatures near the floor—so that the average room temperature can remain at the lowest possible level consistent with comfort requirements.

The body loses heat not only by air convection but also by radiation to windows and other cold surfaces. Higher air temperatures compensate for such radiation losses, but only at a corresponding compromise in the energy efficiency of the house as a unit. Double or triple glazing not only helps to reduce heat losses through the glass but also leads to higher glass surface temperatures which, in turn, permit lower room air temperatures for comparable human comfort.

Contrary to past practices, in energy-efficient design the primary objective is not heating the house but keeping its occupants comfortable. Even if code requirements are oriented toward steady state (unoccupied) conditions, design must be based on occupied conditions with their resulting dynamic interactions of heat loss and gain.

Further Design Perspectives

Until more specific guidelines become available, architectural design for energy efficiency may have to remain as intuitive as in the past. The art of passive solar design is still in developmental stages and many past references may prove unreliable. Reasonably accurate qualifications of the various heat gain and loss factors have become possible only with the introduction of computerized analytical models.

The development of solar heating systems—i.e., active solar technology—should lead to considerable reduction in domestic energy usage in future years. To permit future addition of solar equipment, the heating systems of all new houses should be

designed for the air temperatures and velocities associated with solar designs. Solar energy will always remain a low-intensity source and thus will require effective conservation to become a practical alternative. Therefore, design recommendations are based on high levels of insulation and on effective use of passive solar benefits as a prerequisite for cost-effective active solar installations.

Added insulation, however, has a limited potential for energy conservation. Heat losses through the building envelope are proportional to the indoor-outdoor temperature differential and are inversely proportional to insulating value (thermal resistance). These relationships are indicated by the asymptotic curve of figure 5.

Heat loss by conduction through the building envelope is a function of the thermal transmittance of a construction assembly, U, indicated on the vertical axis. The reciprocal of U, the resistance R, is shown on the horizontal axis. Within the range of values applicable to light-frame wood construction, the curve flattens rapidly in both directions from the chosen reference point at a U-value of 0.10.

Along the vertical portion of the curve, which is applicable to windows and uninsulated assemblies, adding insulating materials even in minimal thicknesses reduces heat losses significantly. Along the horizontal portion, however, the gains in efficiency with added insulation decrease markedly. While design optimization also requires consideration of economic factors (the cost of fuel and building materials), the physical relationships indicated by this curve remain unchanged.

The heat loss distribution pattern shown in figure 1 is based on thermal resistance values of R-20 for walls and R-40 for the ceiling/roof assembly. Construction using one 6-inch glass fiber blanket in the walls and two such blankets in the ceiling exceeds these ratings. Nevertheless, these points are already so low on the curve that a small difference in assumed R-values results in only minor variations in the computed heat loss. Beyond these points, improvement in the thermal properties of the assemblies with added insulation alone becomes increasingly difficult.

Introduction of new building materials will undoubtedly offer new design possibilities, particularly for collection and storage of solar energy gained through windows. New developments to control heat loss, on the other hand, seem less promising. The potential for significant further improvements in the energy efficiency of homes by more insulation alone, therefore, is relatively limited. While rising energy costs may make increased quantities of insulation more cost effective, their thermal effectiveness will not grow correspondingly. And, more than one-third of the total heat losses in a well-insulated house may be caused by air leakage effects, so that the magnitude of the heat loss component that could be affected by added insulation also keeps getting smaller.

The houses of the future may be considerably different from those of the past. Attached and clustered housing types may gain popularity because of reduced exterior wall surface area. Detached homes may make greater use of ground effects, not only as below-grade floors or earth berms against outside walls, but also as roof covering. Wood foundations (7) permit such construction with light-frame wood technology. Although relatively little is still known about the thermal properties of wood systems in ground contact, they do represent a readily available design alternative.

The solution to the challenge of more energy-efficient house design obviously lies in more imaginative approaches to this complex problem than in the past. More efficient design will also require more careful engineering, rather than just selection and specification of materials on the basis of outdated rule-of-thumb methods.

ENGINEERING DESIGN AND CONSTRUCTION

Design of a home, its orientation, and its site and landscaping all affect its energy efficiency; however, construction decisions will also make a great difference in fuel requirements for heating and cooling.

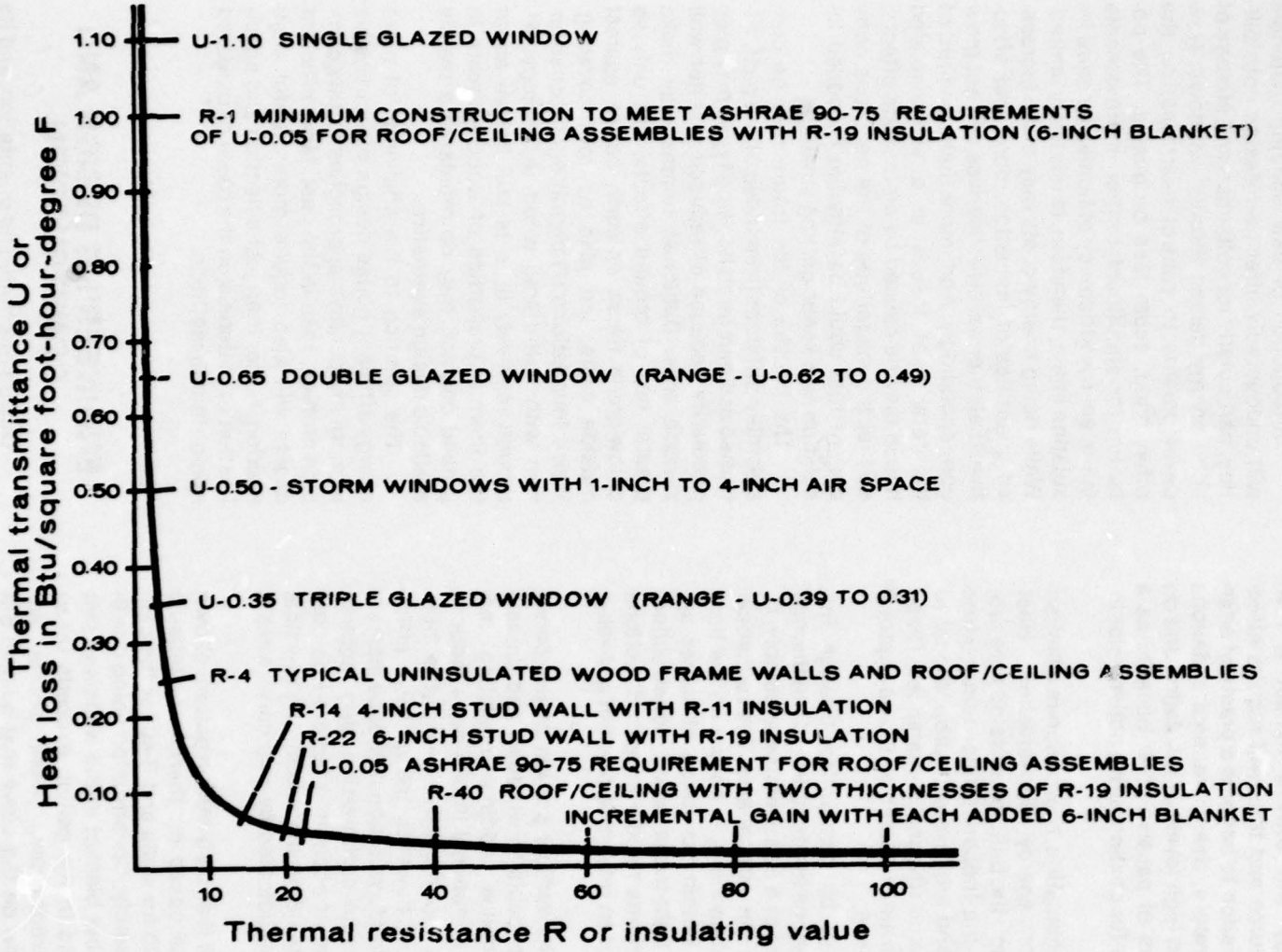


Figure 5.—Plot of thermal transmittance (*U*) against thermal resistance (*R*); at U values below 0.10, increases in efficiency become increasingly expensive.

(M 146 364)

To select materials and construction electives intelligently, it is advantageous to understand the mechanics of heat transfer. Without such knowledge, it is impossible to determine relative efficiencies of different materials and types of construction. This section of the report will also discuss effectiveness of various insulation materials, and will discuss alternative constructions for low heat transfer.

Modes of Heat Transfer

Heat seeks to attain a balance with surrounding conditions, just as water will flow from a higher to a lower level. When occupied buildings are heated to maintain inside temperature in the comfort range, a difference in temperature exists between inside and outside. Heat will therefore be transferred through walls, floors, ceilings, windows, and doors at a rate related to the temperature difference and to the resistance to heat flow of intervening materials. The transfer of heat takes place by one or more of three methods—conduction, convection, and radiation.

Conduction is the mode of heat flow through solid materials; for example, the conduction of heat along a metal rod when one end is heated in a fire. Convection involves transfer of heat by air currents; for example, air moving across a hot radiator carries heat to other parts of the room or space. Heat also may be transmitted from a warm body to a cold body by radiation. Heat obtained directly from a heat source, such as a fire, is radiant heat.

Heat transfer through a structural assembly composed of a variety of materials may be by one or more of the three methods described. Consider a frame house with an exterior wall composed of gypsum lath and plaster, 2- by 4-inch studs, sheathing, sheathing paper, and bevel siding (fig. 6). In such a house, heat is transferred from the room atmosphere to the plaster by radiation, conduction, and convection, and through the lath and plaster by conduction. Heat transfer across the uninsulated stud space is mainly by radiation and convection. By radiation, it moves from the back of the gypsum lath to the colder sheathing; by convection, the air warmed by the lath moves upward on the warm side of the stud space, and that cooled by the sheathing moves downward on the cold side. Heat transfer through sheathing, sheathing paper, and siding is by conduction. Some small air spaces will be found back of the siding, and the heat transfer across these spaces is principally by radiation. Through the studs from gypsum lath to sheathing, heat is transferred by conduction and from the outer surface of the wall to the atmosphere, it is transferred mainly by convection and radiation.

The thermal conductivity of a material is inversely proportional to the insulating value of that material. Heat conductivity in a homogeneous material is customarily measured as the amount of heat (in British thermal units) that will flow in 1 hour through a layer of the material which is 1 foot square and 1 inch thick, where the faces of the layer have a temperature difference of 1° F. Heat conductivity is usually expressed by the symbol *k*.

Where a material is not homogeneous in structure, such as one containing air spaces like hollow tile, the term *conductance* is used instead of conductivity. The conductance, usually designated by the symbol *C*, is the amount of heat (in Btu's) that will flow in 1 hour through 1 square foot of the material or combination of materials per 1° F temperature difference between surfaces of the material. (A dead air space with or without a reflective surface may also be rated for conductance by the same method.)

Resistivity and resistance (direct measures of the insulating value) are the reciprocals of transmission (conductivity or conductance) and are represented by the symbol *R*. Resistivity, which is unit resistance, is the reciprocal of *k* and is given the same symbol *R* as resistance in the technical literature because resistances are added together to calculate the total for any construction. This is the same *R* commonly used to rate commercial insulation. The overall coefficient of heat transmission through a wall or similar unit air to air, including surface resistances, is represented by the symbol *U*. *U* defines the transmittance in Btu's per hour, per square foot, per 1° F temperature differential. Thus, the total equivalent resistance of a construc-

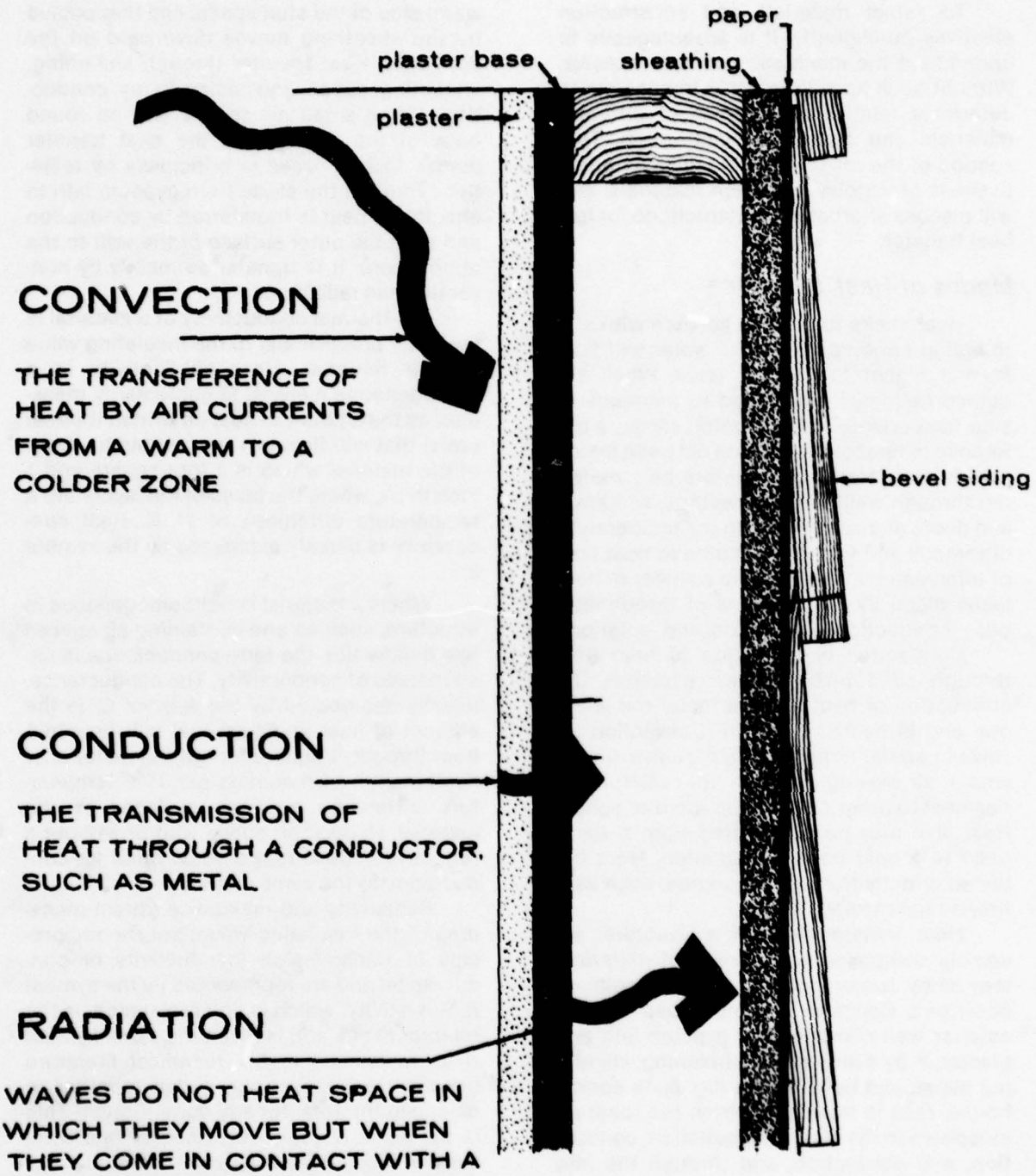


Figure 6.—Modes of heat transfer in light-frame wall. (M 139 201)

tion section is the $R = \frac{1}{U}$, where air film values are expressed as equivalent *R*'s.

Figure 5 illustrates the relationship between *R* and *U*. As *R* is increased, the incremental reduction in rate of heat loss becomes progressively less. Common construction components are identified on the curve. Note that at R = 10, the slope of the curve begins to change rapidly. Beyond R = 20, the curve becomes nearly flat.

Thermal Performance of Material

The rate of heat transfer through a material depends on the material composition, its density, and factors such as the material's mean temperature and moisture content. Another important aspect of a material's thermal performance is capacitance, or its ability to store heat. This depends largely on the mass of the material. The overall rate of heat transfer through a combination of materials is further affected by surface conditions such as roughness, color, and reflectivity, as variations in these properties will lead to variations in the component of the total heat loss by convection, conduction, and radiation.

Thermal Resistance and Capacitance

Materials used for construction and insulation of buildings can be divided into several types depending on characteristics which have a major influence on their thermal properties. Fibrous materials are in the form of loose fill, blankets, or batts specifically for use as thermal insulation. Foams are available in rigid sheets, loose beads, or for forming in place. Materials of construction include wood, metal, glass, and various panel products. Masonry materials are considered in a separate category because of their weight and consequent special heat capacitance characteristics. Soil is not generally considered as a construction material, but it does contribute to insulation of buildings, especially where basements are used. Heat transmission coefficients (*3*) for building and insulating materials are presented in table 1. Transmission coefficients for door and glass areas are shown in tables 2 and 3.

Building Insulation

Fibrous Materials

Fibrous insulating materials are commonly rock wool, glass fiber, or cellulose. These materials are often further classified in two categories: (1) vegetable fiber, such as wood fiber, is made from plants; (2) mineral fiber is derived from nonorganic materials, and includes rock wool and glass fiber.

Fibrous materials are available in the forms of blanket, batt, and loose fill. Blankets and batts are generally in a specific thickness and have a higher resistance to heat transfer than the same material as loose fill. Batts are semirigid, purchased flat, and may be installed in structural spaces with a friction fit which holds them in place. Blankets are quite flexible, and are purchased in rolls. Loose fill is available in bags for pouring, as into an attic by the homeowner, or it may be blown into structural cavities by commercial crews. The quality of application affects the resulting density and thus the thermal resistance of the end product.

A maximum resistance value for fibrous insulations is obtained when the fibers are spaced uniformly and are perpendicular to the direction of heat flow. The fiber diameter also affects the insulation value; smaller fiber diameters at the same density have higher resistance values. The type and amount of binder, which influences the bond or contact of the fibers, may also affect the thermal conductivity.

Density affects the thermal resistance of all materials, but fibrous insulating materials are especially influenced by density because they can usually be compressed or expanded at the time of construction. The resistance to heat flow depends mainly on air trapped in and between the fibers. As the insulation is compressed, more fibrous materials are required to achieve the same thickness; the compression creates more air spaces and thus more resistance to heat flow. However, at some density part of the air spaces close and the fibrous material begins to lose insulating value. The optimum density varies with the fiber diameter, and in place is achieved when the insulation can support its own weight without settling.

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
BUILDING BOARD[3/]								
Boards, Panels, Subflooring, Sheathing, Woodboard Panel Products								
Asbestos-cement board	120	4.0	--	0.25	--	0.24	1.73	
0.125 in.	120	--	33.00	--	0.03			0.005
0.25 in.	120	--	16.50	--	.06			.01
Gypsum or plaster board								
0.375 in.	50	--	3.10	--	.32	.26		.06
0.5 in.	50	--	2.22	--	.45			.08
0.625 in.	50	--	1.78	--	.56			.10
Plywood, Douglas Fir	34	.80	--	1.25	--	.29	8.66	
0.25 in.	34	--	3.20	--	.31			.05
0.375 in.	34	--	2.13	--	.47			.08
0.5 in.	34	--	1.60	--	.62			.11
0.625 in.	34	--	1.29	--	.77			.19
Plywood or wood panels 0.75 in.	34	--	1.07	--	.93	.29		.16
Vegetable Fiber Board								
Sheathing								
Regular density								
0.5 in.	18	--	.76	--	1.32	.31		.23
0.78125 in.	18	--	.49	--	2.06			.36
Intermediate density, 0.5 in.	22	--	.82	--	1.22	.31		.21
Nail-base, 0.5 in.	25	--	.88	--	1.14	.31		.20
Shingle backer								
0.375 in.	18	--	1.06	--	.94	.31		.17
0.3125 in.	18	--	1.28	--	.78			.14
Sound deadening board, 0.5 in.	15	--	.74	--	1.35	.30		.24
Tile and lay-in panels, plain or acoustic	18	.40	--	2.50	--	.14	17.33	
0.5 in.	18	--	.80	--	1.25			.22
0.75 in.	18	--	.53	--	1.89			.33
Laminated paperboard	30	.50	--	2.00	--	.33	13.86	
Homogeneous board from repulped paper	30	.50	--	2.00	--	.28	13.86	
Hardboard								
Medium density	50	.73	--	1.37	--	.31	9.49	
High density								
Service tempered, service underlay	55	.82	--	1.22	--	.32	8.46	
Standard tempered	63	1.00	--	1.00	--	.32	6.93	

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]--con.

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
BUILDING BOARD[3/]--con.								
Particleboard								
Low density	37	0.54	--	1.85	--	0.31	12.82	
Medium density	50	.94	--	1.06	--	.31	7.35	
High density	62.5	1.18	--	.85	--	.31	5.89	
Underlyment, 0.625 in.	40	--	1.22	--	.82	.29		0.14
Wood subfloor, 0.75		--	1.06	--	.94	.33		.17
BUILDING MEMBRANE								
Vapor								
Permeable felt	--	--	16.70	--	.06			.01
Seal								
Two layers of mopped 15-lb felt	--	--	8.35	--	.12			.02
Plastic film	--	--	--	--	Negl.			
FINISH FLOORING MATERIALS								
Carpet and fibrous pad	--	--	.48	--	2.08	.34		.37
Carpet and rubber pad	--	--	.81	--	1.23	.33		.22
Cork tile, 0.125 in.	--	--	3.60	--	.28	.48		.05
Terrazzo, 1 in.	--	--	12.50	--	.08	.19		.01
Tile								
Asphalt, linoleum, vinyl, rubber	--	--	20.00	--	.05	.30		.01
Vinyl asbestos						.24		
Ceramic						.19		
Wood, hardwood finish, 0.75 in.			1.47		.68			.12
INSULATING MATERIALS								
Blanket and Batt								
Mineral fiber, fibrous form, processed from rock, slag, or glass								
Approximately[4/] 2 to 2.75 in.	.3-2.0	--	.143	--	[5/]7	.17-0.23		1.23
Approximately[4/] 3-3.5 in.	.3-2.0	--	.091	--	[5/]11			1.94
Approximately[4/] 3.50-6.5	.3-2.0	--	.053	--	[5/]19			3.35
Approximately[4/] 6-7 in.	.3-2.0		.045		[5/]22			3.87
Approximately[4/] 8.5 in.	.3-2.0		.033		[5/]30			5.28

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]--con.

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
INSULATING MATERIALS--con.								
Board and slabs								
Cellular glass	8.5	0.38	--	2.63	--	0.24	18.23	
Glass fiber, organic bonded	4-9	.25	--	4.00	--	.23	27.72	
Expanded rubber, rigid	4.5	.22	--	4.55	--	.40	31.53	
Expanded polystyrene extruded								
Cut cell surface	1.8	.25	--	4.00	--	.29	27.72	
Smooth skin surface	2.2	.20	--	5.00	--	.29	34.65	
Smooth skin surface	3.5	.19	--	5.26	--		36.45	
Expanded polystyrene, molded beads	1.0	.28	--	3.57	--	.29	24.74	
Expanded polyurethane[6/], R-11 exp., thickness 1 in. or greater	1.5 2.5	.16	--	6.25	--	.38	43.82	
Mineral fiber with resin binder	15	.29	--	3.45	--	.17	23.91	
Mineral fiberboard,								
Wet felted								
Core or roof insulation	16-17	.34	--	2.94	--		20.38	
Acoustical tile	18	.35	--	2.86	--	.19	19.82	
Acoustical tile	21	.37	--	2.70	--		18.71	
Wet molded, acoustical tile[7/]	23	.42	--	2.38	--	.14	16.49	
Wood or cane fiberboard, acoustical tile[7/]								
0.5 in.	--	--	0.80	--	1.25	.31		0.22
0.75 in.	--	--	.53	--	1.89			.33
Interior finish, plank, tile	15	.35	--	2.86	--	.32	19.82	
Wood, shredded, cemented in preformed slabs	22	.60	--	1.67	--	.31	11.57	
LOOSE FILL								
Cellulosic insulation, milled paper or wood pulp	2.3-3.2	.27-0.32	--	3.13-3.70	--	.33	21.69-25.64	
Sawdust or shavings	8.0-15.0	.45	--	2.22	--	.33	15.39	
Wood fiber, softwoods	2.0-3.5	.30	--	3.33	--	.33	23.08	
Perlite, expanded	5.0-8.0	.37	--	2.70	--	.26	18.71	
Mineral fiber, rock, slag, or glass								
Approximately[4/] 3.75-5 in	.6-2.0	--	--		11	.17		1.94
Approximately[4/] 6.5-8.75 in	.6-2.0	--	--		19			3.35
Approximately[4/] 7.5-10 in	.6-2.0	--	--		22			3.87
Approximately[4/] 10.25-13.75 in	.6-2.0	--	--		30			5.28

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]--con.

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
LOOSE FILL--con.								
Vermiculite, exfoliated	7.0-8.2	0.47	--	2.13	--	3.20	14.76	
Vermiculite, exfoliated	4.0-6.0	.44	--	2.27	--		15.73	
Roof Insulation, preformed, for use above-deck[8/]			0.72-0.12		1.39-8.33		--	0.24-1.47
MASONRY MATERIALS								
Cement mortar	116	5.0	--	.20	--		1.39	
Gypsum-fiber concrete--87.5 pct gypsum, 12.5 pct wood chips	51	1.66	--	.60	--	.21	4.16	
Lightweight aggregates including expanded shale, clay or slate; expanded slags; cinders; pumice; vermiculite; also cellular concretes	120	5.2	--	.19	--		1.32	
	100	3.6	--	.28	--		1.94	
	80	2.5	--	.40	--		2.77	
	60	1.7	--	.59	--		4.09	
	40	1.15	--	.86	--		5.96	
	30	.90	--	1.11	--		7.69	
	20	.70	--	1.43			9.91	
Perlite, expanded	40	.93		1.08			7.48	
	30	.71		1.41			9.77	
	20	.50		2.00		.32	13.86	
Sand and gravel or stone aggregate								
Oven dried	140	9.0	--	.11		.22	.76	
Not dried	140	12.0	--	.08			.55	
Stucco	116	5.0	--	.20			1.39	
MASONRY UNITS								
Brick								
Common[9/]	120	5.0	--	.20	--	.19	1.39	
Face[9/]	130	9.0	--	.11	--		.76	
Clay tile, hollow								
One cell deep								
3 in.	--	--	1.25	--	.80	.21		.14
4 in.	--	--	.90	--	1.11			.20
Two cells deep								
6 in.	--	--	.66	--	1.52			.27
8 in.	--	--	.54	--	1.85			.33
10 in.	--	--	.45	--	2.22			.39
Three cells deep, 12 in.	--	--	.40	--	2.50			.44

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]--con.

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
MASONRY UNITS--con.								
Concrete blocks								
Three oval core								
Sand and gravel aggregate								
4 in.	--	--	1.40	--	0.71	0.22		0.13
8 in.	--	--	.90	--	1.11			.20
12 in.	--	--	.78	--	1.28			.23
Cinder aggregate								
3 in.	--	--	1.16	--	.86	.21		.15
4 in.	--	--	.90	--	1.11			.20
8 in.	--	--	.58	--	1.72			.30
12 in.	--	--	.53	--	1.89			.33
Lightweight aggregate, expanded shale, clay, slate, or slag; pumice								
3 in.	--	--	.79	--	1.27	.21		.22
4 in.	--	--	.67	--	1.50			.26
8 in.	--	--	.50	--	2.00			.35
12 in.	--	--	.44	--	2.27			.40
Concrete block, rectangular core*[10/]								
Sand and gravel aggregate, two cores, 8 in., 36 lb[11/*]	--	--	.96	--	1.04	.22		.18
Same with filled cores[10/*]	--	--	.52	--	1.93	.22		.34
Lightweight aggregate, expanded shale, clay, slate or slag; pumice								
Three cores, 6 in., 19 lb[11/*]	--	--	.61	--	1.65	.21		.29
Same with filled cores[12/*]	--	--	.33	--	2.99			.53
Two cores, 8 in., 24 lb[11/*]	--	--	.46	--	2.18			.38
Same with filled cores[12/*]	--	--	.20	--	5.03			.89
Three cores, 12 in., 38 lb[11/*]	--	--	.40	--	2.48			.44
Same with filled cores[12/*]	--	--	.17	--	5.82			1.02
Stone, lime or sand	--	12.50	--	.08	--	.19	.55	
Gypsum partition tile								
3 x 12 x 30 in. solid	--	--	.79	--	1.26	.19		.22
3 x 12 x 30 in. four cells	--	--	.74	--	1.35			.24
4 x 12 x 30 in. three cells	--	--	.60	--	1.67			.29

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]--con.

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
PLASTERING MATERIALS								
Cement plaster, sand aggregate	116	5.0	--	0.20	--	0.20	1.39	
0.375 in.	--	--	13.3	--	0.08	.20		0.01
0.75 in.	--	--	6.66	--	.15	.20		.03
Gypsum plaster								
Lightweight aggregate								
0.5 in.	45	--	3.12	--	.32			.06
0.625 in.	45	--	2.67	--	.39			.07
On metal lath, 0.75 in.	--	--	2.13	--	.47			.08
Perlite aggregate	45	1.5	--	.67	--	.32	4.64	
Sand aggregate	105	5.6	--	.18	--	.20	1.25	
0.5 in.	105	--	11.10	--	.09			.02
0.625 in.	105	--	9.10	--	.11			.02
On metal lath, 0.75 in.	--	--	7.70	--	.13			.02
Vermiculite aggregate	45	1.7	--	.59	--		4.09	
ROOFING								
Asbestos-cement shingles	120	--	4.76	--	.21	.24		.04
Asphalt roll roofing	70	--	6.50	--	.15	.36		.03
Asphalt shingles	70	--	2.27	--	.44	.30		.06
Built-up roofing, 0.375 in.	70	--	3.00	--	.33	.35		.06
Slate, 0.5 in.	--	--	20.00	--	.05	.30		.01
Wood shingles, plain and plastic film faced	--	--	1.06	--	.94	.31		.17
SIDING MATERIALS ON FLAT SURFACE								
Shingles								
Asbestos-cement	120	--	4.75	--	.21			.04
Wood								
16 in., 7.5-in. exposure	--	--	1.15	--	.87	.31		.15
Double, 16 in., 12-in. exposure	--	--	.84	--	1.19	.28		.21
Plus insulating backer board, 0.3125 in.	--	--	.71	--	1.40	.31		.25
Siding								
Asbestos-cement, 0.25 in., lapped	--	--	4.76	--	.21	.24		.04
Asphalt roll siding	--	--	6.50	--	.15	.35		.03
Asphalt insulating siding, 0.5 in. bed.	--	--	.69	--	1.46	.35		.26

Table 1.--Thermal properties of typical building and insulating materials--design values from ASHRAE Handbook, 1977[1/]--con.

Description	Density	Conductivity (k)	Conductance (C)	Resistance (R)[2/] for customary unit: Per inch thickness (1/k)	Resistance (R)[2/] for customary unit: For thickness listed (1/C)	Specific heat	Resistance (R)[2/] for SI unit: $\frac{(m \cdot K)}{W}$	Resistance (R)[2/] for SI unit: $\frac{(m^2 \cdot K)}{W}$
	Lb/ft³					Btu/lb/°F		
SIDING MATERIALS ON FLAT SURFACE--con.								
Wood								
Drop, 1 x 8 in.	--	--	1.27	--	0.79	0.28		0.14
Bevel, lapped								
0.5 x 8 in.	--	--	1.23	--	.81	.28		.14
0.75 x 10 in.	--	--	.95	--	1.05	.28		.18
Plywood, 0.375 in., lapped	--	--	1.59	--	.59	.29		.16
Medium density, 0.4375 in.	40	1.49	--	0.67		.28	4.65	
Aluminum or steel[13/], over sheathing								
Hollow-backed	--	--	1.61	--	.61	.29		.11
Insulating-board backed, nominal								
0.375 in.	--	--	.55	--	1.82	.32		.32
Foil backed	--	--	.34	--	2.96			.52
Architectural glass	--	--	10.00	--	.10	.20		.02
WOODS								
Maple, oak, and similar hardwoods	45	1.10	--	.91	--	.30	6.31	
Fir, pine, and similar softwoods	32	.80	--	1.25	--	.33	8.66	
0.75 in.	32	--	1.06	--	.94	.33		.17
1.5 in.		--	.53	--	1.89			.33
2.5 in.		--	.32	--	3.12			.60
3.5 in.		--	.23	--	4.35			.75

1/ Representative values for dry materials were selected by ASHRAE TC4.4, Insulation and Moisture Barriers. They are intended as design (not specification) values for materials in normal use. For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests. These constants are expressed in Btu per hour per square foot per °F 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.

2/ Resistance values are the reciprocals of C before rounding off C to two decimal places.

3/ Also see Insulating Materials, Board.

4/ Conductivity varies with fiber diameter. 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.

5/ Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an air space, see tables 6 and 7 for the insulating value of air space for the appropriate effective emittance and temperature conditions of the space.

6/ Values are for aged board stock.

7/ Insulating values of acoustical tile vary, depending on density of the board and on type, size, and depth of perforations.

8/ The U.S. Department of Commerce Simplified Practice Recommendation for Thermal Conductance Factors for Preformed Above-Deck Roof Insulation, No. R 257-55, recognizes the specification of roof insulation on the basis of the C values shown. Roof insulation is made in thicknesses to meet these values. Different roof insulations are available in different thicknesses to provide the design C values listed. Consult individual manufacturers for actual thickness of their material.

9/ 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.

10/ 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.

11/ 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.

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

13/ 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 pct or more from the values given may occur.

Table 2.--Coefficients of transmission (U) of windows, skylights, and light transmitting partitions from ASHRAE Handbook, 1977[1/]

Description	Exterior[2/]		Interior
	Winter	Summer	
PART A--VERTICAL PANELS (EXTERIOR WINDOWS, SLIDING PATIO DOORS, AND PARTITIONS)--FLAT GLASS, GLASS BLOCK, AND PLASTIC SHEET			
Flat glass[3/]			
Single glass	1.10	1.04	0.73
Insulating glass--double[4/]			
0.1875-in. air space[5/]	.62	.65	.51
0.25-in. air space[5/]	.58	.61	.49
0.5-in. air space[6/]	.49	.56	.46
0.5-in. air space, low emittance coating[7/]			
e = 0.20	.32	.38	.32
e = 0.40	.38	.45	.38
e = 0.60	.43	.51	.42
Insulating glass--triple[4/]			
0.25-in. air spaces[5/]	.39	.44	.38
0.5-in. air spaces[8/]	.31	.39	.30
Storm windows			
1- to 4-in. air space[5/]	.50	.50	.44
Plastic sheet			
Single glazed			
0.125 in. thick	1.06	.98	--
0.25 in. thick	.96	.89	--
0.5 in. thick	.81	.76	--
Insulating unit--double[4/]			
0.25-in. air space[5/]	.55	.56	--
0.5-in. air space[4/]	.43	.45	--
Glass block[9/]			
6 x 6 x 4 in. thick	.60	.57	.46
8 x 8 x 4 in. thick	.56	.54	.44
With cavity divider	.48	.46	.38
12 x 12 x 4 in. thick	.52	.50	.41
With cavity divider	.44	.42	.36
12 x 12 x 2 in. thick	.60	.57	.46

Table 2.--Coefficients of transmission (U) of windows, skylights, and light transmitting partitions from ASHRAE Handbook, 1977[1/]--con.

Description	Exterior[2/]		Interior
	Winter	Summer	
PART B--HORIZONTAL PANELS (SKYLIGHTS)--FLAT GLASS, GLASS BLOCK, AND PLASTIC DOMES[10/,11/]			
Flat glass[6/]			
Single glass	1.23	0.83	0.96
Insulating glass--double[4/]			
0.1875-in. air space[5/]	.70	.57	.62
0.25-in. air space[5/]	.65	.54	.59
0.5-in. air space[4/]	.59	.49	.56
0.5-in. air space, low emittance coating[7/]			
e = 0.20	.48	.36	.39
e = 0.40	.52	.42	.45
e = 0.60	.56	.46	.50
Glass block[9/]			
11 x 11 x 3 in. thick with cavity divider	.53	.35	.44
12 x 12 x 4 in. thick with cavity divider	.51	.34	.42
Plastic domes[12/]			
Single-walled	1.15	.80	--
Double-walled	.70	.46	--

1/ These values are for heat transfer from air to air, British thermal units per hour per square foot per degree Fahrenheit.

2/ See table 2A for adjustment for various window and sliding patio door types.

3/ Emittance of uncooled glass surface = 0.84.

4/ Double and triple refer to the number of lights of glass.

5/ 0.125-in. glass.

6/ 0.25-in. glass.

7/ Coating on either glass surface facing air space; all other glass surfaces uncoated.

8/ Window design: 0.25-in. glass-0.125-in. glass-0.25-in. glass.

9/ Dimensions are nominal.

10/ Winter: For heat flow up.

11/ Summer: For heat flow down.

12/ Based on area of opening, not total surface area.

Table 2A.--Adjustment factors for various window and sliding patio door types[1/,2/]

Description	Single glass	Double or triple glass	Storm windows
Windows			
All glass[3/]	1.00	1.00	1.00
Wood sash			
80 pct glass	.90	.95	.90
60 pct glass	.80	.85	.80
Metal sash			
80 pct glass	1.00	[4/]1.20	[4/]1.20
Sliding patio doors			
Wood frame	.95	1.00	--
Metal frame	1.00	[3/]1.10	--

1/ Multiply U values in parts A and B of table 2 by these factors.

2/ These values are for heat transfer from air to air, British thermal units per hour per square foot per degree Fahrenhit.

3/ Refers to windows with negligible opaque area.

4/ 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.

Although compressing a fibrous blanket or batt may increase the thermal resistance per unit thickness of the resulting material, it will decrease the overall resistance. For example: A 6-inch blanket compressed into a 3½-inch wall cavity may have a slightly higher resistance than a standard 3½-inch blanket; however, its resistance will not be as high as it would have been in a 6-inch space.

Foams

Commonly used foams in building construction are polystyrene, polyurethane, and urea formaldehyde. The insulating value of foams is derived from cells filled with air or other gases. Heat transfer is mainly by conduction across these cells. Optimum thermal resistance is achieved by a specific combination of cell size and density. The thermal resistance is also greatly affected by the kind of gas in the cells.

Polystyrene is commonly manufactured as rigid sheets and may be extruded or molded. Extruded polystyrene, with closed cells which trap gases in the material, has a higher resistance than molded polystyrene with open cells. Polystyrene beads are also

Table 3.--Coefficients of transmission (U) for slab doors in British thermal units per hour per square foot per degree Fahrenheit (adapted from ASHRAE Handbook, 1977)

Nominal thickness	Winter						Summer			
	Solid wood, no storm door	Steel door[1/]			Storm door[2/]		No storm door	Steel door[1/]		
		A	B	C	Wood	Metal		A	B	C
In.										
1	0.64				0.30	0.39	0.61			
1.25	.55	--	--	--	.28	.34	.53	--	--	--
1.5	.49	--	--	--	.27	.33	.47	--	--	--
2	.43	--	--	--	.24	.29	.42	--	--	--
1.75	--	0.59	0.19	0.47	--	--	--	0.58	0.18	0.46

1/ A = mineral fiber core (2 lb/ft^3); B = solid urethane foam core with thermal break; C = solid polystyrene core with thermal break.

2/ Values for wood storm doors are for approximately 50 pct. glass; for metal storm door values apply for any percent of glass.

available as a loose-fill insulation which has larger cells with lower resistance than the rigid forms.

Polyurethane may be produced in rigid sheets, foamed in place into cavities, or applied to surfaces of building components as a fast-setting foam. This foam has 90 percent or more closed cells, and retains fluorocarbon gases for extended periods of time. However, as air permeates into cells and dilutes the fluorocarbon gas, the thermal resistance slowly decreases. Some factors affecting the rate of air permeation are environmental temperature, thickness, and surface protection. Encasing the foam in gas-impermeable membranes greatly reduces the rate of air permeation.

The urea-formaldehyde currently used in building construction is a cold-setting, low-density, resilient foam. There is no further expansion of the material after it leaves the applicator gun, so it can be used to fill voids without danger of subsequent pressure buildup. Rated shrinkage during the drying-out period is about 1.8 to 3 percent. Rapid drying may increase the amount of shrinkage, and slow drying will decrease shrinkage. Thermal resistance values for this material were not available at the time table 1 was assembled. Values listed by manufacturers for a density of 0.7 pound per cubic foot (lb/ft^3) are: an "R" factor of 5.0 at an average temperature of 70° F, and an "R" factor of 5.5 at an average temperature of 35° F. (The effect of the temperature at which a material is tested is discussed in a later section.) Tests by the National Bureau of Standards indicate that an in-place R of 4.2 at 75° F should be used to compensate for shrinkage and variations in density.

Materials of Construction

Density of construction materials is the major factor influencing their thermal con-

ductivity. Very dense materials such as steel and glass have high conductivities. Wood and fiber panel products have lower conductivities because of a porous structure that includes voids in and between fibers. In most construction systems, a high percentage of insulation is provided by nonstructural insulating materials, so conductivity of the construction materials is not critical. However, the high-conductivity materials must be used with some discretion to avoid thermal bridges—that is, dense materials extending all the way through the building component—between warm and cold faces.

Masonry

Most masonry has a relatively high density, and consequently a high thermal conductivity. However, because it is often used in relatively large masses, its capacitance, or ability to store heat, may offer some advantage for certain climates especially during the air-conditioning season. Where there is a large diurnal cycling of temperature, the material can slowly collect heat during the day and release heat to the inside during the night. If the masonry is sufficiently cooled during the night cycle, the building interior will remain cool during the day while the masonry is slowly storing heat that would otherwise be transferred to the interior.

Thermal conductivity of concrete or manufactured masonry units, such as concrete block, can be reduced by using a lightweight aggregate, but this also reduces heat storage capacity.

Soil

The insulating value of soil varies with type, density, and moisture content. Of these, moisture content is the most critical factor. Although the thermal resistance is low, in practice soil is used in large quantities that result in an overall low conductance.

Basement floors and walls below the frostline generally do not require additional insulation because of the protection provided by soil. Where a basement is built partially out of the ground with berms added against the walls, soil still adds greatly to the insulation. With the growing concern for energy conservation, underground structures are seriously being considered, so soil in combination with below-surface insulation will play a greater role as insulation in the future.

Environmental Conditions

The Effect of Temperature

Thermal conductivity is affected by the mean temperature of an insulating material during rating under test conditions. Most of the insulating values in table 1 were obtained at 75° F; however, product literature often lists conductivity values obtained from tests conducted at other temperatures, making comparison difficult. For a meaningful comparison of thermal efficiency of materials, data must be from tests at the temperature which the material will achieve in service. Each type of insulation varies differently with temperature. Some have a decreasing conductivity with decreasing temperature, while the reverse effect occurs in others. Figure 7 shows the relationship between temperature and thermal conductivity for some insulations.

The Effect of Moisture

Water or ice in insulation impairs or destroys its insulating value, and may cause structural damage by decay, corrosion, or the expansive action of freezing water. The extent that moisture affects the material depends on the physical structure of the material. Most insulations are hygroscopic, so they gain or lose moisture in proportion to the relative humidity of the air in contact with the insulation. Closed-cell foams are essentially nonhygroscopic, so their insulating value is not appreciably affected by moisture; however, urea-formaldehyde foam has open cells and is more absorbent.

One of the main sources of moisture in insulation is from water vapor being driven by vapor pressure differences from the warm to the cold side of insulation. Air leakage through building components also transports moisture. This vapor condenses as free water when it reaches its dewpoint tempera-

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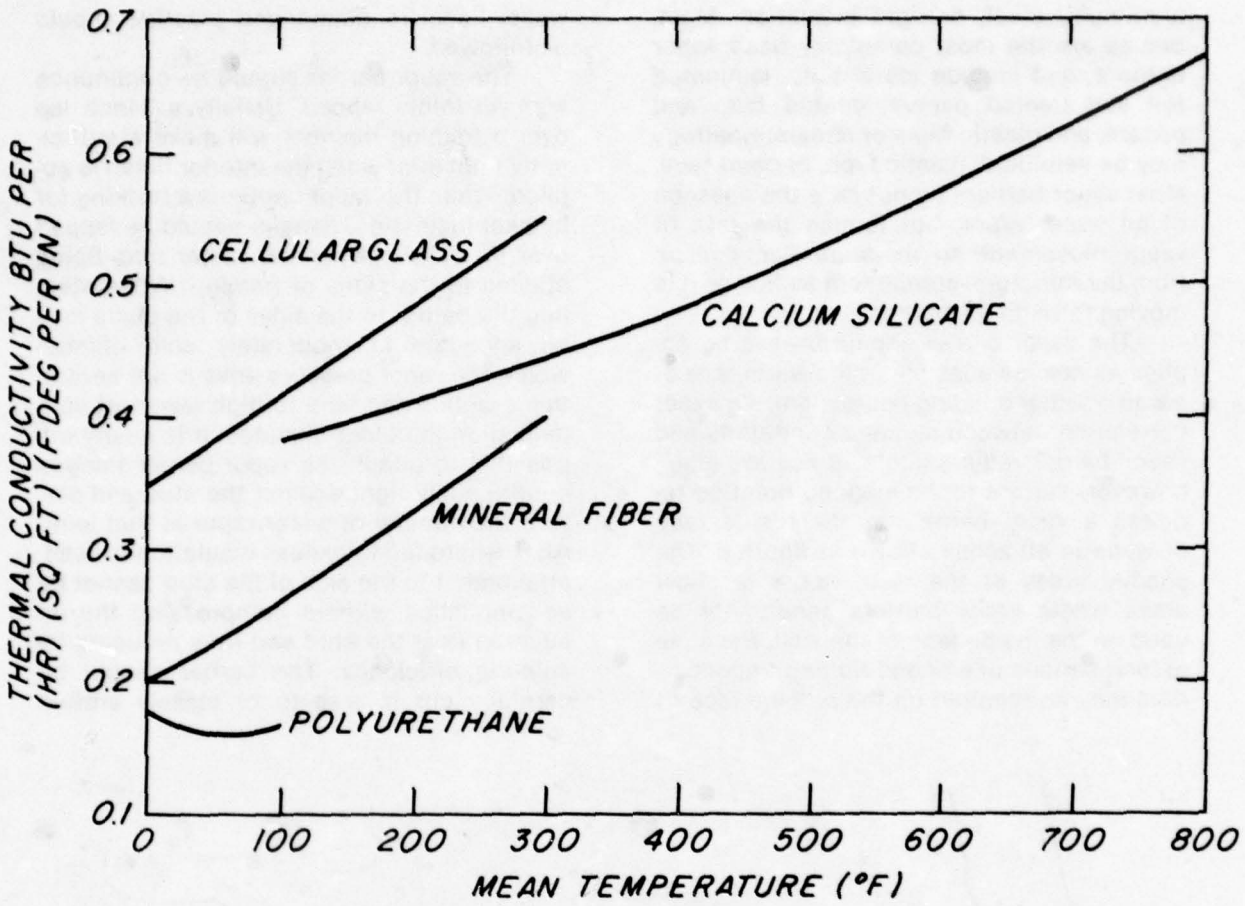


Figure 7.—Typical variation of thermal conductivity with mean temperature (ASHRAE Handbook, 1977). (M 146 477)

ture. If the insulation has a high permeability, this moisture moves on through the insulation to the coldest surface. Such condensation occurring inside a structural component, such as a wall, is referred to as concealed condensation. Where condensation occurs on an exposed surface, such as a window or uninsulated wall, it is called visible condensation.

Moisture Control

Moisture control in structural spaces is generally accomplished by the use of vapor barriers, ventilation, or a combination of these. In addition, reduction of moisture in living spaces may be required in order to reduce the vapor pressure drive through the exterior envelope of the building. Air change from normal infiltration is usually enough to remove the water vapor generated by a family. However, in some cases, bathroom and kitchen vents may be necessary. Condensation on windows is one indication that humidity is too high. In extreme cases, such as a large family living in a small, tight house, mechanical dehumidification may be necessary. The same requirement may exist in buildings heated electrically since there is no chimney draw to increase air infiltration. The usual fuel-burning heating systems require air for combustion. This creates a negative pressure in the building, which accelerates air exchange and consequently lowers relative humidity in the building.

Vapor barriers are in the form of structural sheets, membranes, or coatings. The structural sheets may be reinforced plastics,

aluminum, steel, or rigid insulation. Membranes are the most commonly used vapor barriers, and include metal foils, laminated foil and treated papers, coated felts and papers, and plastic films or sheets. Coatings may be semifluid, mastic type, or paint type. Most vapor barriers do not stop the passage of all water vapor, but reduce the rate of vapor movement so moisture can escape from the structural component as fast as it is moving through the barrier.

The vapor barrier should always be applied as near as possible to the warm face of a wall or other building component. An exact correlation between climatic conditions and vapor barrier requirements is not available; however, current recommended practice requires a vapor barrier on the inside face of walls in all zones shown in figure 8. The shaded areas of the map, figure 8, show areas where vapor barriers should not be used on the inside face of the wall. Because of long periods of air-conditioning, vapor barriers may be required on the outside face of walls. Local recommended practice should be followed.

The vapor barrier should be continuous with all joints lapped. Usually a 2-inch lap over a framing member will make a sufficiently tight joint when the interior finish is applied. When the vapor barrier is a backing for blanket insulation, flanges should be lapped over the framing member rather than being stapled to the sides of framing. While stapling the barrier to the sides of the studs may be adequate in moderately cold climate where the vapor pressure drive is not severe, this practice can lead to high levels of condensation in colder climates. It is nearly impossible to attach the vapor barrier flanges continuously tight against the stud and prevent the transfer of water vapor at that joint. Also, where full-thickness insulation is used, attachment to the side of the stud cannot be accomplished without compressing the insulation near the stud and thus reducing insulating efficiency. The barrier should be carefully cut to size to fit closely around

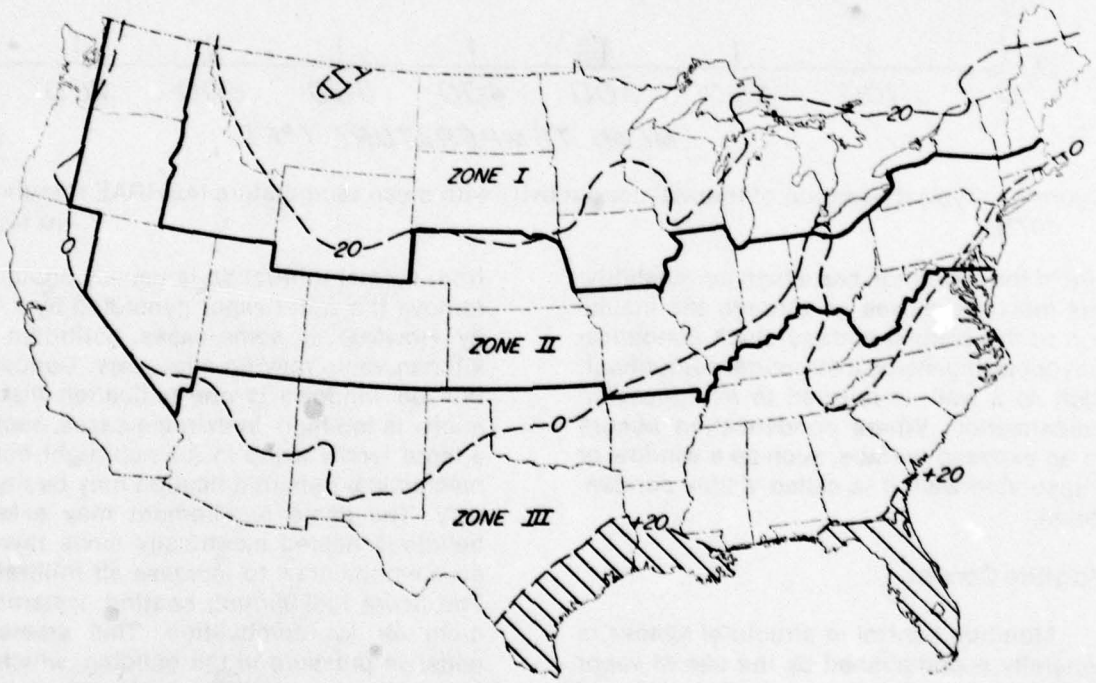


Figure 8.—Condensation zones in the United States (from ASHRAE Handbook, 1977). Zones include areas with design temperatures about as follows: Zone 1, – 20° F and lower; zone 2, 0° F to – 20° F; and zone 3, above 0° F. (Note that cross hatched areas are outside of zones 1 and 3.)

(M 146 479)

openings such as electrical outlets and windows.

Ceiling vapor barriers are required in colder climates as indicated in table 4. Ventilation of attic or roof spaces is also necessary because most roofing is quite resistant to the passage of water vapor. Where practical, outlet vents should be provided at a higher level than inlet vents, and all ventilation should be well distributed to move air through all parts of the structural space. Amounts of ventilation required for various types of roofs are presented in table 4.

Ventilation is also required in crawl spaces. At least four openings, one at each corner, as high as possible, should be provided. A minimum value for their total net area may be calculated by the formula:

$$a = \frac{2L}{100} + \frac{A}{300}$$

where

L is the perimeter of the crawl space, linear feet,

A is the area of the crawl space, square feet, and

a is the total net area of all vents (or the gross area if a 4-mesh screen is used), square feet.

Ventilation of the crawl space can be reduced to only 10 percent of that calculated by the above equation if a ground cover that resists moisture transmission is laid over the soil. Materials commonly used for this are roll roofing and 4- or 6-mil polyethylene film. The ground cover should be laid with all edges lapped at least 4 inches.

Where roof decks also serve as ceiling, such as in plank-and-beam construction, there is no structural space to ventilate. Here, the concept of a limited vapor barrier rather than a near absolute barrier may be considered. A limited barrier restricts the flow of water vapor during periods of condensation to the amount that can be tolerated by the construction without deterioration or measurable loss in insulating or other efficiency. Yet moisture can move back through a limited barrier during the noncondensation periods. Criteria do not exist to determine the perm rating for this type of application; however, construction using barriers with permeance values in the range between 0 and 0.05 perm have shown cumulative build-up of moisture in unventilated decks. This suggests vapor barriers with permeance values in the range of 0.15 to 0.50 perm may be more suitable.

Adjustment for Moisture in Wood

Some moisture exists in all insulating materials; however, most heat loss calculations are based on materials at zero percent moisture content. For accuracy a moisture content adjustment should be made. Adjustment factors are not available for most materials; however, the chart shown in figure 9 has been developed for determining thermal conductivity of wood at various moisture contents. To use this chart, obtain the average specific gravity from table 5 for the species under consideration. Determine or assume the moisture content of the wood. When the actual moisture content is not known, assume it is 15 percent for wood siding or sheathing and 7 percent for inside woodwork or finish. On the chart, find the moisture content of the wood and follow the vertical line upward until it intersects the sloping line that corresponds to the specific gravity of the wood. The reading on the vertical scale at the left of this intersection point is the desired thermal conductivity, *k*, for the wood at the assumed moisture content.

The specific gravity data of table 5 are average values for species listed. There are, of course, appreciable variations in specific gravity between boards and even between shipments of the same species. Substances such as gums and resins, and such defects as checks, knots, and irregular grain, may also influence conductivity, but for purpose of calculation those factors may be ignored.

The conductivity value for plywood is essentially the same as that for solid wood of the same thickness.

Table 4.--Recommended good practice for loft and attic ventilation (adapted from ASHRAE Handbook, 1977)[1]

Roof type and slope	Condensation zone[2] I	II	III
Flat; 3 in 12 or less	Total net area[3] of ventilation should be 1/300th distributed uniformly at the eaves plus a vapor barrier in the top story ceiling. Free circulation must be provided through all spaces.	Same as zone I	Same as zone I
Gable; over 3 in 12	Total net area of at least two louvers on opposite sides located near the ridge to be 1/300th plus a vapor barrier in the top story ceiling.	Same as zone I	Same ventilation as zone II. A vapor barrier is not considered necessary.
Hip	Total net area of ventilation should be 1/300th with 1/600th distributed uniformly at the eaves and 1/600th located at the ridge with all spaces interconnected. A vapor barrier should also be used in the top story ceiling.	Same as zone I	Same ventilation as zone II. Avapor barrier is not considered necessary.
Gable or hip[4]	Total net area of ventilation should be 1/300th with 1/600th distributed uniformly at the eaves and 1/600th located at the ridge with all spaces interconnnected. A vapor barrier should also be used on the warm side of the top full story ceiling, the dwarf walls, the sloping part of the roof, and the attic story ceiling.	Same as zone I	Same as zone I except that a vapor barrier is not considered necessary if insulation is omitted.

1/ In many areas increased ventilation may be desirable for summer comfort. For winter comfort, insulation is recommended between a living space and a loft or attic ventilated at these rates.

2/ The zone numbers refer to fig. 8.

3/ Total net area refers to area enclosed within building lines at eave level.

4/ With occupancy contemplated.

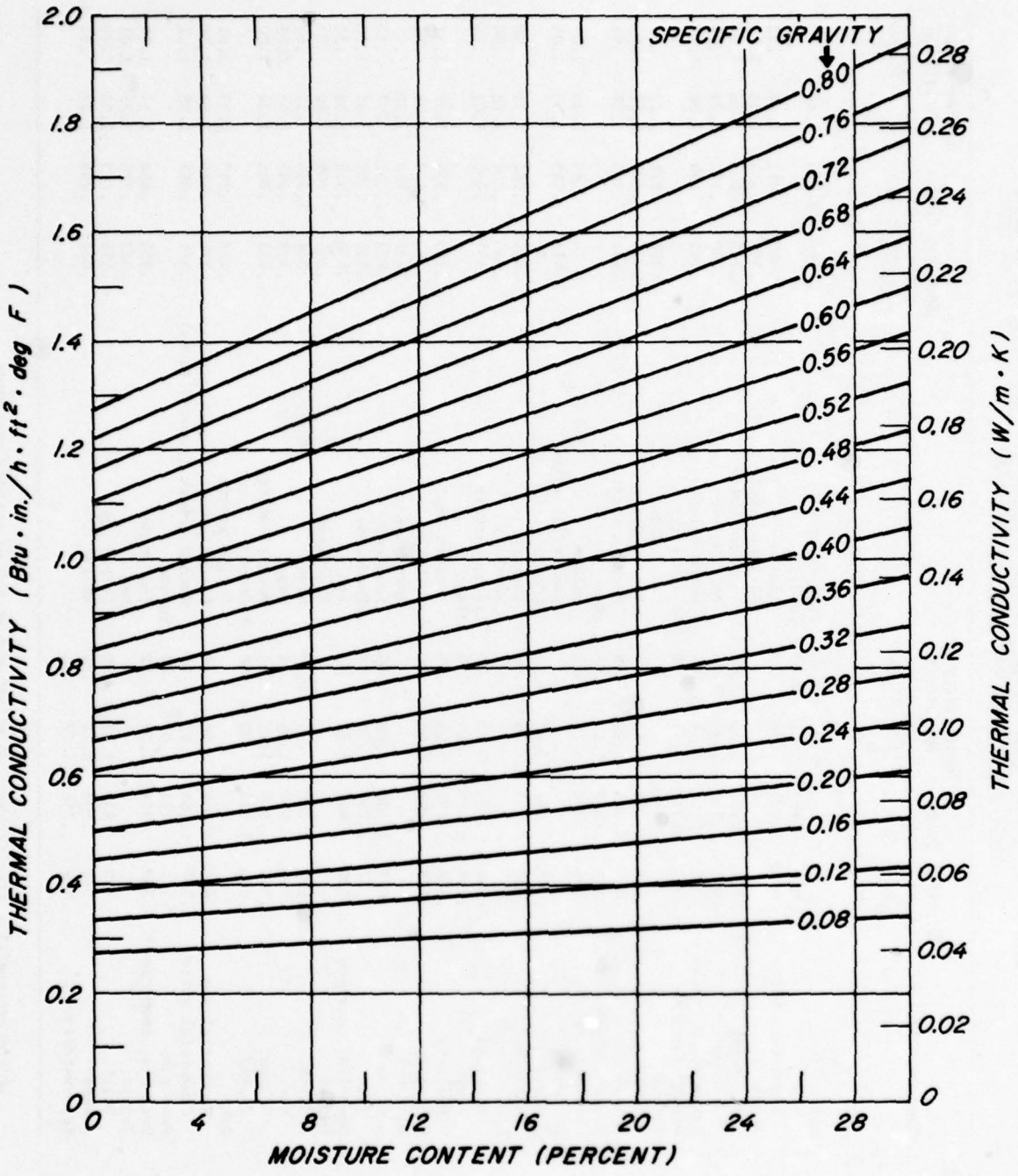


Figure 9.—Relation between computed conductivity and moisture content for wood having different specific gravity values. (Specific gravity based on volume at current moisture content and weight when ovendry. Conductivity computed from formula K = S [1.39 + 0.028M] + 0.165.)

(M 140 415)

Table 5.--Average specific gravity, thermal conductivity, and resistance values of various species of hardwoods and softwoods

Species, hardwoods	Specific gravity[1]	Conductivity k	Resistivity or resistance	
			1/k	3/4-in.[2]
Ash:				
Black	0.531	0.903	1.11	0.83
Commercial white	.618	1.024	.98	.74
Aspen:				
Big tooth	.412	.738	1.36	1.02
Quaking	.401	.722	1.39	1.04
Basswood, American	.398	.718	1.39	1.04
Birch, American	.671	1.098	.91	.68
Birch:				
Sweet	.714	1.157	.86	.64
Yellow	.662	1.085	.92	.69
Cherry, black	.534	.907	1.10	.83
Chestnut, American	.454	.796	1.26	.94
Cottonwood:				
Black	.368	.677	1.48	1.11
Eastern	.433	.767	1.30	.98
Elm:				
American	.554	.935	1.07	.80
Rock	.658	1.080	.93	.70
Slippery	.568	.955	1.05	.79
Hackberry	.558	.941	1.06	.80
Hickory:				
Pecan	.694	1.130	.88	.66
True	.787	1.259	.79	.59
Magnolia, southern	.530	.902	1.11	.83
Maple:				
Black	.620	1.027	.97	.73
Red	.546	.924	1.08	.81
Silver	.506	.868	1.15	.86
Sugar	.676	1.105	.90	.68
Oak:				
Commercial red	.676	1.105	.90	.68
Commercial white	.719	1.164	.86	.64
Sweetgum	.551	.931	1.07	.80
Sycamore, American	.539	.914	1.09	.82
Tupelo:				
Black	.552	.932	1.07	.80
Water	.524	.893	1.12	.84
Yellow-poplar	.449	.789	1.27	.95

Species, softwoods	Specific gravity[1]	Conductivity k	Resistivity or resistance	
			1/k	3/4-in.[2]
Bald cypress	0.482	0.835	1.20	.90
Cedar:				
Alaska	.465	.811	1.23	.92
Atlantic white	.352	.654	1.53	1.15
Northern white	.315	.603	1.66	1.24
Port Orford	.440	.777	1.29	.97
Western redcedar	.342	.640	1.56	1.17
Douglas-fir:				
Coast-type	.508	.871	1.15	.86
Intermediate	.476	.827	1.21	.91
Rocky Mountain	.446	.785	1.27	.95
Fir:				
Balsam	.414	.740	1.35	1.01
Commercial white	.413	.739	1.35	1.01
Hemlock:				
Eastern	.429	.761	1.31	.98
Western	.443	.781	1.28	.96
Larch, western	.591	.986	1.01	.76
Pine:				
Eastern white	.367	.675	1.48	1.11
Loblolly	.545	.923	1.08	.81
Lodgepole	.434	.768	1.30	.98
Longleaf	.623	1.031	.97	.73
Ponderosa	.420	.749	1.34	1.00
Red	.470	.818	1.22	.92
Shortleaf	.535	.909	1.10	.83
Slash	.661	1.084	.92	.69
Sugar	.378	.690	1.45	1.09
Western white	.418	.746	1.34	1.00
Redwood:				
Virgin growth	.416	.743	1.35	1.01
Second growth (openly grown)	.310	.596	1.68	1.26
Second growth (closely grown)	.361	.667	1.50	1.12
Spruce:				
Engelmann	.355	.658	1.52	1.14
Red	.413	.739	1.35	1.01
Sitka	.416	.743	1.35	1.01
White	.446	.785	1.27	.95

1/ Average specific gravity based on volume and weight of ovendry specimens.
2/ The thickness of nominal 1-in. boards is 3/4-in.

Reflectance and Surface Effects

Air Films and Spaces

In addition to the insulation provided by the construction materials, each face of a component of construction has an air film that provides some resistance to heat flow. Where the air is still, the conductance varies with the position of the surface, the direction of heat flow, and the surface emissivity. Where there is movement of air over the surface, the above variables do not apply. Conductance values for winter conditions are usually based on 15-mile-per-hour wind. For summer, 7½-mile-per-hour wind speed is used. The conductivity values for air films are given in table 6.

The transfer of heat across an air space is accomplished by a combination of radiation, convection, and conduction. The radiation component is affected by the temperature of the two boundary surfaces and their surface emissivities. The other elements of heat flow are affected by the temperature difference, the thickness of the space, the orientation (horizontal or vertical), and the direction of heat flow. Thermal conductance values for air spaces are given in table 7. The transfer of heat through an air space cannot be determined by extrapolation, so exact values are given for ½, ¾, 1½, and 3½ inches.

Reflective Insulation

High thermal resistance is obtained by multiple air layers bounded by reflective surfaces. The total resistance is the sum of the resistance values across each air space. One or both sides of the air space may have reflective surfaces; however, there is little gained by adding a second reflective surface to the same air spaces except for thick, horizontal air spaces with heat flow down. It makes no appreciable difference in resistance to heat transfer on which side the reflective surface is placed; however, it should usually be placed on the warm side of the air space because moisture usually will not condense on the warm surface. Changes in the reflective surface which may reduce its reflectivity are chemical action, dust accumulations, and the presence of condensation or frost.

Thermal conductance values for air spaces with reflective surfaces are given in table 7.

Heating and Cooling Load Computations

The thermal load on a building is made up of numerous elements. A major factor is the area of the building envelope—walls, ceilings, and floor. The heat conducted through these construction assemblies is directly proportional to their area, their thermal conductivity, and the temperature difference between the inside and outside of the building.

Infiltration or air leakage through openings or cracks also contributes to thermal load. Air also passes directly through some construction assemblies such as walls. Infiltration is quite dependent upon wind speed and direction, so that heating requirements increase with wind speed. Also, the higher the rate of infiltration, the greater the effect of wind speed on the thermal load. It is possible that a building might require more heat on a windy day with a moderately low outdoor temperature than on a still day with a much lower outdoor temperature. The most common wind speed for making heating load computations is 15 miles per hour; however, local experience may have established other wind speeds as appropriate for a particular location. The wind pressure affects the surface heat loss coefficient as well as infiltration.

Design Temperature

The ideal heating system would be designed for maximum output exactly equal to the heating load under the most severe weather conditions. In reality, the median of extreme temperatures is usually selected as the outdoor design temperature. For a moderate heat capacity where there is some internal load and daytime occupancy, 99 percent of the median of extreme temperatures is a reasonable choice. Massive, institutional buildings that have little glass can usually be

Table 6.--Surface conductances and resistances for air (ASHRAE Handbook, 1977)[1/,2/]

Position of surface	Direction of heat flow	Wind speed		Surface Emittance							
				Nonreflective ε = 0.90				Reflective ε = 0.20		Reflective ε = 0.05	
		Summer	Winter	h_i	R	h_o	R	h_i	R	h_i	R
		Mph	Mph								
Still air											
Horizontal	Upward	--	--	1.63	0.61	--	--	0.91	1.10	0.76	1.32
45° slope	Upward	--	--	1.60	.62	--	--	.88	1.14	.73	1.37
Vertical	Horizontal	--	--	1.46	.68	--	--	.74	1.35	.59	1.70
45° slope	Downward	--	--	1.32	.76	--	--	.60	1.67	.45	2.22
Horizontal	Downward	--	--	1.08	.92	--	--	.37	2.70	.22	4.55
Moving air											
Any	Any	--	15	--	--	6.00	0.17	--	--	--	--
Any	Any	7.5	--	--	--	4.00	.25	--	--	--	--

1/ All conductance values expressed in British thermal units per hour per square foot per degree Fahrenheit. 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.

2/ Conductances are for surfaces of the stated emittance facing virtual blackbody surroundings at the same temperature as the ambient air. Values are based on a surface-air temperature difference of 10° F and for surface temperature of 70° F.

Table 6A.--Reflectivity and emittance values of various surfaces and effective emittances of air spaces

Surface	Reflectivity	Average Emittance ε	Effective Emittance E of air space: One surface emittance ε; the other 0.90	Effective Emittance E of air space: Both surfaces emittances ε
	Pct			
Aluminum				
Foil, bright	92 to 97	0.05	0.05	0.03
Sheet	80 to 95	.12	.12	.06
Coated paper, polished	75 to 84	.20	.20	.11
Steel, galvanized, bright	70 to 80	.25	.24	.15
Aluminum paint	30 to 70	.50	.47	.35
Building materials				
Wood, paper, masonry, nonmetallic paints	5 to 15	.90	.82	.82
Regular glass	5 to 15	.84	.77	.72

designed for an outdoor temperature 97½ percent of the median extreme.

Indoor design temperatures may vary with the type of occupancy, but 72° F is commonly used for winter and 78° F for summer.

Attic Temperature

A common expedient in calculating heat loss through ceilings is to neglect the roof and assume the attic temperature equals the outdoor temperature. Another expedient is to assume the attic temperature equals the average between the indoor and outdoor temperature. The actual attic temperature is usually somewhere between these two values. A more accurate estimate of the attic temperature can be calculated from the following equation (3):

$$t_a = \frac{A_c V_c t_c + t_o(A_r U_r + A_w U_w + A_g U_g)}{A_c V_c + A_r U_w + A_w U_w + A_g U_g}$$

where

t_a is attic temperature,
t_c is indoor temperature near top floor ceiling,
t_o is outdoor temperature,
A_c is area of ceiling, square feet,
A_r is area of roof, square feet,
A_w is area of net vertical attic wall space, square feet,
A_g is area of attic glass, square feet,
U_c is coefficient of transmission of ceiling, based on surface conductance of 2.20; 2.28 = reciprocal of one-half the air space resistance,
U_r is coefficient of transmission of roof, based on surface conductance of 2.20,
U_w is coefficient of transmission of vertical wall surface, and
U_g is coefficient of transmission of glass.

Table 7.--Thermal resistances of plane air spaces[1-4/]

Position of air space	Direction of heat flow	Air space[5/]		Value of E[5/,6/]				
		Mean temperature	Temperature difference	0.03	0.05	0.2	0.5	0.82
		°F	°F					
		0.5-INCH AIR SPACE[2/]						
Horizontal	Up	90	10	2.13	2.03	1.51	0.99	0.73
		50	30	1.62	1.57	1.29	.96	.75
		50	10	2.13	2.05	1.60	1.11	.84
		0	20	1.73	1.70	1.45	1.12	.91
		0	10	2.10	2.04	1.70	1.27	1.00
		-50	20	1.69	1.66	1.49	1.23	1.04
		-50	10	2.04	2.00	1.75	1.40	1.16
45° Slope	Up	90	10	2.44	2.31	1.65	1.06	.76
		50	30	2.06	1.98	1.56	1.10	.83
		50	10	2.55	2.44	1.83	1.22	.90
		0	20	2.20	2.14	1.76	1.30	1.02
		0	10	2.63	2.54	2.03	1.44	1.10
		-50	20	2.08	2.04	1.78	1.42	1.17
		-50	10	2.62	2.56	2.17	1.66	1.33
Vertical	Horizontal	90	10	2.47	2.34	1.67	1.06	.77
		50	30	2.57	2.46	1.84	1.23	.90
		50	10	2.66	2.54	1.88	1.24	.91
		0	20	2.82	2.72	2.14	1.50	1.13
		0	10	2.93	2.82	2.20	1.53	1.15
		-50	20	2.90	2.82	2.35	1.76	1.39
		-50	10	3.20	3.10	2.54	1.87	1.46
45° Slope	Down	90	10	2.48	2.34	1.67	1.06	.77
		50	30	2.64	2.52	1.87	1.24	.91
		50	10	2.67	2.55	1.89	1.25	.92
		0	20	2.91	2.80	2.19	1.52	1.15
		0	10	2.94	2.83	2.21	1.53	1.15
		-50	20	3.16	3.07	2.52	1.86	1.45
		-50	10	3.26	3.16	2.58	1.89	1.47
Horizontal	Down	90	10	2.48	2.34	1.67	1.06	.77
		50	30	2.66	2.54	1.88	1.24	.91
		50	10	2.67	2.55	1.89	1.25	.92
		0	20	2.94	2.83	2.20	1.53	1.15
		0	10	2.96	2.85	2.22	1.53	1.16
		-50	20	3.25	3.15	2.58	1.89	1.47
		-50	10	3.28	3.18	2.60	1.90	1.47

Table 7.--Thermal resistances of plane air spaces[1-4]--con.

Position of air space	Direction of heat flow	Air space[5]		Value of E[5,6]				
		Mean temperature	Temperature difference	0.03	0.05	0.2	0.5	0.82
		°F	°F					
		0.75-INCH AIR SPACE[2]						
Horizontal	Up	90	10	2.34	2.22	1.61	1.04	0.75
		50	30	1.71	1.66	1.35	.99	.77
		50	10	2.30	2.21	1.70	1.16	.87
		0	20	1.83	1.79	1.52	1.16	.93
		0	10	2.23	2.16	1.78	1.31	1.02
		-50	20	1.77	1.74	1.55	1.27	1.07
		-50	10	2.16	2.11	1.84	1.46	1.20
45° Slope	Up	90	10	2.96	2.78	1.88	1.15	.81
		50	30	1.99	1.92	1.52	1.08	.82
		50	10	2.90	2.75	2.00	1.29	.94
		0	20	2.13	2.07	1.72	1.28	1.00
		0	10	2.72	2.62	2.08	1.47	1.12
		-50	20	2.05	2.01	1.76	1.41	1.16
		-50	10	2.53	2.47	2.10	1.62	1.30
Vertical	Horizontal	90	10	3.50	3.24	2.08	1.22	.84
		50	30	2.91	2.77	2.01	1.30	.94
		50	10	3.70	3.46	2.35	1.43	1.01
		0	20	3.14	3.02	2.32	1.58	1.18
		0	10	3.77	3.59	2.64	1.73	1.26
		-50	20	2.90	2.83	2.36	1.77	1.39
		-50	10	3.72	3.60	2.87	2.04	1.56
45° Slope	Down	90	10	3.53	3.27	2.10	1.22	.84
		50	30	3.43	3.23	2.24	1.39	.99
		50	10	3.81	3.57	2.40	1.45	1.02
		0	20	3.75	3.57	2.63	1.72	1.26
		0	10	4.12	3.91	2.81	1.80	1.30
		-50	20	3.78	3.65	2.90	2.05	1.57
		-50	10	4.35	4.18	3.22	2.21	1.66
Horizontal	Down	90	10	3.55	3.29	2.10	1.22	.85
		50	30	3.77	3.52	2.38	1.44	1.02
		50	10	3.84	3.59	2.41	1.45	1.02
		0	20	4.18	3.96	2.83	1.81	1.30
		0	10	4.25	4.02	2.87	1.82	1.31
		-50	20	4.60	4.41	3.36	2.28	1.69
		-50	10	4.71	4.51	3.42	2.30	1.71

Table 7.--Thermal resistances of plane air spaces[1-4]--con.

Position of air space	Direction of heat flow	Air space[5] Mean temperature	Air space[5] Temperature difference	Value of E[5,6] 0.03	0.05	0.2	0.5	0.82
		°F	°F					
		1.5-INCH AIR SPACE[2]						
Horizontal	Up	90	10	2.55	2.41	1.71	1.08	0.77
		50	30	1.87	1.81	1.45	1.04	.80
		50	10	2.50	2.40	1.81	1.21	.89
		0	20	2.01	1.95	1.63	1.23	.97
		0	10	2.43	2.35	1.90	1.38	1.06
		-50	20	1.94	1.91	1.68	1.36	1.13
		-50	10	2.37	2.31	1.99	1.55	1.26
45° Slope	Up	90	10	2.92	2.73	1.86	1.14	.80
		50	30	2.14	2.06	1.61	1.12	.84
		50	10	2.88	2.74	1.99	1.29	.94
		0	20	2.30	2.23	1.82	1.34	1.04
		0	10	2.79	2.69	2.12	1.49	1.13
		-50	20	2.22	2.17	1.88	1.49	1.21
		-50	10	2.71	2.64	2.23	1.69	1.35
Vertical	Horizontal	90	10	3.99	3.66	2.25	1.27	.87
		50	30	2.58	2.46	1.84	1.23	.90
		50	10	3.79	3.55	2.39	1.45	1.02
		0	20	2.76	2.66	2.10	1.48	1.12
		0	10	3.51	3.35	2.51	1.67	1.23
		-50	20	2.64	2.58	2.18	1.66	1.33
		-50	10	3.31	3.21	2.62	1.91	1.48
45° Slope	Down	90	10	5.07	4.55	2.56	1.36	.91
		50	30	3.58	3.36	2.31	1.42	1.00
		50	10	5.10	4.66	2.85	1.60	1.09
		0	20	3.85	3.66	2.68	1.74	1.27
		0	10	4.92	4.62	3.16	1.94	1.37
		-50	20	3.62	3.50	2.80	2.01	1.54
		-50	10	4.67	4.47	3.40	2.29	1.70
Horizontal	Down	90	10	6.09	5.35	2.79	1.43	.94
		50	30	6.27	5.63	3.18	1.70	1.14
		50	10	6.61	5.90	3.27	1.73	1.15
		0	20	7.03	6.43	3.91	2.19	1.49
		0	10	7.31	6.66	4.00	2.22	1.51
		-50	20	7.73	7.20	4.77	2.85	1.99
		-50	10	8.09	7.52	4.91	2.89	2.01

Table 7.--Thermal resistances of plane air spaces[1-4]--con.

Position of air space	Direction of heat flow	Air space[5]		Value of E[5,6]				
		Mean temperature	Temperature difference	0.03	0.05	0.2	0.5	0.82
		°F	°F					
		3.5-INCH AIR SPACE[2]						
Horizontal	Up	90	10	2.84	2.66	1.83	1.13	0.80
		50	30	2.09	2.01	1.58	1.10	.84
		50	10	2.80	2.66	1.95	1.28	.93
		0	20	2.25	2.18	1.79	1.32	1.03
		0	10	2.71	2.62	2.07	1.47	1.12
		-50	20	2.19	2.14	1.86	1.47	1.20
		-50	10	2.65	2.58	2.18	1.67	1.33
45° Slope	Up	90	10	3.18	2.96	1.97	1.18	.82
		50	30	2.26	2.17	1.67	1.15	.86
		50	10	3.12	2.95	2.10	1.34	.96
		0	20	2.42	2.35	1.90	1.38	1.06
		0	10	2.98	2.87	2.23	1.54	1.16
		-50	20	2.34	2.29	1.97	1.54	1.25
		-50	10	2.87	2.79	2.33	1.75	1.39
Vertical	Horizontal	90	10	3.69	3.40	2.15	1.24	.85
		50	30	2.67	2.55	1.89	1.25	.91
		50	10	3.63	3.40	2.32	1.42	1.01
		0	20	2.88	2.78	2.17	1.51	1.14
		0	10	3.49	3.33	2.50	1.67	1.23
		-50	20	2.82	2.75	2.30	1.73	1.37
		-50	10	3.40	3.30	2.67	1.94	1.50
45° Slope	Down	90	10	4.81	4.33	2.49	1.34	.90
		50	30	3.51	3.30	2.28	1.40	1.00
		50	10	4.74	4.36	2.73	1.57	1.08
		0	20	3.81	3.63	2.66	1.74	1.27
		0	10	4.59	4.32	3.02	1.88	1.34
		-50	20	3.77	3.64	2.90	2.05	1.57
		-50	10	4.50	4.32	3.31	2.25	1.68
Horizontal	Down	90	10	10.07	8.19	3.41	1.57	1.00
		50	30	9.60	8.17	3.86	1.88	1.22
		50	10	11.15	9.27	4.09	1.93	1.24
		0	20	10.90	9.52	4.87	2.47	1.62
		0	10	11.97	10.32	5.08	2.52	1.64
		-50	20	11.64	10.49	6.02	3.25	2.18
		-50	10	12.98	11.56	6.36	3.34	2.22

(Footnotes on p. 42)

Table 7--concl.

1/ All resistance values expressed in British thermal units per hour per square foot per degree Fahrenheit temperature difference. 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. Thermal resistance values for multiple air spaces must be based on careful estimates of mean temperature differences for each air space.

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

3/ Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

4/ 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 $\cong 0.00686E[(460 + t_m)/100]^3$, and t_m is the mean temperature of the air space. For interpretation from table 7 to air space thicknesses less than 0.5 in. (as in insulating window glass), assume $h_c = 0.795(1 + 0.0016)$ and compute R values from the above relations for an air space thickness of 0.2 in.

5/ 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.

6/ 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 table 6A).

The attic temperature calculated from the above equation neglects the effect of ventilation. Where the usual ventilation requirements are met, the ventilation rate is about 0.5 cubic foot per minute per square foot of ceiling area. Such ventilation reduces the difference between attic air temperature and outdoor temperature by approximately 50 percent. For other ventilation rates down to zero cubic foot per minute, the reduction is linear. For example, a ventilation rate of 0.1 cubic foot per minute reduces the temperature difference by about 10 percent.

Ground Temperatures

The ground temperature under basement floor slabs is about the same as water temperature at depths of 20 to 60 feet. This is not influenced by atmospheric conditions. Temperature of soil adjacent to basement walls is affected by outdoor temperature at locations near the surface. Frost penetrates to a depth of over 4 feet in some localities if the ground is not protected by snow; however, the ground temperature adjacent to the walls of a heated basement is greatly affected by the heat gain from the basement. The rate of heat flow through a basement wall decreases with depth because the total insulation provided by the soil depends on the distance to the surface. A precise calculation would be extremely difficult, and would involve such variables as the type of soil, but an approximate method of calculation has been developed by the National Research Council of Canada (5). Tables 8 and 9 present conductivity values that were experimentally derived. These values can simply be multiplied by the area of wall or floor and the temperature difference between indoors and outdoors. The effects of 1, 2, and 3 inches of insulation added to the basement walls are also shown. Windows and basement walls above ground should have heat loss calculated the same as other construction components exposed to outdoor temperatures.

Concrete slabs on grade are usually

Table 8.--Heat loss below grade in British thermal units per hour per degree Fahrenheit per square foot (from National Research Council of Canada, 1973)[1/]

Depth	Path length through soil	Heat loss			
		Uninsulated	Insulation		
			1 inch	2 inches	3 inches
Ft	Ft				
0-1	0.68	0.410	0.152	0.093	0.067
1-2	2.27	.222	.116	.079	.059
2-3	3.88	.155	.094	.068	.053
3-4	5.52	.119	.079	.060	.048
4-5	7.05	.096	.069	.053	.044
5-6	8.65	.079	.060	.048	.040
6-7	10.28	.069	.054	.044	.037

1/ Insulation with k = 0.24 Btu/(h)(ft^2)(°F/in.)
= 0.02 Btu/(h)(ft)(°F)
Soil k = 0.8 Btu/(h)(ft)(°F)

Table 9.--Mean basement floor heat loss in British thermal units per hour per degree Fahrenheit per square foot (from National Research Council of Canada, 1973)

Depth of foundation wall below grade	Width of house			
	20 feet	24 feet	28 feet	32 feet
Ft				
5	0.032	0.029	0.026	0.023
6	.030	.027	.025	.022
7	.029	.026	.023	.021

placed on a gravel fill 4 inches thick or more which helps insulate the floor from the earth and retards the rise of ground water by capillarity. A waterproof membrane should also be placed over the gravel fill. It is important that the floor be several inches above grade and have effective subsoil drainage. A slab that is soaked by rain or melting snow will have excessive heat loss. For design purposes the total heat loss for a concrete slab is dependent upon the length of exposed edge rather than the area of the slab. For small floor areas with no insulation, 0.81 Btu per hour may be used times the length of exposed edge in feet times the difference between indoor and outdoor temperature.

Heat Loss Computations

Total heat loss from a building can be divided into two major categories: (1) Transmission of heat through building elements and (2) infiltration of cold air that must be heated.

Transmission Heat Loss

Heat loss through a building element is calculated by multiplying the coefficient of transmission (U value) times the area of the element (wall, ceiling, floor, or window) times the difference between indoor and outdoor temperatures. *The U value is the reciprocal of* the total resistance of a combination of materials. First total the resistance of each material plus the resistance of air films on each face. Then divide this total into 1. Thermal resistance of most materials of construction is given in table 1, *and factors for air* spaces and air films are given in tables 6 and 7. For example, the *U* value for a typical wall section is calculated as follows:

	Resistance value
Interior surface resistance	0.68
Wallboard (½-in. gypsum)	.45
3½-inch blanket insulation (glass fiber)	11.00
Insulating board (½-in. regular density sheathing)	1.25
Wood bevel siding (½ by 8 in.)	.81
Exterior surface resistance (15-mph wind speed)	.17
Total resistance	14.36

$$U = \frac{1}{14.36} = 0.070$$

In many elements of construction, framing members (studs or joists) reduce overall thermal efficiency. The effect of framing members is often neglected, but for accurate heat loss computations framing must be considered. The adjustment factor for the wall shown above is calculated as follows:

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

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.

From the above example, total resistance is	14.36
Subtract resistance of insulation	−11.00
	3.36
Add resistance of 3½-inch softwood	4.35
Total resistance at wood stud	7.71

$$U_s = \frac{1}{7.71} = 0.130$$

From previous example, $U_i = 0.070$

If the wall backed by framing is 10 percent,

$$U_{av} = \frac{10}{100}(0.130) + 1 - \frac{10}{100}(0.070)$$

$$= 0.013 + 0.063 = 0.076$$

Infiltration Heat Loss

Infiltration heat loss includes both sensible and latent losses. The sensible heat loss is the heat required to warm the outdoor air entering by infiltration. Latent heat loss is the heat equivalent of any moisture which must be added to replace moisture being lost through infiltration.

Heat required to raise the temperature of air 1° F is the specific heat of air (0.240) times the density of air at outdoor temperature (assume "standard air" at 0.075 lb/ft³) times the volume of air in cubic feet per hour. This reduces to 0.018 times the volume of air. For the total sensible heat requirement, multiply 0.018 times the volume of air times the difference between indoor and outdoor temperature. When the volume is infiltration per hour, the heat load will be in Btu's per hour.

A certain amount of judgment is required regarding quality of construction and other factors in estimating infiltration by any method, so that infiltration is often based upon an estimated number of air changes per hour. One to one and one-half changes per hour is usually assumed for residences; however, this can be reduced by high quality construction. This is a total air change, including such sources as opening doors. The rate of infiltration may be computed by the crack-length method in which the rate of infiltration for a certain type of crack is multiplied by the length of the crack.

Latent heat is required to evaporate water when water vapor must be added for winter comfort conditions. Total heat needed is based on the volume of infiltration and the amount of water vapor per unit volume required to achieve the desired humidity. The equation for calculating the latent heat is (*3*):

$$H_l = Qp\,(W_i - W_o)\,h_{fg}$$

where

H_l is heat required to increase moisture content of air leaking into building from W_o to W_i Btu per hour,

Q is volume of outdoor air entering the building, cubic feet per hour,

p is density of air at temperature t_o, pounds per cubic feet,

W_i is humidity ratio of indoor air, pounds per pound of dry air,

W_o is humidity ratio of outdoor air, pounds per pound of dry air,

and

h_{fg} is latent heat of vapor at W_o, Btu per pound.

If the latent heat of vapor (h_{fg}) is assumed to be 1,060 Btu per pound and the air density is 0.075 pound per cubic foot, the equation reduces to:

$$H_l = 79.5\,Q(W_i - W_o)$$

Total Heat Loss

Total rate of heat loss is the sum of hourly rates of transmission and infiltration losses. Transmission loss for each element of the exterior envelope is the average "U" times the area of that element. Rate of infiltration heat loss is 0.018 times the volume of air change per hour. Latent heat loss is minor in most cases, and therefore, is usually disregarded in this type of calculation. Total seasonal loss in Btu's is the total rate of heat loss times 24 hours times adjusted heating degree days for a particular geographic location. Heating degree days are available from the local weather station and from utility and fuel companies. The degree day is a unit based upon temperature difference and time. For any one day, when the temperature is less than 65° F, there exist as many degree days as there are Fahrenheit degrees difference between the mean temperature for the day and 65° F. The base of 65° F to define the degree day was selected in the 1930's because the internal gain from such things as appliances plus the solar gain made up the difference between 65° F and the design indoor temperature. With better insulated houses and increased use of electrical appliances, the internal and solar gains now provide a larger part of heat required. Since the degree day base of 65° F is well established, a modification factor is used for arriving at an adjusted degree day. The factors for specific winter design temperatures are:

Outdoor design temp. F	-20	-10	0	+10	+20
Modification factor	0.57	0.64	0.71	0.79	0.89

Multiply the appropriate factor times the degree days to establish the adjusted degree days.

Seasonal fuel usage can be estimated by using values in table 10. Divide the total seasonal heat loss by the Btu's shown in table 10 for the type of fuel used to arrive at the units of fuel required for a heating season. Typical efficiencies are shown for heating equipment. The higher efficiency is for equipment in good operating condition. The lower rating is for equipment in need of maintenance or repairs.

Heat Gain Computations

Rate of heat gain through the building envelope is computed in a similar manner to heat loss calculations. Thermal resistance values are the same except that different values are given for heat flow down than for heat flow up, as indicated in table 7. These differences are particularly significant where reflective surfaces are used in conjunction with air spaces. Another difference in heat gain computations is the significant effect of solar heat gain on the walls. The absorption

Table 10.--Calorific values for fuel and combustion efficiency of small heating plants

Fuel	Unit	Type of firing	Approximate calorific value	Probable combustion efficiency
			Btu	Pct
Coal	Pound	Hand fired	12,000	50 to 55
Coal	Pound	Stoker	12,000	55 to 65
Oil	Gallon	Conversion burner	140,000	55 to 65
Oil	Gallon	Oil design unit	140,000	75 to 80
Manufactured gas	Cubic foot	Conversion burner	535	60 to 70
Manufactured gas	Cubic foot	Gas designed unit	535	75 to 80
Natural gas	Cubic foot	Conversion burner	1,000	60 to 70
Natural gas	Cubic foot	Gas designed unit	1,000	75 to 80

Table 11.--Design equivalent temperature differences (adapted from ASHRAE Handbook, 1977)

Construction	Daily temperature range[1/] and design temperature											
	Low			Medium				High				
	85	90	95	85	90	95	100	90	95	100	105	110
	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F	°F
WALLS AND DOORS												
Frame and veneer-on-frame	17.6	22.6	27.6	13.6	18.6	23.6	28.6	13.6	18.6	23.6	28.6	33.6
Masonry walls, 8-in. block or brick	10.3	15.3	20.3	6.3	11.3	16.3	21.3	6.3	11.3	16.3	21.3	26.3
Partitions												
Frame	9.0	14.0	19.0	5.0	10.0	15.0	20.0	5.0	10.0	15.0	20.0	25.0
Masonry	2.5	7.5	12.5	0	3.5	8.5	13.5	0	3.5	8.5	13.5	18.5
Wood doors	17.6	22.6	27.6	13.6	18.6	23.6	28.6	13.6	18.6	23.6	28.6	33.6
CEILINGS AND ROOFS[2/]												
Ceilings under naturally vented attic or vented flat roof												
Dark	38.0	43.0	48.0	34.0	39.0	44.0	49.0	34.0	39.0	44.0	49.0	54.0
Light	30.0	35.0	40.0	26.0	31.0	36.0	41.0	26.0	31.0	36.0	41.0	46.0
Built-up roof, no ceiling												
Dark	38.0	43.0	48.0	34.0	39.0	44.0	49.0	34.0	39.0	44.0	49.0	54.0
Light	30.0	35.0	40.0	26.0	31.0	36.0	41.0	26.0	31.0	36.0	41.0	46.0
Ceilings under unconditioned rooms	9.0	14.0	19.0	5.0	10.0	15.0	20.0	5.0	10.0	15.0	20.0	25.0
FLOORS												
Over unconditioned rooms	9.0	14.0	19.0	5.0	10.0	15.0	20.0	5.0	10.0	15.0	20.0	25.0
Over basement, enclosed crawl space, or concrete slab-on-ground	0	0	0	0	0	0	0	0	0	0	0	0
Over open crawl space	9.0	14.0	19.0	5.0	10.0	15.0	20.0	5.0	10.0	15.0	20.0	25.0

1/ Daily temperature range calculation value: Low--12° F, applicable range is less than 15° F; medium--20° F, applicable range is 15° to 25° F; high--30° F, applicable range is more than 25° F.

2/ For roofs in shade, 18-h average = 11° F temperature differential. At 90° F design and medium daily range, equivalent temperature differential for light-colored roof equals 11 + (0.71)(39 - 11) = 31° F.

of solar heat has the effect of changing the temperature differential between indoors and outdoors. This temperature differential varies with the time of day, sun angle, and wall color. To compensate for these variations, equivalent temperature differentials for various materials and exposures were developed from actual temperature measurements (table 11). Equivalent temperature differentials are merely used in place of the difference between indoor and outdoor air temperature for calculating heat transfer.

The heat transfer methods that have been presented were based on the steady-state heat flow concept which has served well for many years. These concepts are relatively uncomplicated to apply and result in a good degree of accuracy; however, they do not account for the heat storage effects of the building structure. This heat storage capacity has a greater effect on heat gain to air-conditioned spaces than on heat loss. More sophisticated methods of calculating heating and cooling loads have been developed; one of them, the response factor method, involves complex mathematical treatment. Computer programs have been developed and are available at both the National Research Council and the National Bureau of Standards.

Thermal Performance of Assemblies

Information has been presented for calculating heat flow through various combinations of materials. For convenience of the designer, thermal coefficients of some commonly used assemblies are presented in tables 12 through 15. In these tables, *U* values are given for several typical frame construction assemblies. Where an air space is included in the table, the *U* value is based on the assumption that the air space is empty and that its surfaces are of ordinary building materials of low thermal reflectivity. Variations in conditions, materials, or workmanship may cause variations in the *U* value greater than variations resulting from mean temperature differences, so temperature differences are not reflected in these tables.

To calculate thermal coefficients for various amounts of insulation added to the air spaces of these assemblies, simply subtract the resistance of the air space from the total resistance of the assembly and add the resistance of the insulating material. Thermal coefficients for heat flow through walls are the same for winter and summer; however, for ceilings, different coefficients are used for heat flow up and heat flow down.

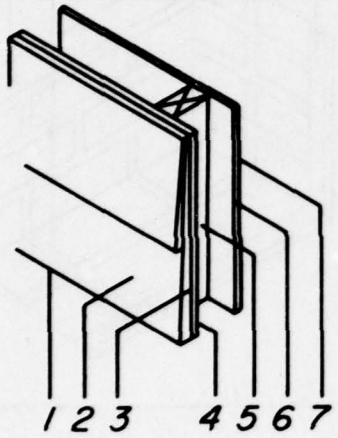
Enhancing Thermal Performance

Thermal performance of ceilings can usually be enhanced by simply adding to the thickness of insulation. Where structural spaces restrict the insulation thickness, such as in a wall cavity, methods of adding insulation are more complex. Some possibilities include compressing fibrous insulation into a smaller cavity; making a larger cavity, such as by using 6-inch wall studs (*11*); or adding a rigid foam to one side of the construction assembly to supplement normal stud space insulation.

Fibrous insulation in batt or blanket form is usually manufactured in an efficient density. Compressing these insulations into lesser thicknesses reduces their thermal resistance. The amount of reduction is shown in figure 10. Even with the reduced thermal resistance, the compressed insulation may have a higher resistance than the blanket manufactured to fill a cavity; however, the added resistance may not be adequate to justify the differences in cost between the two thicknesses.

The wall cavity is conventional wood-frame construction is 3½ inches thick because 2 by 4 framing members are used. Increasing the framing size to 2 by 6's would provide space for an additional 2 inches of insulation. This system would permit the use of R-19 insulation, although if the thickness is 6 inches, compressing it into a 5½-inch cavity would reduce its value to R-18. The use of ½-inch fiberboard sheathing would bring the total back to R-19 without covering materials. Advocates of this system point out that 2 by 6 studs permit 24-inch spacing, as opposed to the commonly used 16-inch spacing with 2 by 4's. (The 24-inch spacing cuts

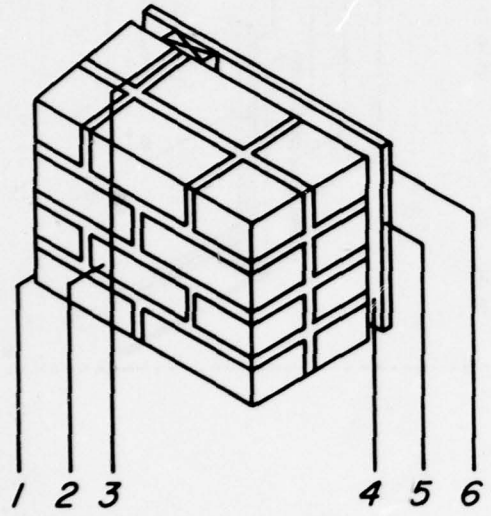
Table 12.--Coefficient of transmission (U) of frame walls--replace air space with 3.5-inch R-11 blanket insulation (adapted from ASHRAE Handbook, 1977)

Construction	Resistance (R)			
	Construction No. 1[1/]		Construction No. 2[2/]	
	Between framing (R_i)	At framing (R_s)	Between framing (R_i)	At framing (R_s)
				
1. Outside surface (15 mph wind)	0.17	0.17	0.17	0.17
2. Siding, wood, 0.5 x 8 in. lapped (average)	.81	.81	.81	.81
3. Sheathing, 0.5-in. asphalt impregnated	1.32	1.32	1.32	1.32
4. Nonreflective air space, 3.5 in. (50° F mean; 10° F temperature difference)	1.01	--	11.00	--
5. Nominal 2- x 4-in. wood stud	--	4.38	--	4.38
6. Gypsum wallboard, 0.5 in.	.45	.45	.45	.45
7. Inside surface (still air)	.68	.68	.68	.68
Total thermal resistance (R)	4.44	7.81	14.43	7.81

1/ $U_i = 1/4.44 = 0.225$; $U_s = 1/7.81 = 0.128$. With 20 pct framing (typical of 2- x 4-in. studs 16 in. on center), $U_{av} = 0.8(0.225) + 0.2(0.128) = 0.206$ (see eq. 9).

2/ $U_i = 1/14.43 = 0.069$; $U_s = 0.128$. With framing unchanged, $U_{av} = 0.8(0.069) + 0.2(0.128) = 0.081$.

Table 13.--Coefficient of transmission (U) of solid masonry walls--replacing furring strips and air space with 1-inch extruded polystyrene (adapted from ASHRAE Handbook, 1977)

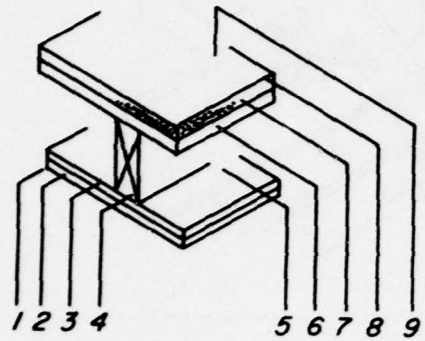


Construction	Resistance (R) for construction No. 1 1/		Construction No. 2 2/
	Between furring (R_i)	At furring (R_s)	(R_i)
1. Outside surface (15 mph wind)	0.17	0.17	0.17
2. Common brick, 8 in.	1.60	1.60	1.60
3. Nominal 1- x 3-in. vertical furring	--	.94	--
4. Nonreflective air space, 0.75 in. (50° F mean; 10° F temperature difference)	1.01	--	5.00
5. Gypsum wallboard, 0.5 in.	.45	.45	.45
6. Inside surface (still air)	.68	.68	.68
Total thermal resistance (R)	3.91	3.84	7.90 = R_s

1/ $U_i = 1/3.91 = 0.256$; $U_s = 1/3.84 = 0.260$. With 20 pct framing (typical of 1- x 3-in. vertical furring on masonry 16 in. on center), $U_{av} = 0.8(0.256) + 0.2(0.260) = 0.257$.

2/ $U_i = U_s = U_{av} = 1/7.90 = 0.127$.

Table 14.--Coefficients of transmission (U) of wood construction flat roofs and ceilings--winter conditions, upward flow (adapted from ASHRAE Handbook, 1977)[1]

Construction (heat flow up)	Resistance (R)			
	Construction No. 1[2/]		Construction No. 2[3/]	
	Between joists (R_i)	At joists (R_s)	Between joists (R_i)	At joists (R_s)
				
1. Inside surface (still air)	0.61	0.61	0.61	0.61
2. Acoustical tile, fiberboard, glued, 0.5 in.	1.25	1.25	1.25	1.25
3. Gypsum wallboard, 0.5 in.	.45	.45	.45	.45
4. Nominal 2- x 8-in. ceiling joists	--	9.06	--	9.06
5. Nonreflective air space, 7.25 inches (50° F mean; 10° F temperature difference)	.93	--	1.05	--
6. Plywood deck, 0.625 in.	.78	.78	.78	.78
7. Rigid roof deck insulation, c = 0.72 (R = 1/C)	1.39	1.39	19.00	--
8. Built-up roof	.33	.33	.33	.33
9. Outside surface (15 mph wind)	.17	.17	.17	.17
Total thermal resistance (R)	5.91	14.04	23.64	12.65

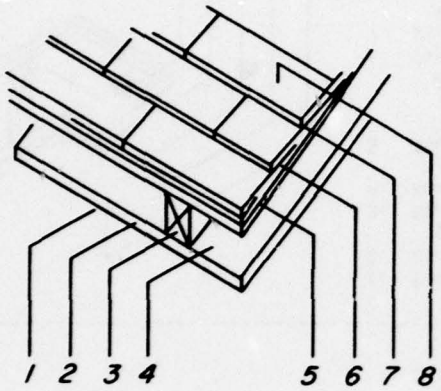
1/ Coefficients are expressed in British thermal units per hour per square foot per degree Fahrenheit difference in temperature between the air on the two sides, and are based upon an outside wind velocity of 15 mph.

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

3/ Construction No. 2: Roof deck insulation and 7.25-in. air space with 6-in. R-19 blanket insulation and 1.25-in. air space. $U_i = 1/23.64 = 0.042$; $U_s = 1/12.65 = 0.079$. With framing unchanged, $U_{av} = 0.9(0.042) + 0.1(0.079) = 0.046$.

Table 15.--Coefficients of transmission (U) of pitched roofs (adapted from ASHRAE Handbook, 1977)[1]

Construction No. 1--heat flow up, reflective air space	Construction No. 1[2]		Construction No. 2[3]	
	Between rafters (R_i)	At rafters (R_s)	Between rafters (R_i)	At rafters (R_s)
1. Inside surface (still air)	0.62	0.62	0.76	0.76
2. Gypsum wallboard, 0.5 in., foil backed	.45	.45	.45	.45
3. Nominal 2- x 4-in. ceiling rafter	--	4.38	--	4.38
4. 45° slope reflective air space, 3.5 in. (50° F mean, 30° F temperature difference)	2.17	--	4.33	--
5. Plywood sheathing, 0.625 in.	.78	.78	.78	.78
6. Felt building membrane	.06	.06	.06	.06
7. Asphalt shingle roofing	.44	.44	.44	.44
8. Outside surface (15 mph wind)	.17	.17	.25	.25
Total thermal resistance (R)	4.69	6.90	7.07	7.12



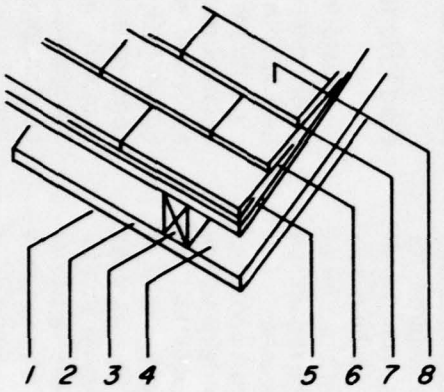
1/ Coefficients are expressed in British thermal units per hour per square foot per degree Fahrenheit difference in temperature between the air on the two sides, and are based on an outside wind velocity of 15 mph for heat flow upward and 7.5 mph for heat flow downward.

2/ $U_i = 1/4.69 = 0.213$; $U_s = 1/6.90 = 0.145$. With 10 pct framing (typical of 2-in. rafters 16 in. on center), $U_{av} = 0.9(0.213) + 0.1(0.145) = 0.206$.

3/ U_{av} for construction 2 with heat flow down (summer conditions). $U_i = 1/7.07 = 0.141$; $U_s = 1/7.12 = 0.140$. With framing unchanged, $U_{av} = 0.9(0.141) + 0.1(0.140) = 0.141$.

Table 15A.--Coefficients of transmission (U) of pitched roofs (adapted from ASHRAE Handbook, 1977)[1]

Construction No. 3--heat flow up, nonreflective air space	Construction No. 3[2]		Construction No. 4[3]	
	Between rafters (R_i)	At rafters (R_s)	Between rafters (R_i)	At rafters (R_s)
1. Inside surface (still air)	0.62	0.62	0.76	0.76
2. Gypsum wallboard, 0.5 in.	.45	.45	.45	.45
3. Nominal 2- x 4-in. ceiling rafter	--	4.38	--	4.38
4. 45° slope, nonreflective air space, 3.5 in. (50° F mean; 10° F temperature difference)	.96	--	.90	--
5. Plywood sheathing, 0.625 in.	.78	.78	.78	.78
6. Felt building membrane	.06	.06	.06	.06
7. Asphalt shingle roofing	.44	.44	.44	.44
8. Outside surface (15 mph wind)	.17	.17	.25	.25
Total thermal resistance (R)	3.48	6.90	3.64	7.12



1/ Coefficients are expressed in British thermal units per hour per square foot per 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 for heat flow downward.

2/ $U_i = 1/3.48 = 0.287$; $U_s = 1/6.90 = 0.145$. With 10 pct framing (typical of 2-in. rafters 16 in. on center), $U_{av} = 0.9(0.287) + 0.1(0.145) = 0.273$.

3/ U_{av} for construction 4 with heat flow down (summer conditions). $U_i = 1/3.64 = 0.275$; $U_s = 1/7.12 = 0.140$. With framing unchanged, $U_{av} = 0.9(0.275) + 0.1(0.140) = 0.262$.

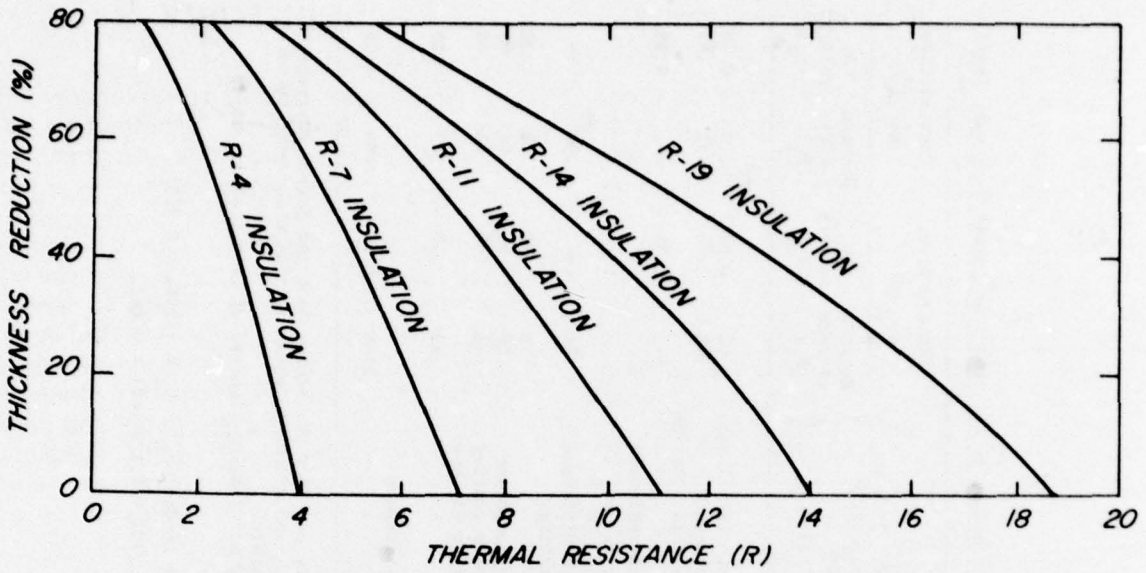


Figure 10.—Reduction in thermal resistance of fibrous insulation due to compression to reduce thickness. (From HUD Mobile Homes Federal Construction and Safety Standards, 1976).
(M 146 478)

down on the area of framing in the wall.) However, major model building codes as well as HUD Minimum Property Standards for One- and Two-Family Dwellings (*15*) permit 2 by 4 studs at 24-inch spacing, so the reduction in area of framing by wider spacing of studs could be used to advantage regardless of whether 2 by 4's or 2 by 6's are used.

The addition of rigid foam to a construction assembly could add materially to the thermal resistance. This could be in the form of sheathing applied to the outside face of studs. Such an application has the advantage of being continuous over the whole wall including the framing. Thus it creates a barrier at the stud which is otherwise a continuous thermal bridge. The insulating value of a polystyrene foam panel having a resistance of 5.26 added to R-13 batt insulation results in a total R of 18.26. This R is comparable to R-19 insulation used in wall sections employing 6-inch studs. The closed cell, rigid foams are somewhat resistant to transmission of water vapor, so in cold climates a good vapor barrier on the warm face of the wall is critical when foam is used on the cold side of the wall. Rigid insulation must be continuous over the entire face with all holes patched for optimum effectiveness.

Code Requirements

Historically, building codes have been safety oriented, and so have not been concerned with energy conservation. HUD Minimum Property Standards (*15*) has included insulation requirements because of concerns for resale value, but prior to 1974 these requirements were not adequate for energy conservation. Since then a more stringent standard has been developed—ASHRAE Standard 90-75 (*2*) which is intended to serve as a national energy standard for new buildings. It is applicable to all houses insured via government loan programs and is recognized by many local code authorities. As this standard is adopted by local code authorities, it is likely to be modified, so there will be many variations. Therefore, the final design of a building remains governed by the applicable local code.

The energy standards are stated in terms of maximum "U" values for the particular element of construction for specific degree-day regions. This value is the recipro-

cal of the sum of resistances including surface air films ($U = \frac{1}{R}$). These maximum values are given in tables 16 and 17. Requirements for slab edge insulation are given in table 18. Variations from these values are permitted by most standards. The following example is given in paragraph 607-3.2(b) of HUD Minimum Property Standards: "Where the stated *U* value of any one component of roof deck, ceiling, wall, or floor cannot be practically obtained, such *U* value may be increased to the maximum figure attainable and the *U* value for other components decreased until the overall heat gain or heat loss does not exceed the total resulting from conformance to the stated *U* values."

SUMMARY

This paper has surveyed energy efficiency in light-frame construction. An understanding of the principles presented should help the designer to plan an energy-efficient house.

The increased use of insulation in recent years has resulted in energy savings, but there are practical limits to savings from insulation alone. One of the largest sources of heat loss is often air leakage, or infiltration. Air leakage can be reduced by good quality windows and doors and generally tight construction. Additional savings are possible by incorporating natural climate control which includes shape and

Table 16.--Maximum "U" values for ceilings, walls, and openings (from HUD Minimum Property Standards, 1977)

Building component	Winter degree-days (65° F base)			
	2,500 or less	2,501 to 4,500	4,501 to 8,000	8,001 or more
Roof deck[1/]	[2/]0.14	0.08	0.08	0.08
Ceiling	.05	.05	.05	.04
Masonry walls	.10	.10	.10	.10
Frame walls	.08	.08	.08	.08
Doors and windows[3/]	1.13	1.13	.69	.69

1/ Roof/ceiling assemblies, in which the finished ceiling surface is the underside of the roof deck.
2/ When mechanical cooling is proposed, use 0.08.
3/ Maximum glass area shall not exceed 15 pct of the gross area of all exterior walls enclosing heated spaces, except when demonstrated that the winter daily solar heat gain exceeds the 24-h heat loss.

orientation of the house, size and placement of windows, shading, and wind patterns.

Environmental design requirements must be known for effective planning. These are presented both in terms of climate zones and indoor human comfort levels.

Properties of insulating materials and the effect of environmental conditions on these properties are essential for determining optimum methods of construction. This information is given and followed by instructions for making heating and cooling load calculations. Finally, the thermal performance of some typical frame assemblies is presented, and methods of enhancing thermal performance of assemblies are given.

Table 17.--Maximum "U" values for floors over unheated spaces, or for foundation wall sections of heated underfloor spaces (from HUD Minimum Property Standards, 1977)

Winter degree-days (65° F base)	Maximum "U" value[1/]	Winter degree-days (65° F base)	Maximum "U" value[1/]
MAXIMUM "U" VALUE OF FLOOR SECTIONS OVER UNHEATED BASEMENTS, UNHEATED GARAGES, OR CRAWL SPACES[2/]		MAXIMUM "U" VALUES OF THE FOUNDATION WALL SECTIONS OF HEATED BASEMENT OR HEATED CRAWL SPACE	
500 or less	0.36	2,500 or less	No requirement
1,000	.32	2,501 to 4,500	0.24
2,000	.26	4,501 or more	.17
3,000	.19		
4,000	.12		
4,501 or more	.08		

1/ For increments between degree-days shown, "U" values may be interpolated, or the values shown in fig. 5 of ASHRAE 90-75 may be substituted.

2/ A basement, crawl space, or garage shall be considered unheated unless it is provided with a positive heat supply to maintain a minimum temperature of 50° F. Positive heat supply is defined by ASHRAE as "heat supplied to a space by design or by heat losses occurring from energy-consuming systems or components associated with that space."

Table 18.--Minimum "R" values of perimeter insulation for slabs-on-grade (from HUD Minimum Property Standards, 1977)

Winter degree-days (65° F base)	Minimum "R" values[1/]		Winter degree-days (65° F base)	Minimum "R" values[1/]	
	Heated slab	Unheated slab		Heated slab	Unheated slab
500 or less	2.8	--	5,000	6.3	4.2
1,000	3.5	--	6,000	7.0	4.8
2,000	4.0	--	7,000	7.8	5.5
2,500	4.4	2.5	8,000	8.5	6.2
3,000	4.8	2.8	9,000	9.2	6.8
4,000	5.5	3.5	10,000 or greater	10.0	6.5

1/ For increments between degree-days shown, "U" values may be interpolated, or the values shown in fig. 2 of ASHRAE 90-75 may be substituted.

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