Chapter Four

Heat Flow and Thermal Insulation

This chapter will examine the exchange of heat between a building and the external environment. In industrialized countries the energy used to heat buildings in winter, and to a lesser extent cool buildings in summer since fewer homes have air conditioning facilities, constitutes a significant portion of the total energy consumption. For example, in the US more than 25% of the total energy consumption is attributable to buildings. About two-thirds of this energy is used for heating and cooling purposes. Even today, in the year 2007, more than 80% of this energy is still produced by fossil fuels, such as oil and coal.

4.1 The Need for Energy Conservation

Prior to the energy crisis that was precipitated by the Middle East oil embargo of the early 1970s, energy was considered to be an inexpensive commodity in the US. As a consequence architects had little opportunity to apply their creativity and skills to building designs that utilized natural means for the heating, cooling, and lighting of buildings. The impact of an abrupt shortage of oil and dramatic escalation of the cost of energy was twofold. First, there was an immediate call for the conservation of energy and, second, the Government sponsored many concurrent research programs aimed at devising methods for maximizing the use of natural sources of energy such as the sun, wind, and daylight in buildings.

It was noted with alarm by the California State Utilities Commission that at the current rate of consumption all of the remaining natural gas would need to be diverted from commercial and industrial uses to residential heating by 1979. At the same time, the availability of fuel oil was becoming increasingly limited due to political and economic factors, while the conversion of coal to a more directly useful form of energy, such as electricity, carried with it the problem of unacceptable levels of pollution. Faced with this potentially serious situation the US Government mobilized all of its responsible agencies and embarked on a massive program of research and incentives to drastically reduce the reliance on foreign imports of energy. To a large extent this program has continued to the present day and is unlikely to subside to any appreciable extent over the foreseeable future.

Three strategies were immediately implemented in the architecture, engineering and construction industry as a means of conserving the world's dwindling supplies of fossil fuel.

Strategy A: **Utilize all energy as efficiently as possible.** This strategy placed the emphasis on thermal insulation. Prior to 1970, the thermal insulation of buildings had not been mandatory in states such as California. It was realized that if by the stroke of a magic wand all existing building envelopes in the US could be provided with the equivalent of three inches of polyurethane insulation overnight, then from the next day onward this would decrease the total national energy consumption by more than 10%. A second focus was placed on improving the efficiency of heating systems such as electric resistance heaters and fireplaces, and household appliances such as refrigerators.

Strategy B: **Utilize less energy.** Reduce the requirement for energy by careful planning, design and construction, as well as the reevaluation of comfort standards. It was realized that an emphasis on daylighting could substantially reduce the need for artificial lighting and a consequential reduction in cooling loads. Research showed that it was not unusual for high-rise office buildings in colder climates to require cooling in winter, due to the heat produced by artificial lights. It was estimated that through the provision of more daylight it would be possible to reduce the average artificial light design loads in office buildings by 50% (i.e., from the prevalent 4 watt per square foot to less than 2 watt per square foot).

Strategy C: **Utilize alternative energy sources.** Natural sources such as solar energy, wind, nuclear power, geothermal energy, and natural gas, were targeted as promising alternatives to fossil fuel. Of these, solar energy immediately assumed a prominent position as an attractive source of hot water and space heating for single family houses.

The need for adequate thermal insulation cannot be overstated. Buildings are normally exposed to direct solar radiation and therefore walls and roof will be subjected to temperatures of 120˚F or more. This temperature in the sun is also referred to as the sol-air temperature. By providing adequate insulation in the building shell, the rate at which heat is transferred can be limited with subsequent reduction in the capital and operating cost of heating and refrigeration plants. The major purpose of insulation is then, the conservation of heat or cold within a building environment by maintaining temperature differences between this environment and ambient external conditions.

4.2 How is Heat Transferred?

Heat is a form of energy and is therefore a physical quantity that may be measured objectively. In the American system of units (i.e., formerly the British system before the United Kingdom adopted the Metric system of units) heat is expressed in terms of British Thermal Units (BTU). One BTU is defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. Similarly, in the Metric system the Calorie heat unit is defined as the amount of heat required to raise the temperature of one kilogram of water by one degree Centigrade. The heat required for this one degree rise in temperature is to a slight extent dependent on the actual temperature of the water and therefore for precise measurements the temperature of the water should be around 60ºF (or 15ºC).

Heat may appear in either of two forms, namely:

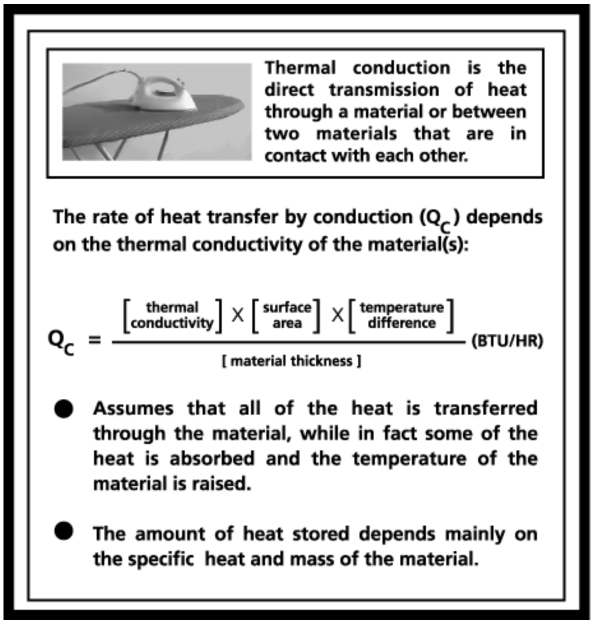
Sensible heat, which is associated with a change of temperature of the substance involved. By virtue of its name, changes in sensible heat are perceived by the senses.

Latent heat, which is the thermal energy used during a change of state of a substance while the temperature remains unaltered. Latent heat cannot be perceived by the senses.

For example, when ice is heated, the heat is absorbed as sensible heat until the melting point is reached. At this stage any further addition of heat will not cause a rise in temperature until all of the ice has melted. Latent heat is therefore absorbed to produce a change of state from ice to water. The addition of more heat to the water will be accompanied by proportionate increases in temperature until boiling point is reached. Thereafter, latent heat will be absorbed by the water to facilitate a further change of state, until all of the water has been converted to steam.

The concepts of heat and temperature are closely interrelated. In fact, it is very difficult to provide a satisfactory definition for either heat or temperature without implying the other. To overcome this difficulty, it has been suggested that the concept of thermal equilibrium might form a convenient starting point. Accordingly, for purposes of definition, two bodies are said to be at the same temperature if they remain in thermal equilibrium when brought into contact with each other, and scales of temperature are related to certain measurable physical properties such as the volumetric expansion of mercury (e.g., a thermometer).

Heat is said to pass from one system or substance to another if the two systems are at different temperatures and in contact with each other. This heat transfer, which always occurs from a region of high temperature to a region of low temperature, may proceed by conduction, convection, or radiation, or any combination of these.



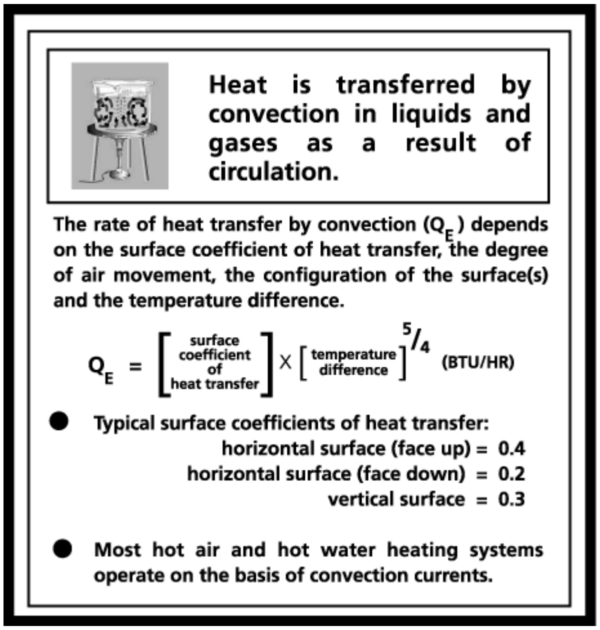
Thermal conduction is the direct transmission of heat through a material or between two materials that are in contact with each other.

The rate of heat transfer by conduction (Q_C) depends on the thermal conductivity of the material(s):

$$Q_C = \frac{[\text{thermal conductivity}] \times [\text{surface area}] \times [\text{temperature difference}]}{[\text{material thickness}]} \text{ (BTU/HR)}$$

- **Assumes that all of the heat is transferred through the material, while in fact some of the heat is absorbed and the temperature of the material is raised.**
- **The amount of heat stored depends mainly on the specific heat and mass of the material.**

Figure 4.1: Heat transfer by conduction



Heat is transferred by convection in liquids and gases as a result of circulation.

The rate of heat transfer by convection (Q_E) depends on the surface coefficient of heat transfer, the degree of air movement, the configuration of the surface(s) and the temperature difference.

$$Q_E = \left[\begin{matrix}\text{surface}\\\text{coefficient}\\\text{of}\\\text{heat transfer}\end{matrix}\right] \times \left[\begin{matrix}\text{temperature}\\\text{difference}\end{matrix}\right]^{5/4} \text{ (BTU/HR)}$$

- **Typical surface coefficients of heat transfer:**
  horizontal surface (face up) = 0.4
  horizontal surface (face down) = 0.2
  vertical surface = 0.3
- **Most hot air and hot water heating systems operate on the basis of convection currents.**

Figure 4.2: Heat transfer by convection

Conduction: Thermal conduction is the direct transmission of heat through a material or between two materials in direct contact with each other (Figure 4.1). All substances, whether solid, liquid or gas will conduct heat, the rate of transfer depending on the thermal conductivity of the substance.

$$\mathbf{Q_C = k\,A\,(T_1 - T_2) / t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{(4.1)}$$

where: Q_C = total heat transfer by conduction
k = thermal conductivity of material
A = contact surface area
t = thickness of material
$(T_1 - T_2)$ = temperature difference

Equation (4.1) applies to a homogenous material under steady state temperature conditions, when a temperature differential (i.e., ($T_1 – T_2$)) exists between the two opposite faces of the material. The assumption of steady state temperature conditions is a significant and convenient one. It implies that all of the heat is transferred through the material; while in fact some of the heat is absorbed, thereby raising the temperature of the material. The amount of heat stored in any material is referred to as its heat capacity and depends mainly on the specific heat and density of the material (i.e., heat capacity is equal to specific heat multiplied by density).

Convection: Heat is transmitted by convection in fluids and gases as a result of circulation. For example, when air is heated it expands and rises, thus allowing colder air to take its place. In the case of buildings, heat transfer by convection takes place at roof and wall surfaces, around heating and cooling units or wherever a material is exposed to air at a different temperature. Consequently, heat loss by convection is a function of the surface coefficient of heat transfer and depends largely on the degree of air movement, the shape and dimensions of the surface and the temperature differential which exists between the air and the surface (Figure 4.2):

$$Q_E = S_C (T_1 - T_2)^{5/4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

where: Q_E = total heat transfer by convection
S_C = coefficient of convective heat transfer
  S_c = 0.4 for horizontal surface (face up).
  S_c = 0.3 for vertical surface.
  S_c = 0.2 for horizontal surface (face down).

Apart from the operation of hot air and hot water heating systems in buildings, convection has far-reaching effects on climatic conditions. Near the equator intense solar radiation will produce considerable thermal air currents, while ocean currents such as the Gulf Stream are also largely produced by convection.

Radiation: Radiant heat transfer is the process of the conversion of heat energy in a substance into electro-magnetic radiation, and the subsequent reconversion of this radiant energy into heat of absorption by another substance in its path. The intensity of radiation emitted by a substance is very much dependent on the type of material and temperature (Figure 4.3). The net heat radiation between two surfaces at different temperatures is given by:

$$Q_R = E_e A (T_1^4 - T_2^4) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

where: Q_C = total heat transfer by radiation
A = surface area
E_e = factor which takes into account the emissivities of the surfaces involved (dimensionless). If "e_1" and "e_2" are the respective emissivities of two parallel surfaces, then: $E_e = (e_1 e_2) / (e_1 + e_2 - 1)$, particular values of E_e for specific situations such as two square surfaces at right angles to each other, and so

on, may be obtained from the ASHRAE Handbook of Fundamentals, 1989.

$(T_1 - T_2)$ = temperature difference

Generally speaking, light surfaces are better reflectors than dark surfaces, although bright metallic surfaces are much more efficient in reflecting short wavelength solar radiation than long wavelength low temperature radiation (Figure 4.4). On the other hand, the opposite is true for white paint.

In radiant heat transfer heat energy is converted into electro-magnetic radiation and reconverted to heat through absorption by another substance in its path.

The rate of heat transfer by radiation (Q_R) depends on the emissivities of the surfaces involved and the temperature difference between the surfaces.

$$Q_R = \left[\text{emissivity factor (E)}\right] \times \left[\text{surface area}\right] \times \left[T_1^4 - T_2^4\right] \quad \text{(BTU/HR)}$$

- **For two parallel surfaces whose emissivities are 'e_1' and 'e_2', respectively, the emissivity factor is given by:**

$$E = \frac{e_1 \times e_2}{e_1 + e_2 - 1}$$

- **Radiant heat transfer is not impacted by air movement.**

Figure 4.3: Heat transfer by radiation

- **Light surfaces are better reflectors of radiation than dark surfaces.**
- **Bright metallic surfaces are very efficient in reflecting solar radiation (i.e., more efficient than white paint).**
- **Reflectivity = (1 - emissivity).**

Type of Surface Material	Reflectivity in Respect to Solar Radiation
aluminum	0.80
galvanized steel	0.45
white paint	0.70
black paint	0.10
cream bricks	0.40
red tiles	0.30

Figure 4.4: Reflectivity and emissivity

The reader may feel that there exists an apparent anomaly in relation to the dark skin color prevalent among indigenous people in the tropics. One would expect a light-colored skin to have better reflecting properties and therefore provide more protection to the human body. In fact, in dark skinned races, the pigment is deposited in the superficial layers of the skin and serves as a screen to filter out the potentially harmful rays in solar radiation. Ultra-violet light is emitted by the sun, and is even more abundantly reflected from a blue sky. If applied to the skin suddenly and in large doses, inflammation, wheeling and blistering (i.e., sunburn) will result. Consequently, pigmentation of the skin is believed to lessen the possibility of injury from solar radiation.

4.3 Steady State Heat Transfer Assumptions

Since the desired thermal building environment is at most times different from ambient atmospheric conditions, there will exist a temperature differential between indoor and outdoor regions. Accordingly, the amount of heat transferred through the building envelope must be closely related to the heat exchange parameters at the surfaces of the envelope layers (if composite) and the thermal properties of the materials. These parameters may be conveniently grouped into three broadly defined categories (Figure 4.5):

Enclosure factors such as the thermal properties of materials of construction, orientation, planning, and design specifications.

Climatic factors involving thermal indices such as temperature, radiation, and air movement.

Occupancy factors such as the functional use of a building space that will establish the required comfort conditions and resultant heat loads.

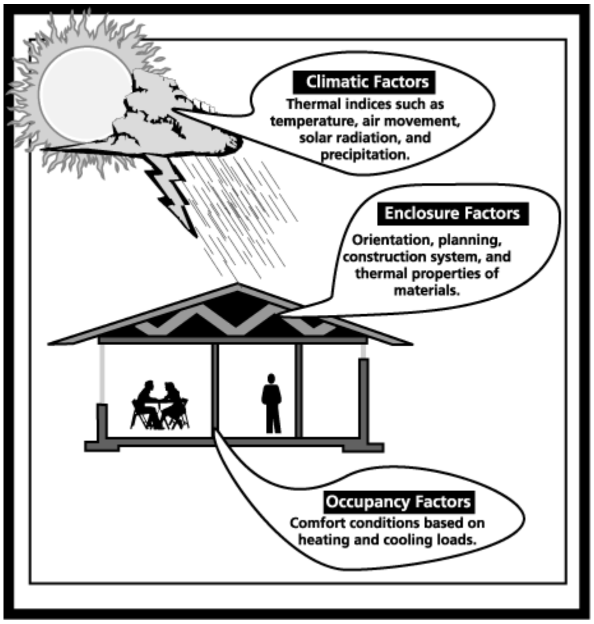
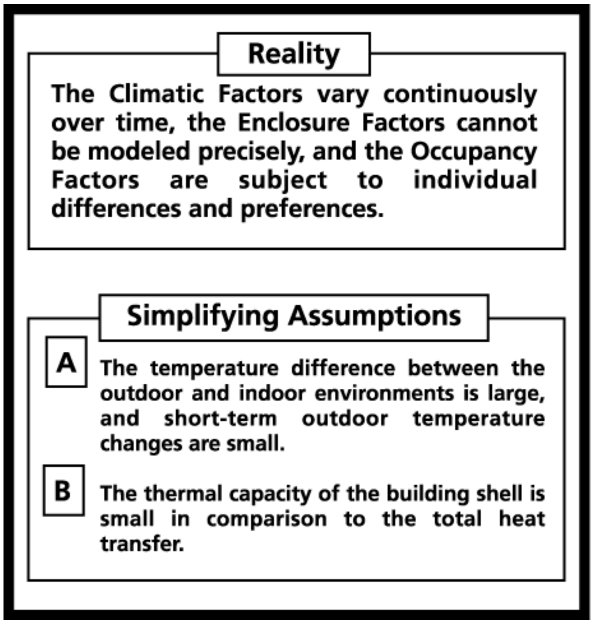


Figure 4.5: Heat transfer parameters



Reality

The Climatic Factors vary continuously over time, the Enclosure Factors cannot be modeled precisely, and the Occupancy Factors are subject to individual differences and preferences.

Simplifying Assumptions

A **The temperature difference between the outdoor and indoor environments is large, and short-term outdoor temperature changes are small.**

B **The thermal capacity of the building shell is small in comparison to the total heat transfer.**

Figure 4.6: Steady state assumptions

While all of these parameters may be assigned numerical values at any particular time, some of them, in particular the climatic factors are subject to considerable short-term change. Strictly speaking therefore, heat transfer through building walls and roofs is of an unsteady character. However, to avoid the relatively complex calculations that are necessary to determine the time dependent properties of systems of construction, it is common practice to assume very much simplified thermal boundary conditions; namely that the indoor temperature is constant and that either steady heat flow or periodic heat flow conditions apply.

Although steady state heat transfer does not exist in practice, since the outdoor climate fluctuates continuously, it nevertheless does provide a reasonable estimate of the heat flow through a building envelope if the following two conditions are satisfied (Figure 4.6):

Condition 1: When the temperature difference between the outdoor and indoor environments is large and short-term changes in outdoor temperature are small.

Condition 2: When the thermal capacity of the building shell is small in comparison with the total heat transferred.

In practice, heat is transferred through a building envelope by more than one mode of heat transfer. For example, in the case of prefabricated concrete wall panels heat is first transmitted from the air on one side of the panel to the nearest surface mainly by convection, then the heat is conducted through the wall panel, and finally the heat is transferred from the opposite surface by convection to the surrounding air. Accordingly, the rate of heat transfer through a building component is determined not only by the thermal resistance of the material but also by that of the two surfaces. It is normal practice to combine these various resistivities into a single factor, known as the thermal transmittance or U-value (Figure 4.7).

$$\mathbf{Q = U\,A\,(T_1 - T_2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{(4.4)}$$

where: Q = total heat transfer (BTU/HR)
U = overall thermal transmittance value (BTU/SF-HR-^{o}F)
A = surface area (SF)
$(T_1 - T_2)$ = temperature difference (^{o}F)

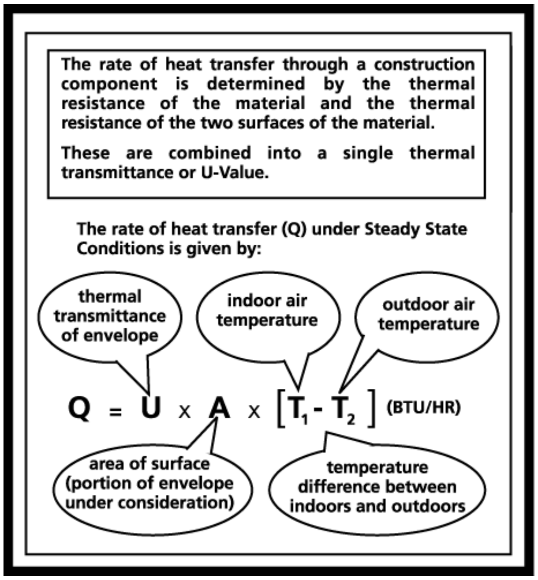


Figure 4.7: Steady state heat transfer through the building envelope

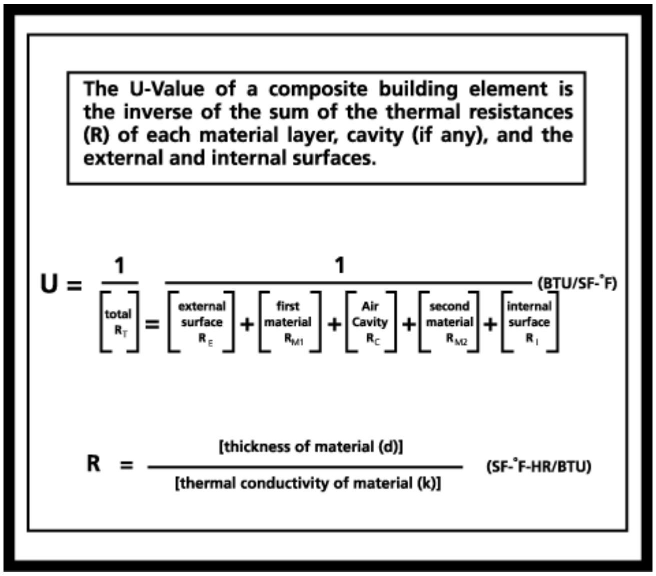


Figure 4.8: Calculation of the thermal transmittance or U-value of a construction assembly

As shown in Figure 4.8, the thermal transmittance for a composite building wall is the reciprocal of the sum of the thermal resistances of the external surface, each layer of material, cavity (if any), and the internal surface. Since the thermal resistance of any material of specified thickness is given by the ratio of the thickness (d) to the thermal conductivity (k), the total resistance of "i" layers of a composite element is given by:

$$R_{total} = \text{(resistance of ext. surface)} + d_1/k_1 + d_2/k_2 + \ldots\ d_i/k_i + \text{(resistance of int. surface)}$$

4.4 The Nature of Thermal Conductivity

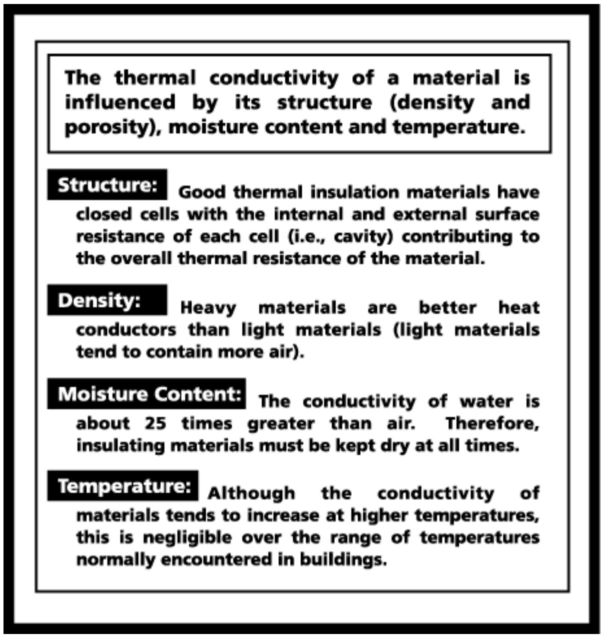
The thermal conductivity of a material is influenced by a considerable number of factors including density, porosity, moisture content and temperature (Figure 4.9).

Structure: Normally, the thermal conductivity of a cellular material is higher than that of a granular material. The explanation being that in cellular materials, the cells tend to form a continuous path, while in granular materials the path is broken at the surface of each granule. In Figure 4.10 we see that the thermal resistance of an air cavity is approximately 0.91 and that 0.78 (i.e., 86%) of this value is made up by the thermal resistance of the surfaces of the enclosure. Accordingly, the ideal thermal insulation material is one that has many closed air cells. By virtue of its enclosing surfaces each of these cells will contribute to the overall thermal resistance of the material. The contribution will of course not be as much as 0.91, but sufficient to provide a closed cell plastic foam material such as polyurethane with a thermal resistance of 6.25 per inch thickness.

Density: Light materials have in general a low conductivity and heavier materials are the better thermal conductors. Materials of low density are apt to contain more air between the pores or particles, thereby lowering the thermal conductivity as long as the pores are closed and not open.

Moisture content: The conductivity of water is some 25 times greater than that of air. Since the low thermal conductivity of porous materials is largely due to the air enclosed by the pores, the replacement of some of this air by water must result in an increase in conductivity. Particularly, insulating materials, such as mineral wool are capable of absorbing large volumes of water, thereby nullifying most of their insulating effect.

Temperature: Thermal conductivity tends to increase as the temperature of the material increases, and this is more pronounced for light-weight porous materials. However, generally speaking, the effect of temperature on the conductivity of materials of construction is negligible over the range of temperatures normally encountered in buildings.



The thermal conductivity of a material is influenced by its structure (density and porosity), moisture content and temperature.

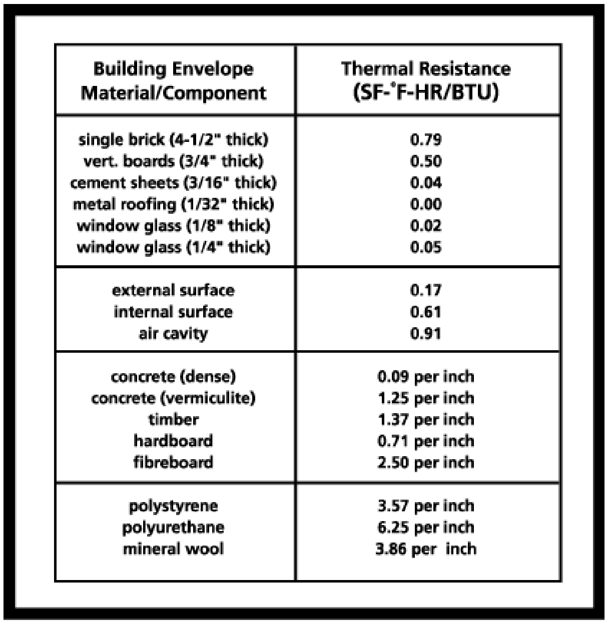
Structure: Good thermal insulation materials have closed cells with the internal and external surface resistance of each cell (i.e., cavity) contributing to the overall thermal resistance of the material.

Density: Heavy materials are better heat conductors than light materials (light materials tend to contain more air).

Moisture Content: The conductivity of water is about 25 times greater than air. Therefore, insulating materials must be kept dry at all times.

Temperature: Although the conductivity of materials tends to increase at higher temperatures, this is negligible over the range of temperatures normally encountered in buildings.

Figure 4.9: Influences on the thermal conductivity of materials



Building Envelope Material/Component	Thermal Resistance (SF-°F-HR/BTU)
single brick (4-1/2" thick)	0.79
vert. boards (3/4" thick)	0.50
cement sheets (3/16" thick)	0.04
metal roofing (1/32" thick)	0.00
window glass (1/8" thick)	0.02
window glass (1/4" thick)	0.05
external surface	0.17
internal surface	0.61
air cavity	0.91
concrete (dense)	0.09 per inch
concrete (vermiculite)	1.25 per inch
timber	1.37 per inch
hardboard	0.71 per inch
fibreboard	2.50 per inch
polystyrene	3.57 per inch
polyurethane	6.25 per inch
mineral wool	3.86 per inch

Figure 4.10: Thermal resistance of common building materials

Although we have used the analogy to many air cavities, for describing the superior heat resistance characteristics of closed cell plastic foam materials, these cells are not exactly the same as air cavities in building construction assemblies such as walls. The thermal insulation value of a one-inch-thick polyurethane foam slab is less than the sum of the resistances of all of the small closed air cells that lie between its opposite surfaces, each taken as contributing the full thermal resistance value of an air cavity (i.e., 0.91). This is due to the small size of the cells and the conductivity of the enclosing material.

The air cavity in a timber frame or brick cavity wall construction is typically continuous, vertically from floor to ceiling and horizontally at least from stud to stud. Some two-thirds of the heat transfer across this large cavity will occur by radiation, to which air will offer little resistance. Accordingly, the insertion of reflective foil can lower the conductivity of the air-space in a cavity wall by some 50%. In respect to the optimum thickness of an air cavity, it has been established experimentally that there is little difference in the thermal conductivity of air spaces varying between 0.75 inches and six inches. For thicknesses less than 0.75 inches, the conductivity increased rapidly.

4.5 Building Heat Flow Calculations

As shown in Figure 4.11, the heat exchange between a building interior and its exterior environment is dependent not only on the thermal resistance of the envelope but also on the heat gain or loss due to air infiltration and the perimeter of the footings. The degree to which each of these components contributes to the total heat exchange is estimated in different ways.

Envelope component: The thermal transmission or U-value of a composite building element is an approximate measure of the thermal insulation provided by that element, and can therefore be used to compare the insulation characteristics of different systems of construction, according to equations 4.4 and 4.5.

$$\mathbf{Q = U\,A\,(T_1 - T_2)} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(4.4)}$$

where:
Q = total heat transfer (BTU/HR)
U = overall thermal transmittance value (BTU/SF-HR-°F)
A = surface area (SF)
$(T_1 - T_2)$ = temperature difference (°F)

$$\mathbf{U = 1 / (R_{ext} + R_{mat(1)} + R_{cavity} + R_{mat(2)} + R_{int})} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(4.5)}$$

where:
R_{ext} = resistance of external surface
$R_{mat(1)}$ = resistance of material layer(s)
R_{cavity} = resistance of air cavity
$R_{mat(2)}$ = resistance material layer(s)
R_{int} = resistance of internal surface

A building envelope normally consists of several elements that may contain different materials and may be assembled in quite different ways. For example, roof assemblies are nearly always very different from wall assemblies, doors typically consist of a single material layer, and windows are certainly made of different materials than the walls in which they are located. Each of these elements has its own U-value. It therefore makes a great deal of sense to calculate the heat transfer of the building envelope in five sequential steps (Figure 4.12). First, we calculate the area of each different element, then we calculate the thermal resistance, U-value and proportional thermal impact of that element, and finally we multiply the sum of all of these thermal impacts by the temperature difference between the inside and the outside of the building.

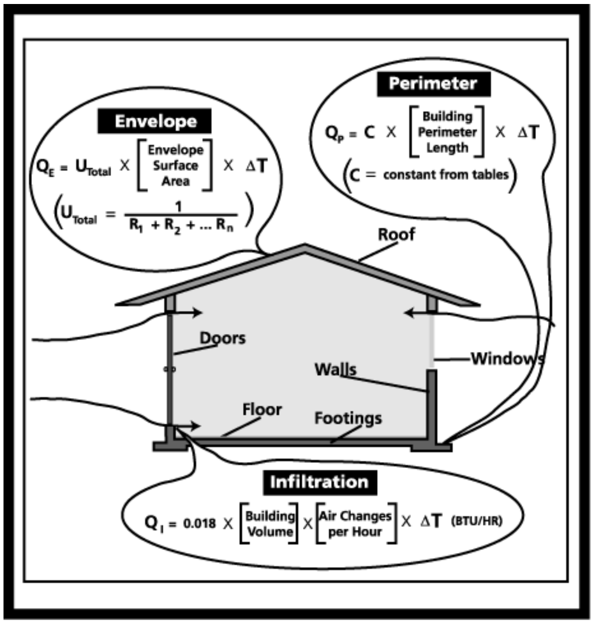
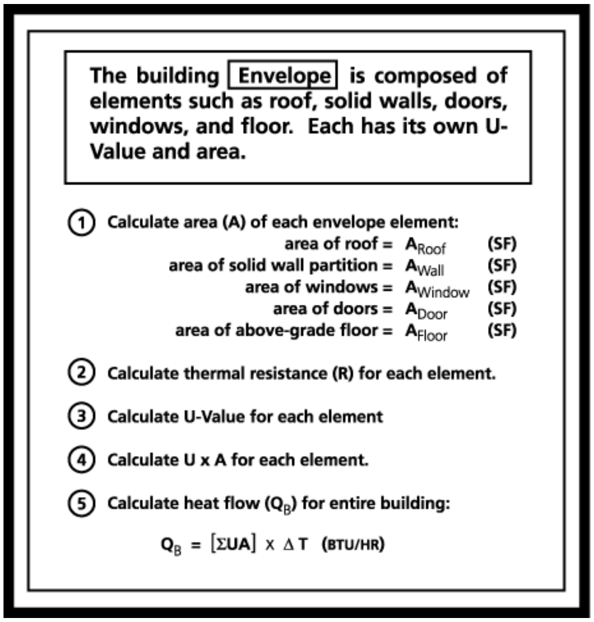


Figure 4.11: The heat exchange between a building and its external environment



The building Envelope is composed of elements such as roof, solid walls, doors, windows, and floor. Each has its own U-Value and area.

① **Calculate area (A) of each envelope element:**

area of roof = A_{Roof} (SF)
area of solid wall partition = A_{Wall} (SF)
area of windows = A_{Window} (SF)
area of doors = A_{Door} (SF)
area of above-grade floor = A_{Floor} (SF)

② **Calculate thermal resistance (R) for each element.**

③ **Calculate U-Value for each element**

④ **Calculate U x A for each element.**

⑤ **Calculate heat flow (Q_B) for entire building:**

$Q_B = [\Sigma UA] \times \Delta T$ (BTU/HR)

Figure 4.12: Steps for estimating the heat gain or loss through the building envelope

As an example of the influence of an air cavity in a wall assembly we will compare the heat transfer through a solid brick wall (i.e., 9 inches thick) and a cavity brick wall (i.e., 11 inches thick) when the external and internal air temperatures are 140˚F (e.g., sol-air temperature of the external surface of a wall exposed to direct solar radiation on a hot summer day) and 80˚F, respectively.

For solid brick wall: external surface resistance = R_{ext} = 0.17
resistance of 9 inches brick wall = R_{mat} = 1.58
internal surface resistance = R_{int} = 0.61

total thermal resistance of solid brick wall = R_{total} = 2.36
U-value = $1/R_{total}$ = 0.43

total heat gain through solid brick wall = Q_{total} = 25.6 BTU/SF-HR

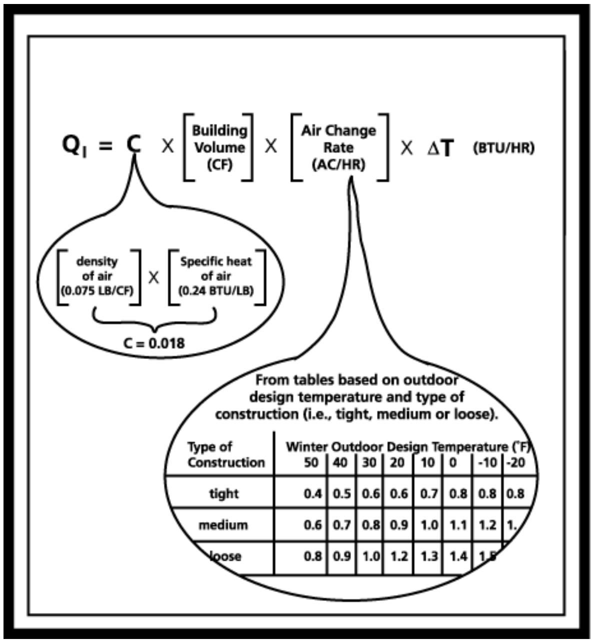
For brick cavity wall: external surface resistance = R_{ext} = 0.17
resistance of external brick leaf wall = $R_{mat(1)}$ = 0.79
resistance of air cavity = R_{cavity} = 0.91
resistance of internal brick leaf wall = $R_{mat(2)}$ = 0.79
internal surface resistance = R_{int} = 0.61

total thermal resistance of brick cavity wall = R_{total} = 3.27
U-value = $1/R_{total}$ = 0.31

total heat gain through solid brick wall = Q_{total} = 18.4 BTU/SF-HR

The impact of the air cavity is considerable, leading to a 40% reduction in the calculated heat gain. However, as discussed earlier, it must be remembered that the heat loads calculated in this manner will not necessarily provide an accurate account of conditions in practice. They are at best only a reasonable estimate of the actual expected heat flows. First, some of the quantities involved such as the thermal conductivities of the materials are not constant under normal climatic conditions. Second, the fundamental assumptions of steady state conditions are very much an oversimplification of the actual nature of these heat transfer parameters.

Air infiltration component: Depending on the tightness of the building the air infiltration component can be considerable. Certainly, in a hot humid climate, where the achievement of thermal comfort by natural means relies mostly on the movement of external air over the building occupants, air infiltration will be the dominant heat transfer component. In colder climates special precautions, such as weather stripping around doors, are taken to minimize the infiltration of cold air into the building. As shown in Figure 4.13, the air infiltration component is a direct product of the building volume, the number of air changes per hour, and a constant that represents the heat capacity of air (i.e., density times specific heat). Recommended air change rates are available from reference tables, such as the ASHRAE Handbook of Fundamentals (1989), and are based on the estimated tightness of the building envelope and the external design temperature.



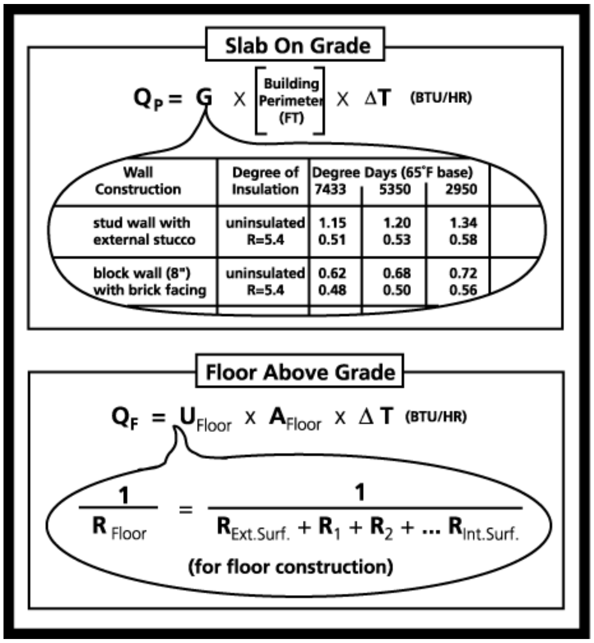
$$Q_I = C \times \begin{bmatrix}\text{Building}\\ \text{Volume}\\ \text{(CF)}\end{bmatrix} \times \begin{bmatrix}\text{Air Change}\\ \text{Rate}\\ \text{(AC/HR)}\end{bmatrix} \times \Delta T \quad \text{(BTU/HR)}$$

$$\underbrace{\begin{bmatrix}\text{density}\\ \text{of air}\\ \text{(0.075 LB/CF)}\end{bmatrix} \times \begin{bmatrix}\text{Specific heat}\\ \text{of air}\\ \text{(0.24 BTU/LB)}\end{bmatrix}}_{C = 0.018}$$

From tables based on outdoor design temperature and type of construction (i.e., tight, medium or loose).

Type of Construction	Winter Outdoor Design Temperature (°F) 50	40	30	20	10	0	-10	-20
tight	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.8
medium	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.
loose	0.8	0.9	1.0	1.2	1.3	1.4	1.	

Figure 4.13: Calculation procedure for the air infiltration component



$$Q_P = G \times \begin{bmatrix}\text{Building}\\ \text{Perimeter}\\ \text{(FT)}\end{bmatrix} \times \Delta T \quad \text{(BTU/HR)}$$

Wall Construction	Degree of Insulation	Degree Days (65°F base) 7433	5350	2950
stud wall with external stucco	uninsulated R=5.4	1.15 0.51	1.20 0.53	1.34 0.58
block wall (8") with brick facing	uninsulated R=5.4	0.62 0.48	0.68 0.50	0.72 0.56

$$Q_F = U_{Floor} \times A_{Floor} \times \Delta T \quad \text{(BTU/HR)}$$

$$\frac{1}{R_{Floor}} = \frac{1}{R_{Ext.Surf.} + R_1 + R_2 + \ldots R_{Int.Surf.}}$$

(for floor construction)

Figure 4.14: Calculation procedure for the perimeter (footings) component

Perimeter component: The heat transfer calculation procedure for the portion of the building that connects to the ground depends on the type of construction employed (Figure 4.14). In the case of a concrete slab on grade the perimeter component is a direct product of the linear building perimeter, the temperature difference between the internal and external environments, and a modifier that may be obtained from reference tables such as those provided by the ASHRAE Handbook of Fundamentals (1989). This modifier is based on three parameters, two of which are rather vague estimates based largely on the expected quality (i.e., materials and workmanship) of construction, namely; type of wall construction and degree of insulation. The third parameter represents an approximate assessment of the severity of the climate in terms of the number of Degree Days (to base 65ºF).

In the case where the lowest floor of the building is elevated above the ground (i.e., for floors above grade) the calculation of the estimated heat loss (i.e., perimeter heat gain is normally not considered) proceeds in exactly the same manner as for the building envelop component.

4.6 Energy Conservation Standards

Over the past several decades the increasing cost and dwindling supplies of fossil fuels have forced most countries to adopt stringent energy standards for buildings. These standards are compiled into building codes that are enforced at local, state and national government levels. In the US such building codes exist both at the state and national levels. For example, in California the Building Energy Efficiency Standards (Title 24) divide buildings into two main categories: residential buildings; and, non-residential buildings. These two building types are covered by different compliance manuals.

What is particularly progressive about the Californian energy standards is that they incorporate the concept of allowing the building designer to select either of two alternative approaches for complying with the standards. The first approach is *prescriptive* in nature. This is the simpler of the two approaches, but offers little flexibility. Each individual component of the building must meet a prescribed minimum energy efficiency. A small degree of flexibility exists in as much as the compliance of major building envelope components, such as walls, may be area-weighted. In other words, even though a portion of the external walls of a building may exceed the specified energy consumption the wall as a whole could still comply.

The *performance* approach is more complicated but offers considerably more design flexibility. It requires the use of an approved computer program to establish an allowed energy budget for the building under consideration. The same program is used during the design process to calculate the expected energy usage of the building and verify the compliance of the evolving design. In the *performance* approach the designer is able to consider window orientation, thermal mass, zonal control, and building plan configuration as variables that can be manipulated into an overall solution that does not exceed the allowed energy budget.

However, with either the *prescriptive* or *performance* approach there are some specific mandatory requirements that must be complied with. These deal typically with infiltration control, lighting, minimum insulation levels, and equipment efficiency. Whenever the mandatory requirements exceed either the *prescriptive* requirements or the *performance* proposals, the mandatory requirements will prevail.

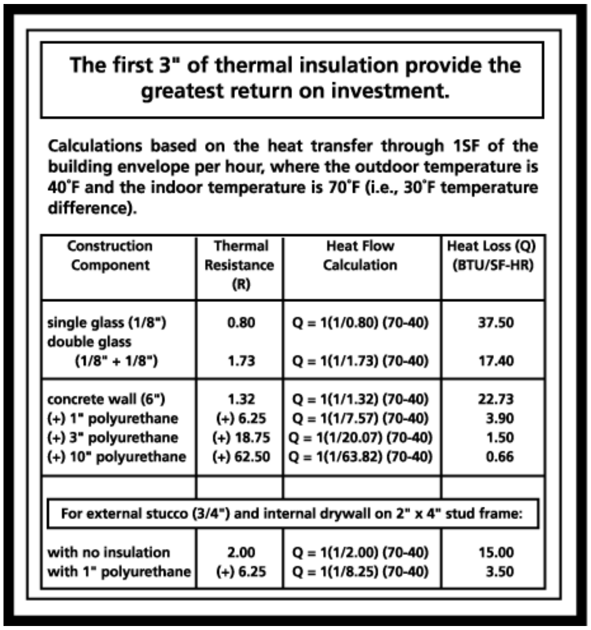
The *prescriptive* requirements are divided into packages that stipulate a set of pre-defined performance levels for various building components. Each building component must meet or exceed the minimum energy efficiency level specified by the package. During periodic updating cycles Packages A and B were eliminated in the 2001 revisions of the standards. Package C applies to locations where natural gas is not available and an all-electric solution is necessary. Package D applies to locations where both natural gas and electricity are available. Also, Package D serves as the basis of the standard design in the *performance* approach to determine the energy budget of the building.

To provide a basis for presenting the *prescriptive* requirements and standardize the energy calculations, California is divided into 16 climate zones. The climate zone definitions and data are the same for both the residential and non-residential building types. Where cities extend into more than one climate zone, the local government authority will normally determine the applicable climate zone and data set.

4.7 Insulation and Insulating Materials

The main purpose of thermal insulation is to retard heat flow, thereby ultimately influencing the degree of discomfort experienced by the building occupants or the size of heating or cooling plant and the consumption of fuel that will be required to mitigate this discomfort. Accordingly, thermal insulation and heat reflection measures have the following important applications in building design:

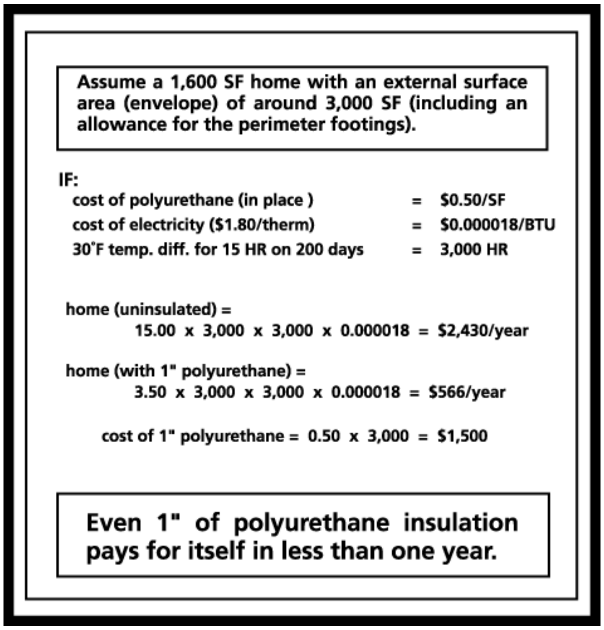
1. To maintain temperature differences between the building environment and the external climate.
2. To minimize heat transfer by conduction and radiation (reflective foil) through roofs and walls when these are exposed to direct solar radiation.
3. To maintain temperature differences between fluids flowing in pipes (e.g., hot water) or ducts (e.g., warm air) and the surrounding environment.
4. To control condensation.



The first 3" of thermal insulation provide the greatest return on investment.

Calculations based on the heat transfer through 1SF of the building envelope per hour, where the outdoor temperature is 40˚F and the indoor temperature is 70˚F (i.e., 30˚F temperature difference).

Construction Component	Thermal Resistance (R)	Heat Flow Calculation	Heat Loss (Q) (BTU/SF-HR)
single glass (1/8")	0.80	Q = 1(1/0.80) (70-40)	37.50
double glass (1/8" + 1/8")	1.73	Q = 1(1/1.73) (70-40)	17.40
concrete wall (6")	1.32	Q = 1(1/1.32) (70-40)	22.73
(+) 1" polyurethane	(+) 6.25	Q = 1(1/7.57) (70-40)	3.90
(+) 3" polyurethane	(+) 18.75	Q = 1(1/20.07) (70-40)	1.50
(+) 10" polyurethane	(+) 62.50	Q = 1(1/63.82) (70-40)	0.66
For external stucco (3/4") and internal drywall on 2" x 4" stud frame:			
with no insulation	2.00	Q = 1(1/2.00) (70-40)	15.00
with 1" polyurethane	(+) 6.25	Q = 1(1/8.25) (70-40)	3.50



Assume a 1,600 SF home with an external surface area (envelope) of around 3,000 SF (including an allowance for the perimeter footings).

IF:

cost of polyurethane (in place)	=	$0.50/SF
cost of electricity ($1.80/therm)	=	$0.000018/BTU
30˚F temp. diff. for 15 HR on 200 days	=	3,000 HR

home (uninsulated) =
15.00 x 3,000 x 3,000 x 0.000018 = $2,430/year

home (with 1" polyurethane) =
3.50 x 3,000 x 3,000 x 0.000018 = $566/year

cost of 1" polyurethane = 0.50 x 3,000 = $1,500

Even 1" of polyurethane insulation pays for itself in less than one year.

Figure 4.15: Thickness as a measure of the efficiency of thermal insulation

Figure 4.16: Return on investment of thermal insulation in a typical home

A note of caution, materials such as polyurethane that are good thermal insulators are typically very poor sound insulators. As will be explained in more detail in later chapters, sound is a form of vibration. In air these vibrations take the form of pressure differences. Therefore, the transfer of sound through a barrier such as a solid wall occurs through the physical movement of the wall.

In other words, as the sound impinges on one side of the wall it sets the whole wall into vibration. This movement of the wall, as slight as it may appear, is sufficient to produce pressure differences (i.e., sound waves) on the opposite side of the wall. Accordingly, a good sound insulator is a heavy barrier because the heavier the barrier the more of the incident sound energy will be converted into mechanical energy leaving less sound energy to be passed onto the other side. This requirement for mass is directly opposed to the requirement for closed air cells in an effective thermal insulator.

Figure 4.15 compares the heat transfer through some typical building construction assemblies. As might be expected the heat transfer through a double-glazed window unit is disproportionally less than through a single-glazed unit, even if only standard window glass is used. The double-glazed window is in excess of 50% more efficient. A six inches thick solid concrete wall is not a good thermal insulator, even though intuitively to the layperson the opposite may appear to be true. The reason is that due to the relatively high heat capacity of the concrete material it takes an appreciable amount of time for the temperature within a concrete wall to be uniformly distributed throughout the wall. However, the heat energy will eventually reach the opposite wall surface and produce either a heat gain (in a warm climate) or a heat loss (in a cold climate). As discussed previously, this heat absorption characteristic of most heavy building materials is commonly used to advantage in hot dry climates with a significant diurnal temperature range, where the building envelope can serve as a buffer between the outside and the internal building environment during day-night temperature fluctuations.

Basically, building envelopes may be insulated by providing one or more layers of insulating material and air-spaces between the external and internal surfaces of the envelope. Air-spaces are most effective when faced with reflective foil, so that heat transfer by radiation is kept to a minimum. Obviously, multiple air-spaces are more effective than a single air-space, provided that each air-space is at least 0.75 IN wide. There are a large variety of insulating materials commercially available today.

- Spray-on insulation such as polyurethane foam for interior or exterior applications. May be sealed with a silicon spray for exterior applications. Spray-on insulation also includes sprayed lightweight aggregate, which has the dual function of thermal insulation and fireproofing.
- Organic fiber-board manufactured from wood pulp, cane or other organic fibers. Normally treated with water-proofing additives and sometimes coated with bitumen. Available in standard sheet sizes.
- Inorganic fiber-boards such as fiberglass products, which incorporate small air cells. Fine glass fibers are sprayed with resin, passed under compression rollers and then cured under heat.
- Cork board was for many years the principal insulation material used for refrigeration plants and cool-rooms. More recently, mainly due to cost, the use of corkboard has been diminishing.
- Vermiculite is a magnesium silicate, processed with Portland cement to produce pellets suitable for placing into wall spaces.
- Lightweight concretes incorporating vermiculite, perlite or similar aggregates, are normally used as structural materials for floors, ceilings and walls.

- Sponge rubber provides a flexible covering to pipes and may be secured with air-drying adhesive.
- Fabricated panels such as metal faced, box-like panels and metal or concrete faced sandwich panels with insulating cores.

The choice of any insulating material or laminated component for a particular situation will depend on a number of conditions, such as the nature of the surface to be insulated, the temperature of that surface or the surrounding air, and the purpose and cost of the insulation. For example, the underside of stagnant solar collectors can easily reach a temperature in excess of 160˚F. Since polyurethane has a fairly low melting point, it may be necessary to apply a layer of fiberglass foam between the collector surface and the polyurethane insulation.

4.8 The Cause and Nature of Condensation

Moisture problems in buildings are normally due to the movement of a mixture of water vapor and air around and through the building shell. The quantity of water vapor in the external atmosphere depends on ambient climatic conditions, while the quantity in the air inside a building also depends on the rate of ventilation and the occupancy. The amount of water vapor that can be held by a given volume of air before saturation occurs (i.e., before the dew point is reached) increases with higher temperatures (Figure 4.17).

The ability of air to hold moisture increases with higher temperatures. Condensation occurs whenever the air temperature falls below the Dew Point.

Surface condensation and interstitial condensation may occur due to:

- **The addition of moisture to the air due to the occupancy of the building (e.g., cooking, rigorous exercising, industrial processes, etc.)**
- **The intentional humidification of air for reasons of comfort or safety.**
- **Humid air coming in contact with much colder surfaces.**

Figure 4.17: Causes of condensation

Cold surfaces and steep temperature gradients are likely to produce condensation.

Surface Condensation: **Occurs whenever the temperature of any exposed surface (e.g., window pane) within a building falls below the Dew Point of the indoor air.**

Remedies: (1) Adequate thermal insulation
(2) Absorbent surface finishes

Interstitial Condensation: **May occur within the layers of the building envelope whenever the temperature difference between the indoor and outdoor air is very large, and the reduction in vapor pressure across the envelope is abrupt.**

Remedies: (1) A vapor barrier (foil or plastic membrane on the warmer side of the envelope).
(2) Avoidance of materials that are impervious to moisture (causing an abrupt vapor pressure drop).

Figure 4.18: Types of condensation

It is no longer a matter of debate that dampness in buildings can have a negative effect on the health of the occupants. In particular, dampness supports the growth of molds that produce allergic reactions. However, just as importantly damp conditions will seriously affect the performance of building materials. It is therefore necessary to control moisture movement, whether in the form of vapor or liquid, so as to keep the components of a building as dry as possible. Dampness arising from the upward passage of moisture, through walls and the penetration of rain water through openings in the building envelope can be effectively controlled by means of damp-proof courses. There remains however, the problem of surface condensation and the flow of water vapor through insulation, which may be due to:

- The addition of moisture to the air due to the occupancy of the building.
- The intentional humidification of air by mechanical means for reasons of safety, comfort or industrial expediency.
- Humid air coming in contact with cold surfaces.

As shown in Figure 4.18, there are fundamentally two kinds of condensation in buildings. Surface condensation will occur whenever the temperature of any exposed surface within a building is below the dew point of the surrounding air. According to the nature of the surface and material the condensation will be visible in the form of water droplets or absorbed by the material. Commonly affected surfaces are window panes, metal window frames, and poorly insulated external walls and ceilings. Surface condensation is particularly prominent in cold climates where humidification of the indoor air is often desirable. To ensure that condensation will not occur on the internal surface of a building envelope it is necessary to provide adequate insulation within the envelope, so that the temperature of the surface remains below the dew point of the indoor air. If it is likely that at odd times the humidity of the indoor air will be very high, it becomes advantageous to provide an absorbent surface finish, capable of retaining a limited amount of moisture for short periods without deterioration.

Interstitial condensation may occur within the thickness of the building envelope whenever the temperature gradient between the indoor air and the outside atmosphere is very large and the reduction in vapor pressure across the envelope is abrupt. When the system of construction includes materials that are impervious to moisture, thus preventing the diffusion of water vapor within the thickness of the material, the reduction in vapor pressure will not be gradual and condensation is likely to occur within the thickness of the construction. Metal, asphalt and bituminous-felt roofs, and metal and glass curtain walls will bring about this situation. Since the primary function of these elements is the exclusion of rain water, they are normally located at the external face of a building. For a heated building the temperature of this external face may often be below the dew point of the indoor air. It is therefore likely that condensation will occur at times, although as soon as the external temperature rises the absorbed moisture will evaporate. Commonly a vapor barrier (i.e., foil or plastic film) is included on the warmer side of the envelope, or at times within a wall, to prevent the passage of water vapor.

4.9 Heat Flow Calculation Example

In the following example of a building heat flow calculation sequence, we are going to determine the heat flow parameters that apply to the envelope (i.e., external walls and roof) of a single classroom in a multi-classroom building and then explore the thermal behavior of the same classroom under three different climatic conditions. First, we will consider a cold climate and establish the need for substantial thermal insulation. Second, we will consider a hot-humid climate and determine whether reasonably comfortable conditions can be maintained inside the classroom through natural air movement alone. Third, we will consider a hot-dry climate and explore the potential for using the building envelope as a heat sink and buffer between external and internal conditions during daytime hours (i.e., from sunrise to sunset).

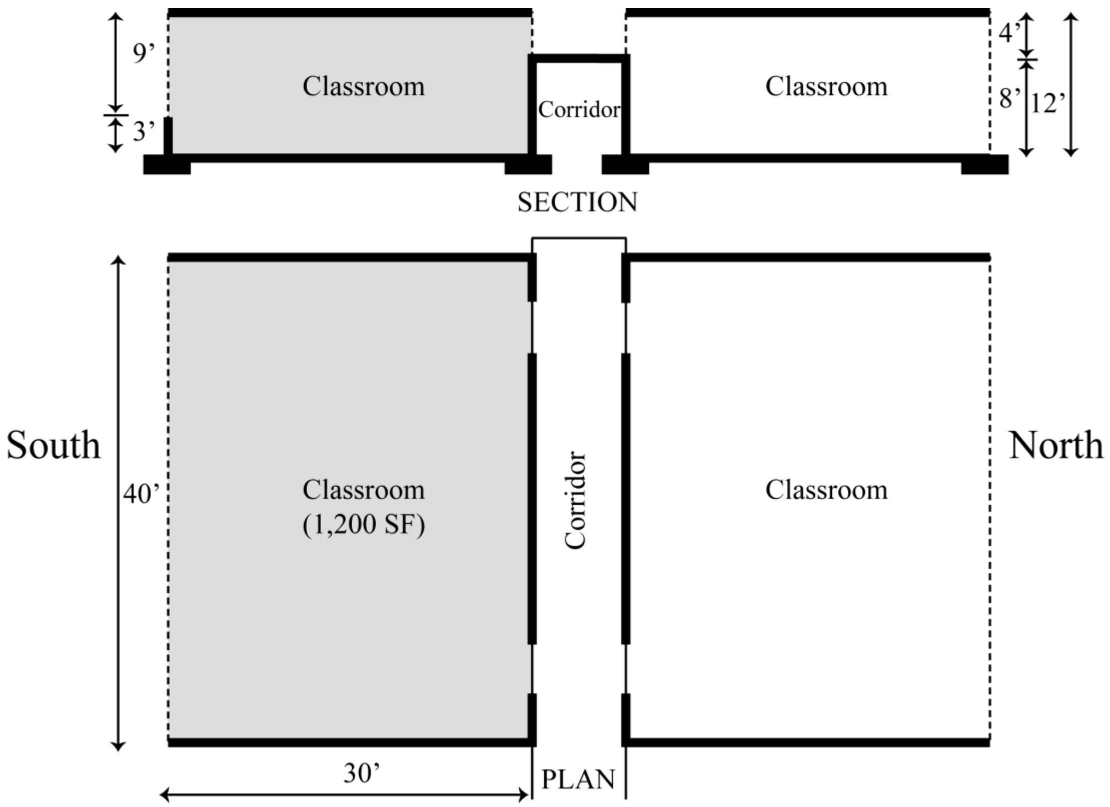


Figure 4.19: Section and floor plan of a portion of a classroom building

In the typical classroom building shown in Figure 4.19, which will form the basis of our heat flow calculations, the large window wall of the classroom on the left side of the plan and section views faces due south. Also, we will assume the following R-Values for the materials used for the construction of the walls and roof:

Classroom walls: external surface resistance = R_{ext} = 0.17
internal surface resistance = R_{int} = 0.61
¾ IN stucco = R_{mat} = 0.15 (or 0.20/IN)
2 IN by 4 IN timber studs = R_{mat} = 3.15
3 IN polystyrene = R_{mat} = 11.55 (or 3.85/IN)
½ IN drywall = R_{mat} = 0.45 (or 0.90/IN)

Classroom windows: external surface resistance = R_{ext} = 0.17
internal surface resistance = R_{int} = 0.61
⅛ IN normal glass pane = R_{mat} = 0.02 (or 0.16/IN)

Classroom roof: external surface resistance = R_{ext} = 0.17
internal surface resistance = R_{int} = 0.61
⅜ IN built-up roofing = R_{mat} = 0.33 (or 0.88/IN)
5 IN polystyrene = R_{mat} = 19.25 (or 3.85/IN)
½ IN plasterboard ceiling = R_{mat} = 0.45 (or 0.90/IN)

Step 1: Adjust the thermal insulation provided by 3 IN of polystyrene in the solid portions of the external walls to allow for timber studs at 16 IN centers.

$$\frac{14.5 + 1.5}{14.5 / 11.55 + 1.5 / 3.15} = \frac{16}{1.26 + 0.48} = \frac{16}{1.74} = 9.2$$

It is interesting to note that the presence of the studs reduces the effective thermal insulation value of the wall by about 20% (i.e., 9.2 / 11.55 x 100 = 79.7%)

Step 2: Calculate the U-Value of the solid wall sections.

$R_{total} = 0.17 + 0.15 + 9.2 + 0.45 + 0.61 = 10.58$

$U_{wall} = 1 / 10.58 = 0.09$

Step 3: Calculate the U-Value of the window portions of the walls.

$R_{total} = 0.17 + 0.02 + 0.61 = 0.80$

$U_{window} = 1 / 0.80 = 1.25$

Step 4: Calculate the U-Value of the roof.

$R_{total} = 0.17 + 0.33 + 15.4 + 0.45 + 0.61 = 16.96$

$U_{roof} = 1 / 16.96 = 0.06$

Step 5: Determine the total thermal transmittance of the external portion of the classroom's building envelope (i.e., the west wall, the south wall, the upper portion of the north wall, and the roof). For the purpose of this limited example, we will neglect the heat transfer due to air infiltration and the perimeter of the floor slab.

Building Element	U-Value	Surface Area (A)	UA
solid wall	0.09	360 + 120 = 480	43
windows	1.25	360 + 160 = 520	650
roof	0.06	1,200	72
		Total:	765

Step 6: Calculate the total heat loss in the case of a *cold* climate, assuming an external temperature of 50˚F and an internal temperature of 68˚F.

$Q_{cold} = 765 \times (50 - 68) = -13{,}770$ BTU/HR

Step 7: Calculate the total heat gain in the case of a *hot-humid* climate, assuming an external temperature in the shade of 78˚F (for walls), a sol-air temperature on the roof of 110˚F, and a desired internal temperature of 80˚F. Then calculate the ventilation rate and wind speed required to maintain an internal temperature of 80˚F.

$Q_{wall} = 693 \times (78 - 80) = -1{,}386$ BTU/HR

$Q_{roof} = 72 \times (110 - 80) = +2{,}160$ BTU/HR

Net heat gain ($Q_{hot\text{-}humid}$) = + 774 BTU/HR

V_{rate} = $Q_{hot\text{-}humid}$ / [0.018 x (78 – 80)] = 774 / 0.036 = 21,500 CF/HR

Assuming 120SF of open windows (i.e., 4FT x 40FT = 160SF):

W_{speed} = V_{rate} / [88 x 0.6 x 160] = 21,500 / 8,448 = 2.5 MPH

Step 8: Calculate the total heat gain in the case of a *hot-dry* climate, assuming an external temperature in the shade of 95˚F (for walls), a sol-air temperature on the roof of 130˚F, and a desired internal temperature of 80˚F. Then determine whether the building envelope could function as a heat sink to buffer the inside of the building from the hot external environment during daytime hours. To increase the heat capacity of the building envelope and at the same time reduce the direct heat flow through the window areas, four constructional modifications will be assumed. First, the external timber stud walls will be replaced by 3IN thick concrete with ½IN drywall on the inside. Second, the timber roof structure will be replaced with a 4IN concrete slab and a ½IN plasterboard ceiling. Third, the solid part of the wall on the south side will be raised to an 8FT height, leaving only a 4FT high strip of windows similar to the north wall. Fourth, all of the single-glazed windows will be replaced by double-glazed windows.

Modified walls:
external surface resistance = R_{ext} = 0.17
internal surface resistance = R_{int} = 0.61
3 IN concrete = R_{mat} = 0.27 (or 1.09/IN)
½ IN drywall = R_{mat} = 0.45 (or 0.90/IN)

Modified windows:
external surface resistance = R_{ext} = 0.17
internal surface resistance = R_{int} = 0.61
⅛ IN normal glass pane = R_{mat} = 0.02 (or 0.16/IN)
air cavity between two sheets of glass = R_{cavity} = 0.91

Modified roof:
external surface resistance = R_{ext} = 0.17
internal surface resistance = R_{int} = 0.61
⅜ IN built-up roofing = R_{mat} = 0.33 (or 0.88/IN)
4 IN concrete = R_{mat} = 0.36 (or 1.09/IN)
½ IN plasterboard ceiling = R_{mat} = 0.45 (or 0.90/IN)

Calculate the U-Value of the modified solid wall sections.

R_{total} = 0.17 + 0.27 + 0.45 + 0.61 = 1.50

U_{wall} = 1 / 1.50 = 0.67

Calculate the U-Value of the modified window portions of the walls.

R_{total} = 0.17 + 0.02 + 0.91 + 0.02 + 0.61 = 1.73

U_{window} = 1 / 1.73 = 0.58

Calculate the U-Value of the modified roof.

R_{total} = 0.17 + 0.33 + 0.36 + 0.45 + 0.61 = 1.92

U_{roof} = 1 / 1.92 = 0.52

Determine the total thermal transmittance of the external portion of the classroom's modified building envelope (i.e., the west wall, the south wall, the upper portion of the north wall, and the roof). Again, for the purpose of this limited example we will neglect the heat transfer due to air infiltration and the perimeter of the floor slab.

Building Element	U-Value	Surface Area (A)	UA
solid wall	0.67	360 + 320 = 680	456
windows	0.58	160 + 160 = 320	186
roof	0.52	1,200	624
		Total:	1,266

Total heat gain for an external temperature in the shade of 95˚F (for walls), a sol-air temperature on the roof of 130˚F, and a desired internal temperature of 80˚F is given by:

Q_{wall} = 642 x (95 – 80) = + 9,630 BTU/HR
Q_{roof} = 624 x (130 – 80) = + 31,200 BTU/HR
Net heat gain ($Q_{hot\text{-}dry}$) = + 40,830 BTU/HR

For a 10-hour day the external building envelope will need to be able to absorb at least 408,300 BTU (i.e., 40,830 x 10). With a weight of 140 LB/CF for concrete the heat capacity ($Q_{capacity}$) of the external building shell is approximately equal to:

$Q_{capacity}$ = (total concrete mass) x (specific heat) x (temperature difference)

$Q_{cap\text{-}wall}$ = (680 x 3 / 12 x 140) x 0.22 x (95 – 80) = 78,540 BTU
$Q_{cap\text{-}roof}$ = (1,200 x 4 / 12 x 140) x 0.22 x (130 – 80) = 616,000 BTU
Total heat capacity ($Q_{capacity}$) = 694,540 BTU

Therefore, the total heat capacity of the concrete portions of the external building shell is some 70% greater than the estimated daily heat load and therefore, the building shell will be able to function as an effective buffer between the external and internal environments during the daytime.

4.10 Questions Relating to Chapter 4

Answers to the following multiple-choice questions with references to the appropriate text (by page number) may be found at back of the book.

1. **How many mistakes (if any) does the following paragraph contain?**

"Although heat is a form of energy, it is a physical quantity which is measured subjectively. In the British system of units, heat is expressed in terms of the Calorie heat unit. Heat may appear in either of two (2) forms, namely:

1. **Sensible heat, which is the thermal energy used during a change of state of a substance while the temperature remains unaltered.**
2. **Latent heat, which is associated with a change of temperature of the substance involved.**

Heat is said to pass from one system to another if the two systems are at different temperatures. This heat transfer always occurs from a region of high temperature to a region of low temperature."

A. no mistakes.
B. less than 2 mistakes.
C. 3 mistakes.
D. 4 mistakes.
E. 5 or more mistakes.

2. **Thermal conduction is the direct transmission of heat between two materials __________________. All substances will conduct heat, the rate of transfer depending on the ________________________ of the substances. Choose the missing words.**

A. joined by air; relative temperatures
B. in direct contact with each other; thermal conductivity
C. in relative proximity to each other; thermal absorption
D. suspended in a vacuum; thermal conductivity
E. indirect contact with each other; thickness

3. **In the past it has been argued that the assumption of steady state conditions in heat transfer may be justified on the basis of:**

   1. **Thermal response predictions for buildings need not be very accurate because of the variability of occupancy.**
   2. **In all buildings the thermal environment can be controlled by mechanical means.**
   3. **The temperature difference between the outdoor and indoor environments is large.**
   4. **The thermal capacity of the building shell is small in comparison with the total heat transferred.**
   5. **Short term changes in outdoor temperature are small.**

   Which (if any) of the above arguments are correctly stated (although they may not be completely justified)?

A. 1, 2, 3, and 4
B. 3, 4, and 5

C. 1, 3, 4 and 5
D. 4 and 5
E. 3 and 4

4. **The thermal conductivity of a material is not influenced by:**
   A. density
   B. porosity
   C. temperature
   D. moisture content
   E. Thermal conductivity of a material is influenced by all of the above (i.e., A, B, C and D).

5. **Which (if any) of the following materials would you consider to be a more efficient thermal insulator per unit thickness than fiber glass?**
   A. polyurethane foam
   B. soft cellular rubber
   C. exfoliated vermiculite
   D. mineral wool
   E. All of the above (i.e., A, B, C and D) are less efficient thermal insulators.

6. **A heavily insulated, massive constructional system with small windows and reflective external surfaces (not mechanically ventilated) would be suitable for?**
   A. hot-arid regions
   B. hot-humid regions
   C. cold regions
   D. temperate regions
   E. regions experiencing high rainfall

7. **A light constructional system in which all surfaces exposed to direct solar radiation are insulated and opposite windows provide cross-ventilation would apply to?**
   A. hot-arid regions
   B. hot-humid regions
   C. cold regions
   D. More than one of the above regions (i.e., A, B and C)
   E. All of the above regions (i.e., A, B and C).

8. **In reference to the Psychrometric Chart diagram shown below, which (if any) of the following statements are correct?**
   A. The word “Dry” is appropriate to be placed in the rectangular box labeled “1”.
   B. The words “Hot & Dry” are appropriate to be placed in the circle labeled “B”.

C. As we move further away from the “Comfort Zone” in the direction of the circle labeled “D” the thermal conditions become increasingly cold and windy.

D. If the Relative Humidity is above 95% on a particular day in a hot and humid climate it will be raining.

E. All of the above statements (i.e., A, B, C and D) are incorrect.