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THERMAL MASS ASSESSMENT

An Explanation of the Mechanisms by Which Building Mass Influences Heating and Cooling Energy Requirements

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PART OF
THE NATIONAL PROGRAM
FOR
BUILDING THERMAL ENVELOPE SYSTEMS
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ABSTRACT

The influence that building mass has on energy consumption for heating and cooling has been the subject of some controversy. This controversy is, in part, due to a lack of understanding of the heat transfer mechanics occurring within a building and of how they affect energy usage. This report offers a step-by-step development of the principles of heat transfer in buildings as they pertain to thermal mass. The report is targeted for persons who are unfamiliar with the topic of thermal mass, but who possess some technical background.

It is concluded that for the mass of a building to reduce energy usage, the building must undergo alternating periods of net energy gain and loss. In other words, during the heating season the indoor temperature must at times float above the thermostat set point temperature to reduce energy consumption. During the cooling season, the indoor temperature must occasionally drop below the set point temperature.

Other issues addressed include the effects of mass on peak loads, equipment cycling, thermostat setback, and comfort. Strategies to maximize benefits of mass are discussed.

1. INTRODUCTION

The effect that the mass of a building (commonly referred to as its thermal mass) has on its heating and cooling energy consumption has become the topic of some discussion and controversy. To resolve this issue, investigators have taken two primary paths: experimentation and analysis (primarily computer simulations). While these approaches are valuable in resolving the issue, they may not in themselves foster an understanding of the underlying principles. There is nothing magical about thermal mass. Any energy savings which may occur are the result of heat transfer mechanisms which do not require one to be an expert to understand.

The main thrust of this report is to provide an understandable, step-by-step development of the principles of thermal mass. It is assumed that the reader is unfamiliar with thermal mass, but does possess some technical background. We begin with some basic concepts and definitions and build on them by introducing additional complexities. In this manner we hope to develop in the reader an intuition for the topic. For this reason, the number of equations presented is kept to a minimum; rather, intuitive explanations are given where possible.

Chapter 2 presents the basic concepts and definitions and begins the building process. In Chap. 3 these concepts are applied in explaining the effect of mass on energy usage for heating and cooling buildings. In Chap. 4 issues concerning the effect of thermal mass other than those pertaining to a direct reduction in cooling or heating load are discussed.

Appendix A gives synopses of several papers which pertain to thermal mass. The appendix is representative of work being done; it is not all inclusive. Appendix B presents a bibliography on thermal mass, which offers a starting point for the reader who is interested in exploring the subject further.

2. CONCEPTS AND DEFINITIONS

In this chapter, some fundamentals of energy transfer in a building will be presented as well as the influence of mass on them. The two areas covered are (1) the flow of energy through the building envelope and the effect mass has on this energy flow, and (2) the storage of energy in mass for later utilization. This chapter will not address the energy usage of a building as a whole, but will lay the necessary foundation for that discussion, which appears in Chap. 3.

2.1 Units and Definitions Used in Heat Transfer

A note about units is in order before proceeding. In this report, metric, or SI,* units will be given precedence. However, since English or engineering units are still widely used in this field, all quantities will also be given in English units in parentheses following the value in SI units. Table 2.1 gives some common SI units and their English equivalents.

In order to understand the following discussions, it will be helpful to present some definitions at this point.

Building envelope — the portion of a building which separates the interior conditioned space from the exterior environment. It includes a building's walls, roof and ceiling, and floor. The building envelope affects the flow of energy between the interior space and the exterior environment.

Table 2.1. SI and English Units

Quantity	SI unit	English unit	Conversion factor
Energy	Joule (J)	British thermal unit (Btu)	1 Btu = 1055 J
Energy rate (power)	Joule/s or watt (W)	Btu/h	1 Btu/h = 0.293 W
Length	Meter (m)	Foot (ft)	1 ft = 0.3048 m
Area	Square meter (m^2)	Square foot (ft^2)	1 ft^2 = 9.29 x 10^{-2} m^2
Volume	Cubic Meter (m^3)	Cubic foot (ft^3)	1 ft^3 = 2.832 x 10^{-2} m^3
Temperature	Degrees Celcius (°C)	Degrees Fahrenheit (°F)	°F = 1.8·°C + 32
Absolute temperature	Kelvin (K)	Degrees Rankine (°R)	°R = 1.8·K
Change in temperature	°C or K (1°C = 1 K)	°F or °R (1°F = 1°R)	°R = 1.8·K
Mass	Kilogram (kg)	Pound mass (lb_m)	1 lb_m = 0.454 kg
Density	kg/m^3	lb_m/ft^3	1 lb_m/ft^3 = 16.02 kg/m^3
Heat capacity	J/kg·K	Btu/lb_m·°F	1 Btu/lb_m·°F = 4187 J/kg·K

Heat — defined by engineers as energy transferred because of a temperature difference. However, in general usage, the terms heat and energy are used interchangeably. In this report, the more general definition is used.

Heat flux or energy flux — the amount of energy flowing through a unit area in a time. The usual units are J/s·m^2 or W/m^2 (Btu/h·ft^2). To determine the total amount of energy that flows through a surface in a given time, the heat flux is multiplied by the time of interest and the total area of the surface.

*From the French Le Système International d'Unités (International System of Units).

Three basic properties of a material are of importance in thermal analyses: density, specific heat, and thermal conductivity.

Density — the mass of material which fills a unit volume. Normal units are kg/m^3 (lb_m/ft^3). Density is given the symbol ρ.

Specific heat — the quantity of energy required to produce a temperature change in a mass of material. Normal units are $J/kg \cdot K$ ($Btu/lb_m \cdot °F$). To determine the total amount of energy which must be added or removed from a material to change its temperature a given amount, the specific heat of the material is multiplied by its mass and the temperature change. Specific heat is given the symbol c.

Thermal conductivity — a measure of the ability of a material to conduct heat. The conductivity is the heat flux which will occur through a unit thickness of material whose two surfaces are at a unit temperature difference. Typical units are $(W/m^2)/m/K$ or $W/m \cdot K$ [$(Btu/h \cdot ft^2)/ft/°F$ or $Btu/h \cdot ft \cdot °F$]. Thermal conductivity is given the symbol k. This is further discussed in Sect. 2.2.1.

The thermal properties of several common building materials are presented in Table 2.2.

Table 2.2. Properties of common building materials

Material (data source)	Conductivity		Density		Specific heat		Thermal diffusivity	
	$W/m \cdot K$	$Btu/h \cdot ft \cdot °F$	kg/m^3	lb/ft^3	$J/kg \cdot K$	$Btu/lb_m \cdot °F$	m^2/s	ft^2/h
Normal-weight concrete[a]	1.90	1.10	2320	145	795	0.19	1.0×10^{-6}	0.040
Structural lightweight concrete[a]	0.61	0.35	1600	100	921	0.22	4.1×10^{-7}	0.016
Insulating lightweight concrete[a]	0.14	0.083	480	30	1000	0.24	2.9×10^{-7}	0.012
Building brick[b]	0.73	0.42	1920	120	921	0.22	4.1×10^{-7}	0.016
Face brick[b]	1.30	0.75	2080	130	1000	0.24	6.2×10^{-7}	0.024
Mineral fiber[c] (loosefill)	0.048	0.028	9.6	0.6	712	0.17	7.1×10^{-6}	0.275
Glass fiberboard[c] (resin binder)	0.042	0.024	240	15	712	0.17	2.4×10^{-7}	0.0094
Expanded polystyrene[c]	0.029	0.017	35	2.2	1214	0.29	6.9×10^{-7}	0.0267
Steel[c]	45.3	26.2	7830	489	502	0.12	1.2×10^{-5}	0.446
Wood[c] (fir, pine, or similar soft wood)	0.12	0.067	510	32	1382	0.33	1.6×10^{-7}	0.0063
Gypsum board[c]	0.16	0.093	800	50.0	1089	0.26	1.8×10^{-7}	0.0072

[a] Portland Cement Association, Construction Technology Laboratories.
[b] Brick Institute of America.
[c] ASHRAE Handbook of Fundamentals.

2.2 Heat Conduction Through the Building Envelope

Heat is transferred through the building envelope primarily by conduction. When voids or cavities are within the envelope, two other mechanisms may be involved: natural convection and radiation. In the subsequent discussion, it is assumed that conduction is the only means of heat transfer through the envelope.

Heat transfer by conduction is governed by Fourier's law of heat conduction, which can be written as

$$q = -k \frac{dT}{dx} ,$$

where q is the heat flux, k is the thermal conductivity, and dT/dx is the temperature gradient. The minus sign is necessary to ensure that the equation agrees with the true physical behavior where heat flow is from the higher temperature toward the lower temperature.

2.2.1 Steady-State Heat Conduction

If the temperatures on both sides of a wall remain unchanged for a long period of time, the heat flux through the wall will approach some constant value. Once the heat flux attains this constant value, it will not change if the temperatures on its surfaces remain unchanged. This condition in which temperatures do not change with time is referred to as steady state.

Figure 2.1 presents the steady-state temperature profile through a homogeneous wall of thickness L. One surface of the wall is maintained at temperature, T_1, and the other surface is maintained at a lower temperature, T_2. Heat flows through the wall from the higher to the lower temperature side. The temperature gradient for one-dimensional conduction can be written as

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} .$$

By application of Fourier's law of heat conduction, the heat flux through the wall can be determined as

$$q = -k \frac{dT}{dx} = -k \frac{T_2 - T_1}{L} .$$

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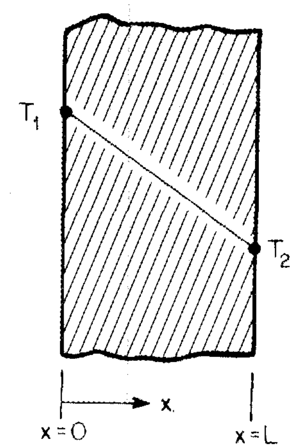

Fig. 2.1. Steady-state temperature profile in a wall.

This can be rewritten as

$$q = U\Delta T ,$$

where the quantity U ($U = k/L$) is referred to as the conductance of the wall, and ΔT is simply the temperature difference across the wall ($T_1 - T_2$). The heat flow is always from the high to the low temperature side. The units of conductance are $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot {}^\circ F$). The conductance of a wall is the heat flux which occurs through that wall when there is a unit temperature difference across it.

This is often written in the form

$$q = \frac{\Delta T}{R} ,$$

where R ($R = 1/U$) is referred to as the R-value, or thermal resistance of the wall. This form is convenient for multilayer walls since an overall R-value can be determined by summing the R-values for each layer. Thus, for a multilayer wall with n layers,

$$q = \frac{\Delta T}{R_1 + R_2 + \cdots + R_n} .$$

The R-value has units of $m^2 \cdot K/W$ ($h \cdot ft^2 \cdot {}^\circ F/Btu$). In steady state, two slabs with the same R-value will conduct the same amount of heat even though the thicknesses and materials may differ. Thus, only the R-value needs to be known to describe the behavior of a wall under steady-state conditions.

2.2.2 Transient Heat Conduction

Unfortunately, the simple analogy just developed is valid only for steady-state heat conduction. To illustrate what happens in non-steady-state (transient) heat flow, consider a homogeneous wall, which is initially at a uniform temperature. If, at time zero, the temperature of one surface is suddenly raised to a higher value and the other surface is maintained at the initial value, the temperature profile through the slab will develop as shown in Fig. 2.2. Part (*a*) of Fig. 2.2 shows the initial uniform temperature. Part (*b*) shows the temperature profile at the instant the surface temperature is raised. The rest of the slab has not had time to react and is still at the initial temperature. Parts (*c*) through (*e*) show the temperature profile at various stages as it progresses through the slab. Finally, in part (*f*), the transient is complete and steady-state conditions have been established.

Fourier's law of heat conduction

$$q = -k \frac{dT}{dx} ,$$

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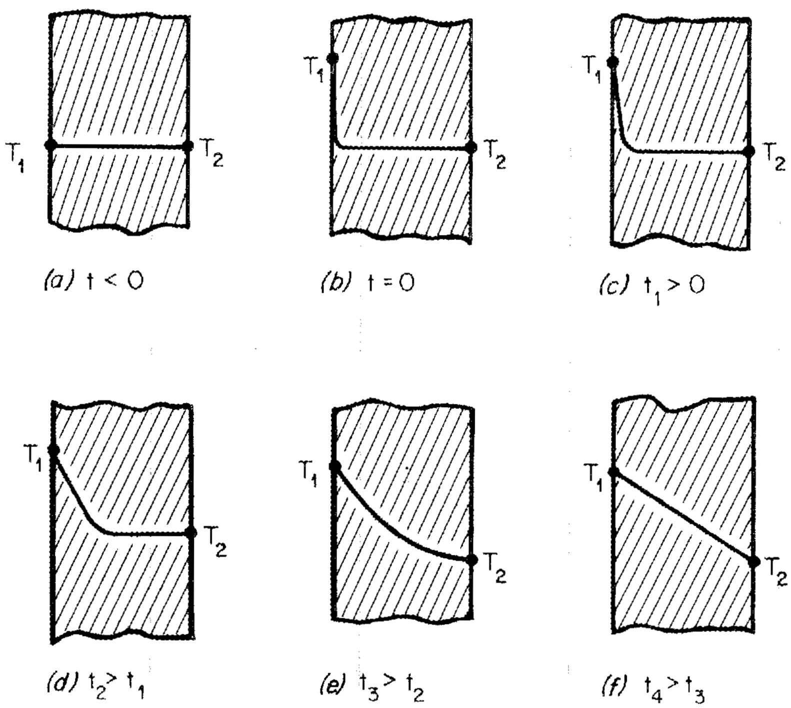

Fig. 2.2. Development of temperature profile in a wall following a change in one surface temperature.

is still valid, but at any time during the transient, the gradient dT/dx is different at various locations in the wall until steady-state conditions are established. The heat fluxes at the two surfaces of the wall can be determined from the temperature profiles and from Fourier's law. These heat fluxes plus the heat flux arrived at by the steady-state calculation are plotted in Fig. 2.3. This figure shows that not only do the surface heat fluxes not agree with the steady-state value, they also do not agree with each other until steady-state conditions are reached. Thus, if a steady-state calculation were used to predict the heat flow through a slab, it could result in a considerable error. In fact, the expression "heat flow through a wall" does not even have a clear meaning in a transient case since at any time the heat flow is different at different positions in the wall. What would normally be of interest is the heat flow at one of the surfaces (usually the inside surface of a wall since this represents the amount of energy entering or leaving the conditioned space).

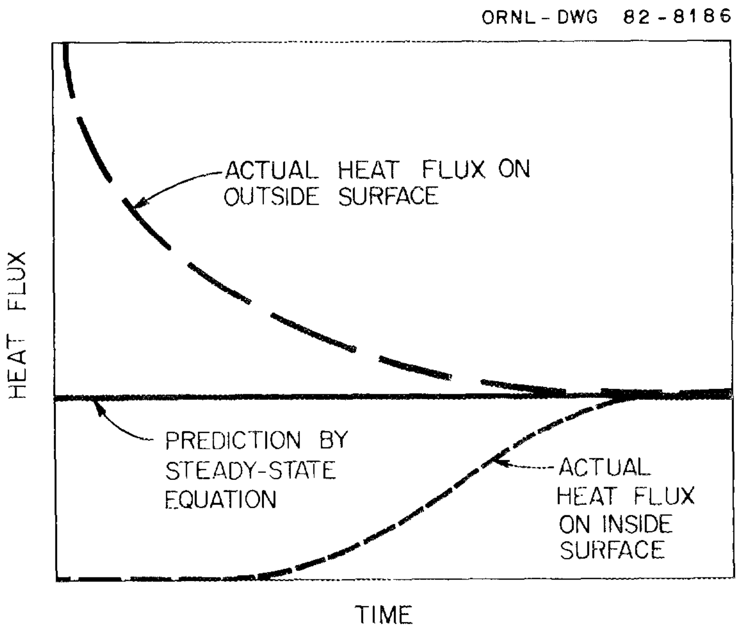

Fig. 2.3. Heat flux on surface of a wall following a change in one surface temperature.

The average temperature of the wall before the transient began was T_2. When steady-state conditions are reached, the average temperature of the wall is $(T_1 + T_2)/2$. The amount of energy required to cause this change in temperature is

$$Q = \rho c V \Delta T$$

$$= \rho c A_s L \left(\frac{T_1 + T_2}{2} - T_2 \right)$$

$$= \rho c A_s L \quad \frac{T_1 - T_2}{2} \quad ,$$

where

ρc = heat storage capacity per unit volume per degree temperature change (ρ = density, c = specific heat),

$V = A_s L$ = volume of material (A_s = surface area, L = thickness),

$\frac{T_1 - T_2}{2}$ = average temperature rise of material.

Steady-state conditions cannot be attained until at least an amount of energy, Q, sufficient to give the steady-state temperature profile has been conducted into the wall.

Rearranging the previous equation gives

$$\frac{Q}{A_s} = \rho c L \; \frac{T_1 - T_2}{2} \; .$$

This form is used because it gives the energy storage per unit surface area of the wall, and the total area of wall need no longer be considered for now. The only properties of the wall appearing on the right-hand side of the equation are ρ, c, and L. (The temperature change is not a property of the wall, but a condition imposed on it.) Thus, the ρcL product is a measure of the wall's ability to store energy.

In the earlier steady-state discussion, it was shown that the wall's U-value ($U = k/L$) is a measure of the rate at which a wall can conduct heat. Even though the steady-state results do not apply to the transient case, the U-value is still an indication of a wall's ability to conduct energy.

The time necessary to attain steady-state conditions is related to the ratio of the wall's ability to store energy to its ability to conduct energy.

$$\begin{aligned}\frac{\text{ability to store energy}}{\text{ability to conduct energy}} &= \frac{\rho c L}{k/L} \\ &= \frac{\rho c L^2}{k} \\ &= \frac{L^2}{\alpha} \; .\end{aligned}$$

Thus, there are two properties of a wall which influence the time required to attain steady state: the wall thickness, L, and the quantity α ($\alpha = k/\rho c$), which is referred to as the thermal diffusivity. The thermal diffusivity is an indication of the speed at which the temperature profile moves through a wall. It has typical units of m^2/s (ft^2/h).

An exact, analytical solution is available for this case. However, it would not give the reader much insight into the behavior of a wall and therefore is not presented. It does confirm that the quantity L^2/α determines the time required to achieve steady-state conditions. The greater this quantity is, the longer the time required to attain steady-state conditions.

A wall will seldom experience a step change in its surface temperature, but there are periods during which the exterior surface undergoes a ramp increase in temperature. Therefore, walls experiencing ramp temperature increases on one side and a constant temperature on the other side will be examined next. This situation is shown in part (a) of Fig. 2.4. The heat flux at the inside wall surface is given in part (b). The heat flux calculated from the steady-state equation is also given for comparison. As can be seen in the figure, the actual heat flux lags behind that predicted by the steady-state equation. Taking an arbitrary value of heat flux, q, the time at which the steady-state equation would predict this value of heat flux, t_{ss}, is earlier than the time at which it actually occurs, t_a. This difference in time is

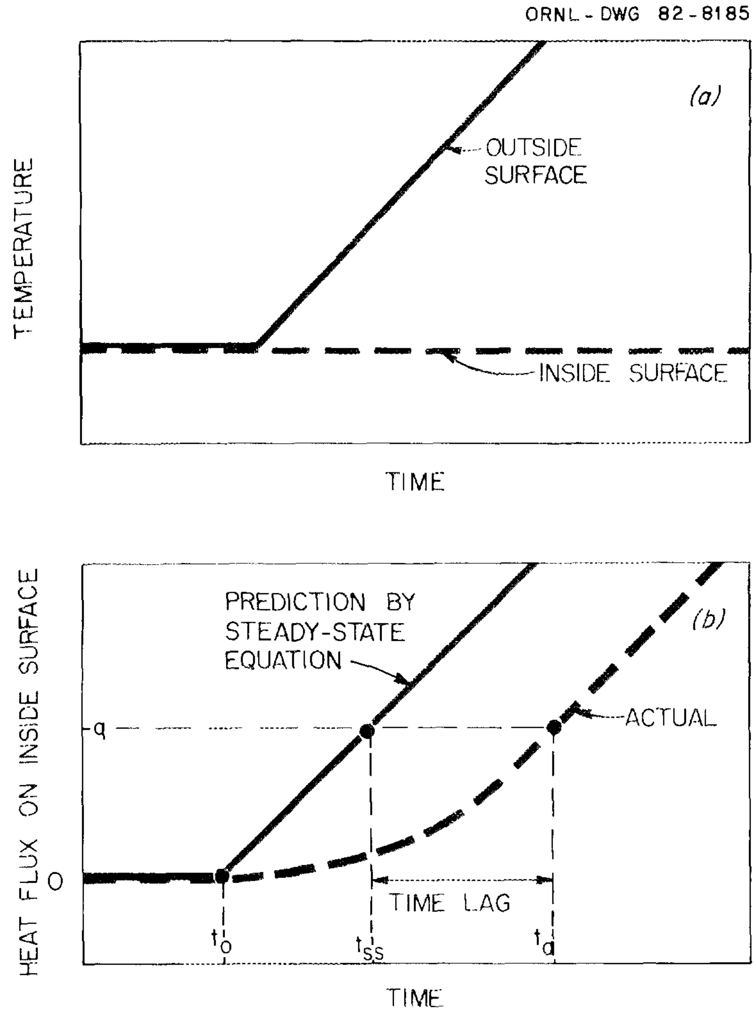

Fig. 2.4. Surface temperature and heat flux history for a wall experiencing a ramp temperature increase on one surface.

referred to as a "time lag." For a single-layer, homogeneous wall, the time lag is less than or equal to $L^2/6\alpha$. When the transient first begins, there is no lag, but as the transient continues, the lag progressively becomes larger approaching the value of $L^2/6\alpha$. The greater the value of L^2/α, the longer the time lag. The time required to reach the ultimate lag time is also of importance. The actual lag approaches $L^2/6\alpha$ exponentially, and, therefore, would take an infinite amount of time to reach it. However, for practical purposes, the final lag time is reached quite early. To determine a time when, for all practical purposes, the lag is no longer changing, another concept is introduced. This is the concept of a "time constant." The time constant is the time required in a transient for a value to reach 36.8% of its final value. After two time constants, it has reached 86.5% of the final value, and after three time constants, it has reached 95.0%. Therefore, after an elapsed time equal to three time constants, a transient is essentially complete even though it theoretically continues forever.

One would expect the time constant to be related to the quantity L^2/α since it has been shown that this quantity gives an indication of the time required to obtain steady state, and this is indeed the case. The time constant for a single-layer, homogeneous wall is $L^2/\pi^2\alpha$. Thus, a time equal to three time constants is approximately 0.3 L^2/α.

Next, consider an outside temperature history in which the temperature is constant up until a time t_0, undergoes a ramp increase until time t_1, and then remains constant at this higher value. This is illustrated in part (*a*) of Fig. 2.5. The corresponding heat flux history on the inside surface is shown in part (*b*). Once again the actual heat flux lags behind the steady-state prediction. The final value of heat flux on the inside surface will be essentially obtained within a time of three time constants (0.3 L^2/α) after time t_1.

If, at some time, t_2, later than t_1, the outside temperature undergoes a ramp decrease back to the original temperature, as shown in part (*a*) of Fig. 2.6, the heat flux history shown in part (*b*) will result. In this case, from the initiation of the transient of time t_0 until steady-state conditions are reached, the heat flux predicted by the steady-state equation is greater than the actual heat flux. The total amount of energy conducted through the wall up to this time is less than that predicted by the steady-state equation by the amount represented by the shaded area labeled 1 in part (*b*) of Fig. 2.6.

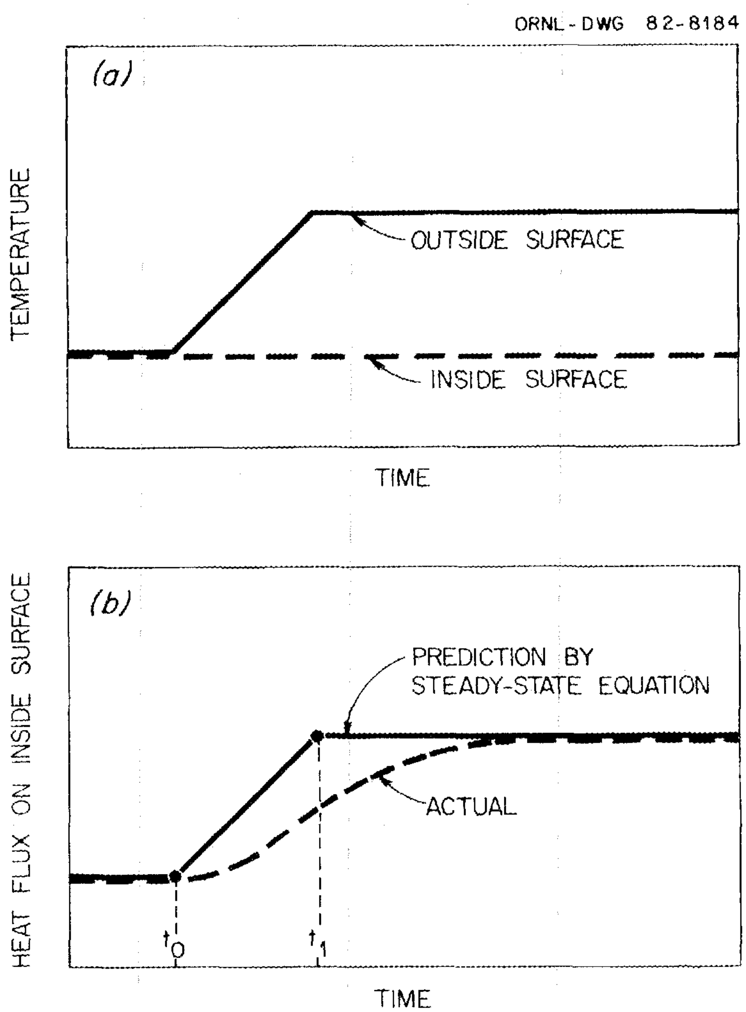

Fig. 2.5. Surface temperature and heat flux history for a wall.

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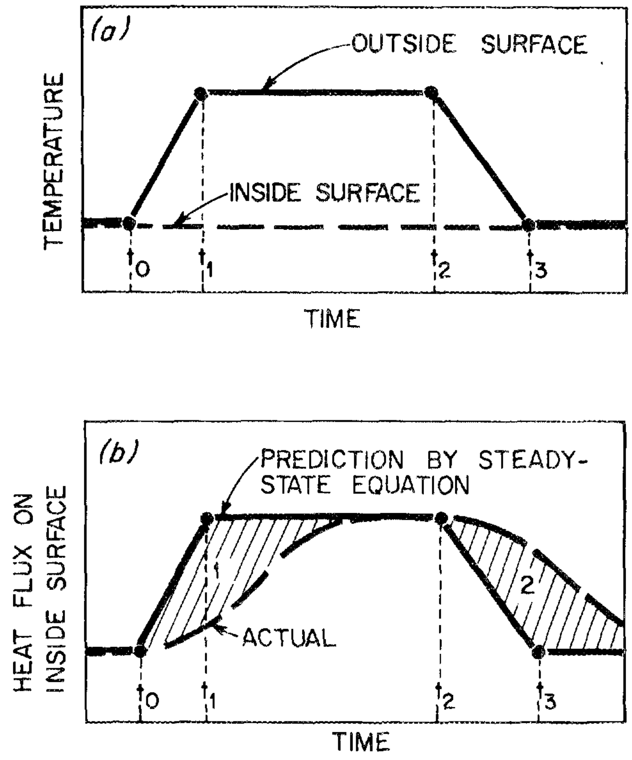

Fig. 2.6. Surface temperature and heat flux history for a wall.

From the beginning of the ramp decrease in temperature at time t_2 until steady-state conditions are once again obtained, the actual heat flux exceeds that predicted by the steady-state equation. The difference in the total amount of energy conducted through the wall during this period is represented by the shaded area labeled 2 in part (*b*) of Fig. 2.6.

What is of primary interest here is that area 1 is equal to area 2. The total amount of energy that flowed through the wall from the initiation of the transient at time t_0 until the original steady-state conditions were re-established is the same as that predicted by the steady-state equation. The steady-state equation can, thus, predict the total energy flow through the wall even though it cannot predict the instantaneous heat flux at any time during the transient.* Since the steady-state equation involves only the wall R-value and not its energy storage capacity (thermal mass), it can be concluded that the mass of the wall does not affect the total energy flow through the wall under these circumstances. The mass does affect when the energy flow reaches the interior of the building.

If the temperature history shown in part (*a*) of Fig. 2.6 is altered so that the time from t_1 to t_2 is not long enough to achieve steady state, a slightly different heat flux behavior is observed. Part (*a*) of Fig. 2.7 shows an extreme example of this in which the time interval from t_1 to t_2 is eliminated. Part (*b*) gives the resulting heat flux history at the inside surface.

In this case there is a reduction in the peak heat flux from that predicted by steady state, and this peak occurs at a later time than that predicted by steady-state calculations. These are both a result of the mass of the material. The area under the triangular shaped

*This can be mathematically verified, but is not done so here because it is as likely to confuse as to enlighten the reader.

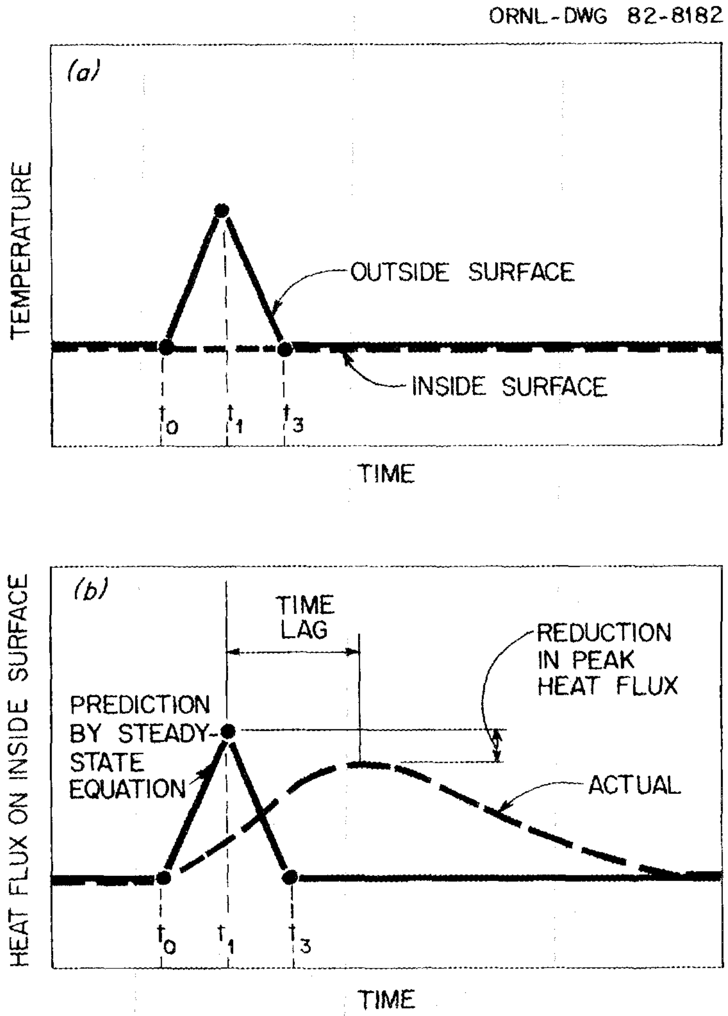

Fig. 2.7. Surface temperature and heat flux history for a wall.

steady-state heat flux curve is the same as the area under the actual heat flux curve. Thus, as in the previous example, the total energy flow through the wall during the transient can be predicted by a steady-state analysis if one knows the wall's R-value. Also, as before, the actual instantaneous heat flux cannot be predicted by a steady-state analysis.

For a homogeneous, single-layer wall, when the quantity L^2/α is increased, the time lag increases and the difference between the actual heat flux peak and the steady-state peak is increased. The transient is essentially completed by three time constants after time t_3.

The previous results can be generalized even more. The transients need not be made up of temperature ramps exclusively. For a wall undergoing any transient which eventually returns it to its original steady-state condition, the total heat flow through the wall during the transient is the same as that predicted by a steady-state type calculation.

2.2.3 Dynamic Heat Conduction

In an actual building the surface temperature varies continuously, and seldom, if ever, are steady-state conditions established. Heat transfer in this situation is referred to as "dynamic heat transfer."

Buildings are often subjected to periodic or nearly periodic conditions, during which the weather conditions are very similar for several days in a row. We will start a discussion of periodic conditions by examining a very simple, albeit nonrealistic, case of a periodic condition consisting of a series of triangular temperature pulses [Fig. 2.8, part (*a*)].

Before proceeding, a brief mention of the principle of superposition is in order.* One aspect of this mathematical principle allows one to take a complicated problem, subdivide it

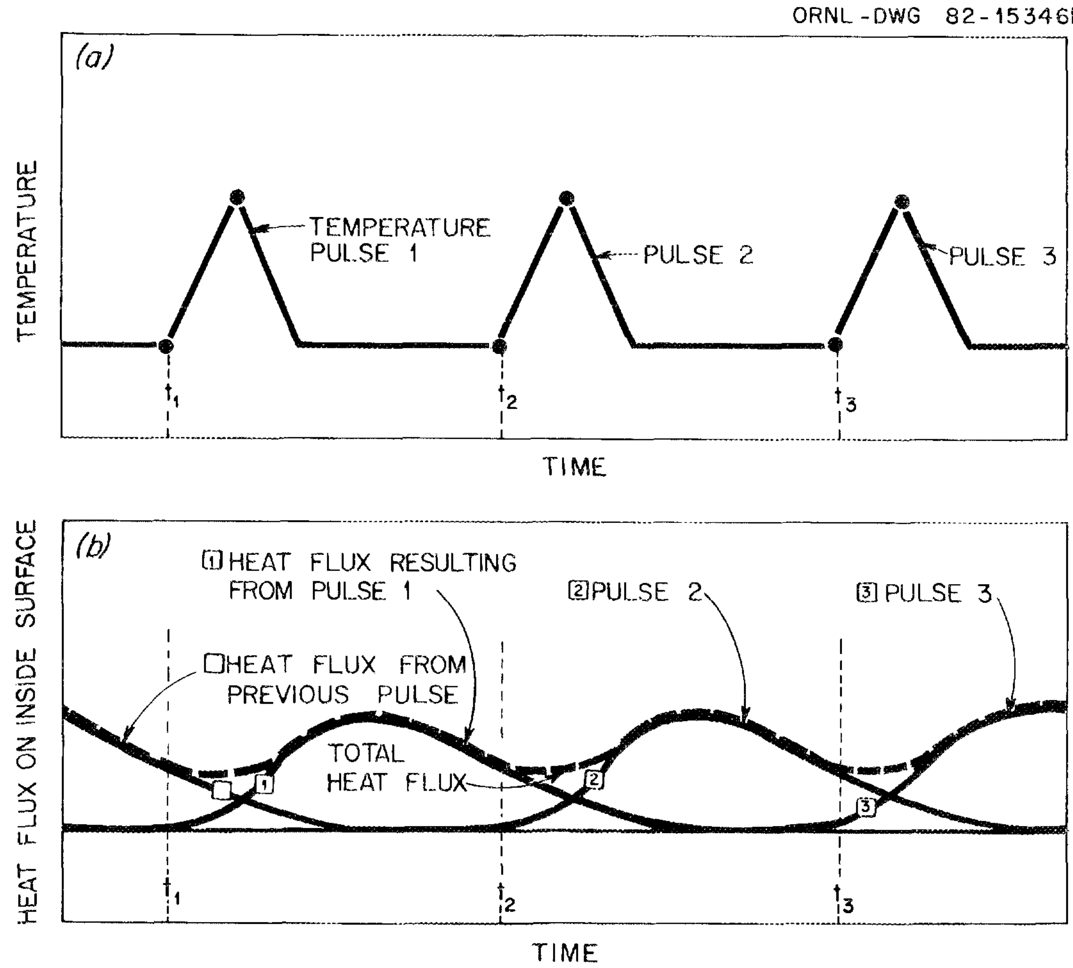

Fig. 2.8. Heat flux resulting from a series of temperature pulses.

into a set of simpler problems, and then sum the individual solutions to obtain the solution to the original problem. Thus, the solution to the periodic problem can be obtained as the sum of the solutions of a series of individual temperature pulses. The heat flux resulting from the individual temperature pulses and the total heat flux obtained from their sum are shown in Fig. 2.8, part (*b*).

*In order to apply the principle of superposition, the mathematical representation of the problem must be a linear differential equation with linear boundary conditions. Conduction heat transfer through a material whose properties are not very temperature-dependent is such a problem.

For a periodic condition such as the temperature in Fig. 2.8, part (*a*), a cycle is the small piece of the curve which is repeated over and over to produce the periodic condition. Thus, the curve from the beginning of one temperature pulse to the beginning of the next one is one cycle. The length of time required to complete one cycle is referred to as a period. A cycle can also be defined as beginning at any time and ending at a time of one period later.

If we examine the cycle beginning at time t_2 and ending at time t_3, we see that the heat flux is influenced by temperature pulses 1 and 2. The first part of the heat flux curve produced by temperature pulse 2 and the last part of the heat flux curve produced by temperature pulse 1 appear in this time interval. However, since pulses 1 and 2 are identical, the equivalent of all of the heat flux resulting from one temperature pulse appears in this interval. Thus, under this particular periodic condition, the total heat flux for an entire cycle (or any integer number of cycles) can be determined by use of a steady-state type calculation. The steady-state calculation cannot predict the instantaneous heat flux during the cycle, however.

It was assumed for convenience in this example that the heat flux was only influenced by two temperature pulses. In fact, the conclusion would not have been altered if several temperature pulses prior to pulse 1 affected the heat flux. The portions of the several heat flux curves resulting from the temperature pulses would still have been equivalent to the heat flux curve resulting from a single pulse.

Making further use of the principle of superposition, several temperature pulses of different heights can be combined to produce any cycle desired (see, for example, Fig. 2.9).† Thus, it can be concluded that for any wall exposed to arbitrary periodic conditions, the total heat flow through the wall over a cycle (or integer number of cycles) can be predicted by steady-state equation. In other words, under periodic conditions, the total heat flow through a wall over a whole number of cycles can be determined from the R-value and the average temperature difference across the wall.

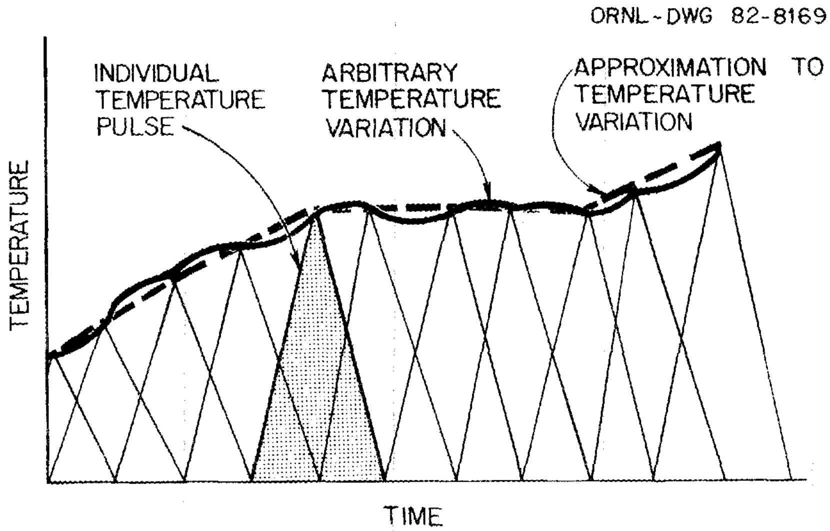

Fig. 2.9. Approximation to an arbitrary temperature variation by a sum of temperature pulses.

†This is similar to how the response factor method, which is used in many large building analysis programs, works. The outdoor conditions are approximated by a series of triangular temperature pulses, and the heat flux is determined as the sum of the response to all of these pulses. The outdoor conditions do not need to be periodic to do this.

Diurnal temperature variations can be approximated by a sine wave. Therefore, a more realistic periodic condition to examine is the behavior of a wall in which the outside surface temperature varies sinusoidally. The simplest case is illustrated in Fig. 2.10, where one surface temperature varies sinusoidally about a mean value and the other surface is held constant at this mean value. For this case the heat flux at the inside surface, as a function of time, is plotted in Fig. 2.11. For comparison, the heat flux obtained by the application of the steady-state heat transfer equation is also plotted. Since the steady-state heat transfer equation depends only on the slab R-value and the instantaneous temperature difference, the flux varies as a sine wave, which is in phase with the temperature variation.

Two points stand out when the actual dynamic heat flux is compared to the value arrived at by application of the steady-state assumption. First, the actual heat flux variation is sinusoidal, but it is out of phase with the steady-state heat flux and outside temperature variation. The actual heat flux lags behind that predicted by steady state. Secondly, there is a reduction in the amplitude of heat flux variation.

To illustrate the behavior of a wall under these conditions, consider a homogeneous, single-layer wall. This wall has an analytical solution in which the influence of individual parameters can easily be seen. An analytical solution for a multilayer wall is available, but it does not lend itself to the tutorial nature of this presentation. A brief note on multilayer walls will be presented later.

The solution will not be presented here, but some results from it will be. Both the time lag and the reduction in the peak heat flux are dependent on the same parameter,

$$\sqrt{\frac{L^2/\alpha}{P}} ,$$

or

$$\sqrt{\frac{L^2}{P\alpha}} .$$

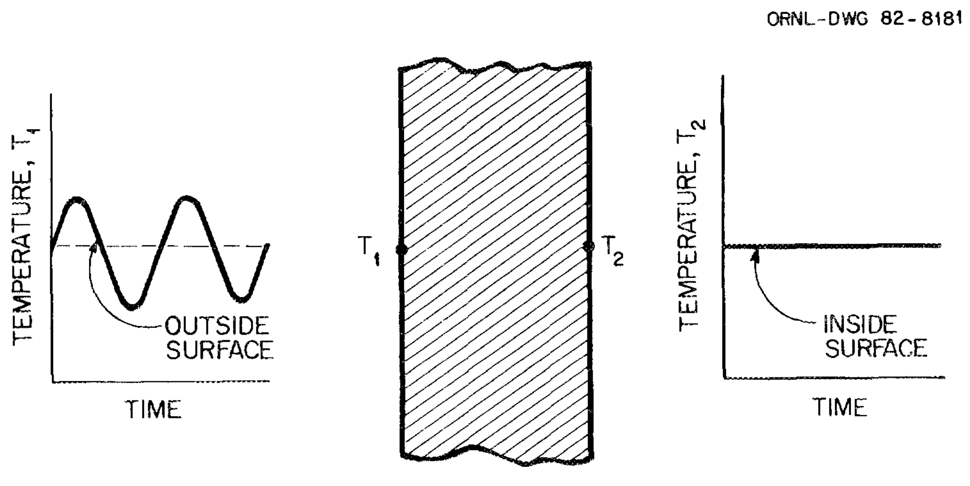

Fig. 2.10. Temperature variation on wall surfaces.

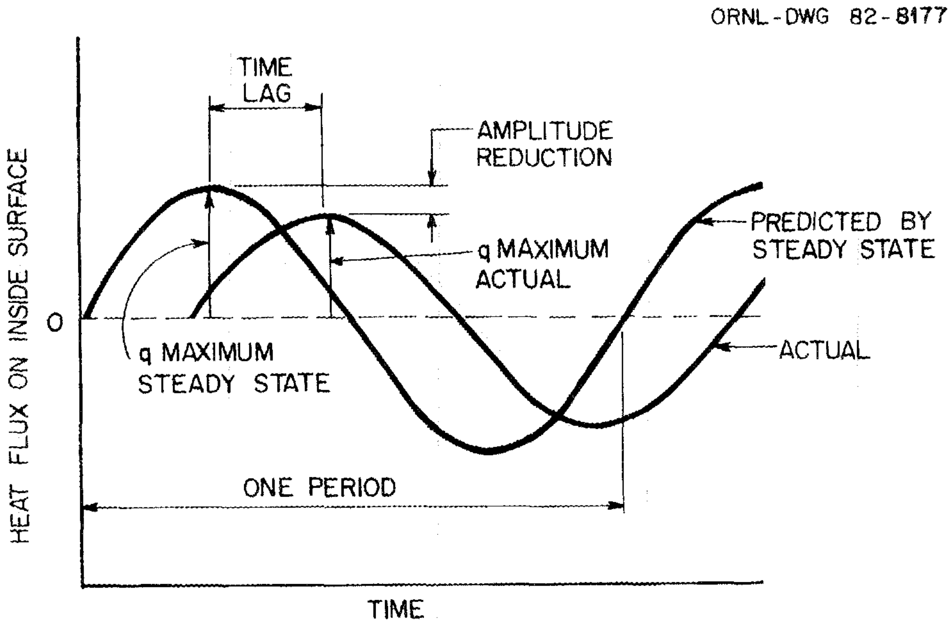

Fig. 2.11. Comparison of actual heat flux and heat flux calculated with the steady-state equation.

This is a dimensionless grouping which is the square root of the ratio of two measures of time. The numerator, L^2/α, as we have seen earlier, is a measure of time required for the wall to thermally respond to a change. The denominator, P, is simply the time period required to complete a single cycle. Plots of the time lag and the ratio of maximum heat flux vs the parameter are given in Figs. 2.12 and 2.13, respectively.

The development of the discussion of wall thermal behavior has now reached a point where the two main attributes of wall mass can be discussed. These attributes are (1) the reduction in the variation in the heat flux through the wall and (2) the shifting of heat flux from one time to another resulting from the lag produced by mass.

For a single-layer wall the ratio of the amplitude of the actual heat flux variation to that predicted by a steady-state calculation can be determined from Fig. 2.13. However, it is the magnitude of the actual heat flux rather than this ratio which is of primary interest. This amplitude can be determined as

$$q_{\text{max} - \text{actual}} = q_{\text{max} - \text{s.s.}} \times \text{heat flux amplitude ratio} .$$

In Table 2.3 eleven common building materials are listed along with the thickness required to give the same maximum heat flux at the inside surface of a wall exposed to a sinusoidal external temperature variation. A mineral fiber wall with a thickness of 10 cm (3.9 in.) is used as a reference since its steady-state and dynamic behavior are virtually the same. The thickness of each of the other materials which would be required to give the same maximum heat flux is calculated by both the steady-state and dynamic methods. They are

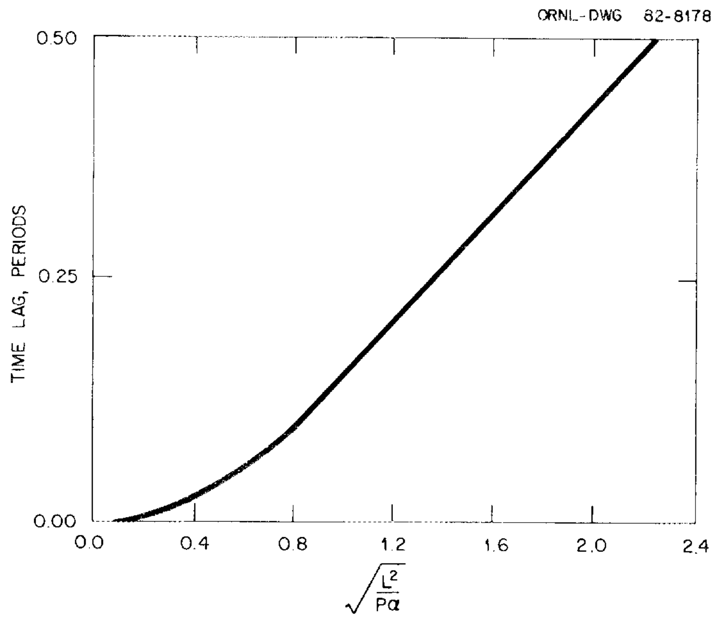

Fig. 2.12. Time lag for homogeneous walls subjected to sinusoidal temperature variation.

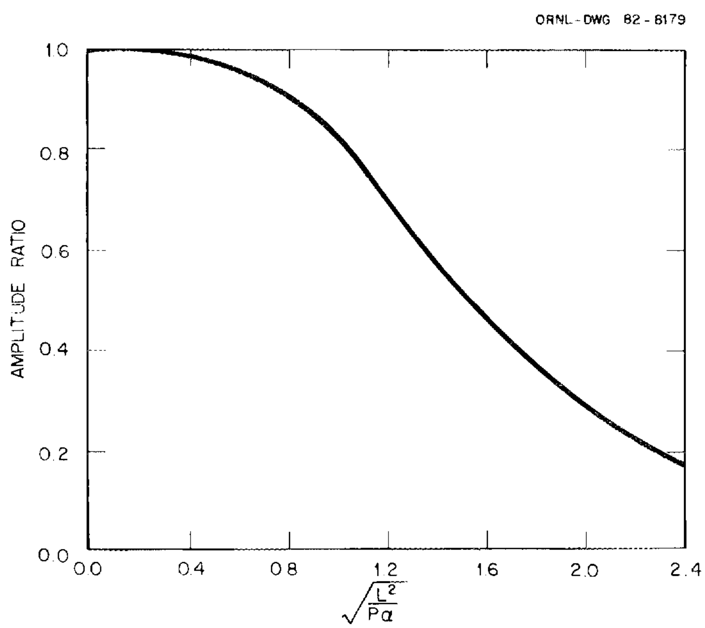

Fig. 2.13. Heat flux amplitude reduction for homogeneous walls subjected to sinusoidal temperature variation.

Table 2.3. Thickness required to give same maximum heat flux at inside surface of walls of different materials exposed to a sinusoidal external temperature variation

Material	Required Thickness predicted by steady-state [cm (in.)]	Actual Thickness Required [cm (in.)]
Expanded polystyrene	6.0 (2.4)	6.0 (2.4)
Glass fiberboard	8.8 (3.4)	8.5 (3.3)
Mineral fiber	10.0 (3.9)	10.0 (3.9)
Wood	25.0 (9.8)	15.7 (6.2)
Gypsum board	32.9 (12.9)	18.3 (7.2)
Insulating lightweight concrete	29.2 (11.5)	19.8 (7.8)
Structural lightweight concrete	136.0 (53.5)	37.4 (14.7)
Building brick	152.0 (59.8)	39.3 (15.5)
Face brick	271.0 (107.0)	53.1 (20.9)
Normal weight concrete	396.0 (156.0)	70.5 (27.8)
Steel	9440.0 (3720.0)	353.0 (139.0)

ranked according to the actual thickness required (that determined by the dynamic calculation), with the thinnest first. Using this criterion, the materials with high R-values and low thermal mass perform the best.

To understand why this is so, we need to examine the parameter $\sqrt{L^2/P\alpha}$. This can be expanded as

$$\sqrt{\frac{L^2}{P\alpha}} = \sqrt{\frac{L^2}{P}\,\frac{\rho c}{k}} = \sqrt{\frac{\frac{L}{k}\;L\rho c}{P}} = \sqrt{\frac{RS}{P}}\,,$$

where R ($R = L/k$) is the wall R-value and S ($S = L\rho c$) is the heat storage capacity of the wall per square foot of surface area. From this form of the parameter, it is clear that increasing the R-value or the energy storage capacity (thermal mass) of a wall has the same effect on the heat flux amplitude ratio. However, increasing the R-value also reduces the maximum heat flux calculated by the steady-state equation, whereas the energy storage capacity does not. Thus, the R-value of a wall has more influence on the maximum heat flux than does the wall thermal mass, as is indicated in Table 2.3.

The other main attribute of the mass in a wall is its ability to shift the time of occurrence of the maximum and minimum heat flux through the wall to a later time. This can have important implications in the total energy usage of a building. These implications will be addressed in Chap. 3.

Figures 2.14 to 2.16 illustrate the behavior of homogeneous walls exposed to a sinusoidal temperature variation on the outside and a fixed temperature on the inside. The behavior of nonhomogeneous walls is similar. Walls were chosen which produced lag times of 3, 6, and 12 h. In part (*a*) of each figure, the actual heat flux for an entire cycle is plotted along with the heat flux calculated by assuming steady-state conditions always exist. In part (*b*), the change is just the difference between the actual and steady-state values. It should be noted that the average heat flux is not influenced by the mass. In part (*b*) of the figures, the area

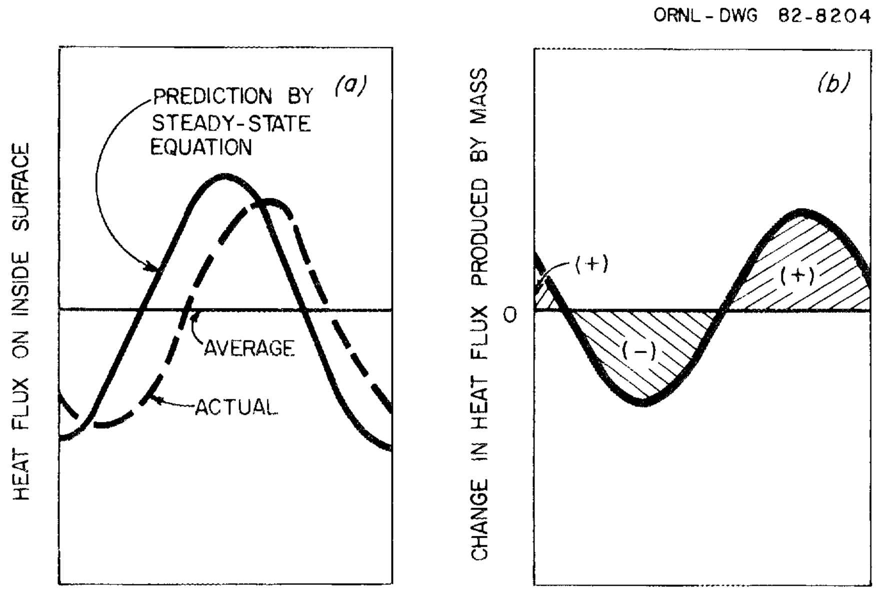

Fig. 2.14. Heat flux on inside surface of a homogeneous wall—3-h lag.

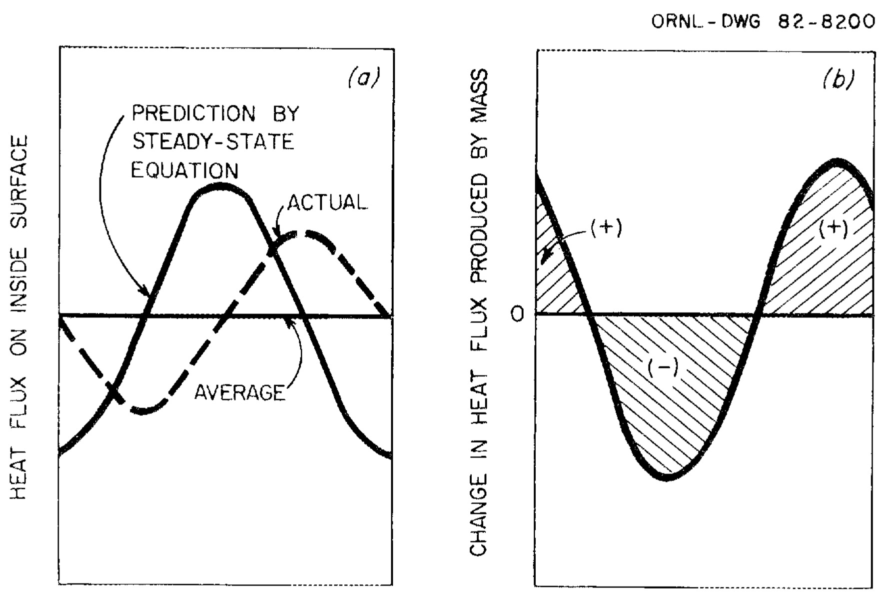

Fig. 2.15. Heat flux on inside surface of a homogeneous wall—6-h lag.

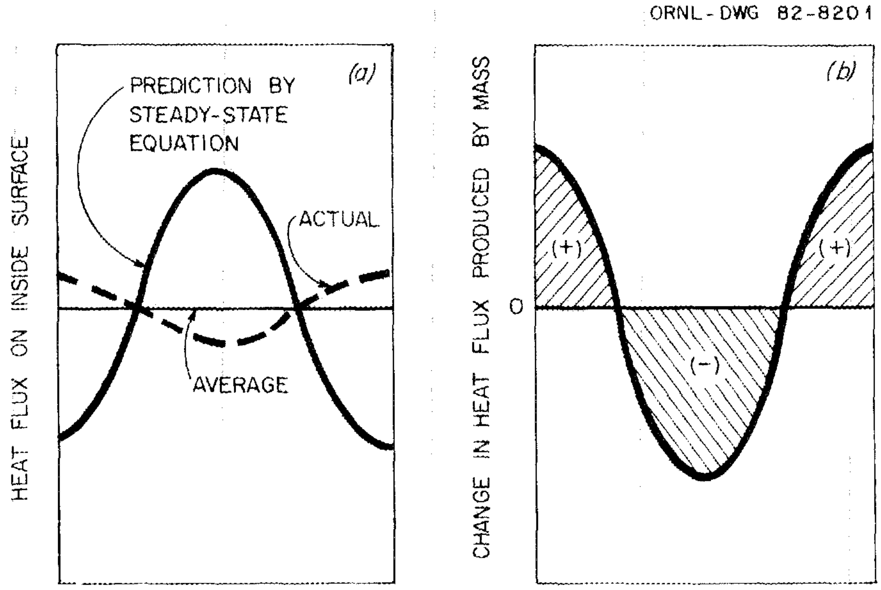

Fig. 2.16. Heat flux on inside surface of a homogeneous wall—12-h lag.

marked with a plus sign (indicating an increase in heat flux compared to steady state) is equal to the area marked with a minus sign (indicating a decrease). Mass does not influence the average or total heat flow through the wall, but does influence when the heat reaches or leaves the interior space.

The maximum change in heat flux from its steady-state value will occur when the mass produces a time lag of half a period (12 h for a diurnal cycle). From Fig. 2.13 it can be determined that this occurs when $\sqrt{L^2/P\alpha}$ is approximately 2.2. For this value of $\sqrt{L^2/P\alpha}$, the heat flux amplitude ratio is 0.22. The maximum heat flux at the inside surface is reduced by an amount equal to 122% of the amplitude of the variation in the heat flux calculated from steady state. Generalizing slightly, this means that the maximum difference in peak heat flux through a lightweight wall and a massive wall with the same R-value will be less than or equal to (usually much less than) 122% of the amplitude of variation in the heat flux through the lightweight wall. The average heat flux will, of course, be the same for both walls. Table 2.4 lists the thickness of various materials required to produce a lag of 12 h and the change in the peak heat flux for a 1° maximum temperature difference across the wall. The walls are ranked according to the change in peak heat flux from the largest change to the smallest. Using this criterion, the walls with large thermal masses and small R-values perform best.

The next step in examining the behavior of a building envelope is to look at a case in which the surface temperature on one side varies about some mean value which is different from the constant temperature on the other side. In Fig. 2.17, part (*a*), the original problem is shown. In parts (*b*) and (*c*), the two simpler problems, into which the original problem is separated, are shown. Note that the sum of the left surface temperature from part (*b*) or (*c*) is equal to the surface temperature for the original problem and likewise for the right-hand surface temperature.

Note that the problem illustrated in Fig. 2.17, part (*b*), is a steady-state problem since the surface temperatures do not vary with time. The problem illustrated in part (*c*) is the problem we have just examined in which one surface temperature fluctuates about a mean value equal to the other surface temperature; in this case, the mean value is zero. Thus, the solution to this problem is the sum of the solutions to two simpler problems already examined.

Table 2.4. Thickness of material required to give a 12-h lag and resulting change in peak heat flux from the "steady-state" value

Material	Thickness cm	Thickness in.	Change in Peak Heat Flux for 1°C amplitude (W/m^2)	Change in Peak Heat Flux for 1°F amplitude ($Btu/h \cdot ft^2$)
Steel	226.0	88.8	25.0	4.3
Normal weight concrete	65.1	25.6	3.6	0.63
Face brick	51.3	20.2	3.1	0.54
Building brick	41.7	16.4	2.1	0.37
Structual lightweight concrete	41.7	16.4	1.8	0.31
Gypsum board	27.9	11.0	0.70	0.12
Wood	26.0	10.2	0.56	0.096
Insulating concrete	35.1	13.8	0.49	0.088
Glass fiberboard	31.9	12.6	0.016	0.028
Expanded polystyrene	54.1	21.3	0.065	0.126
Mineral fiber	174.0	68.5	0.034	0.006

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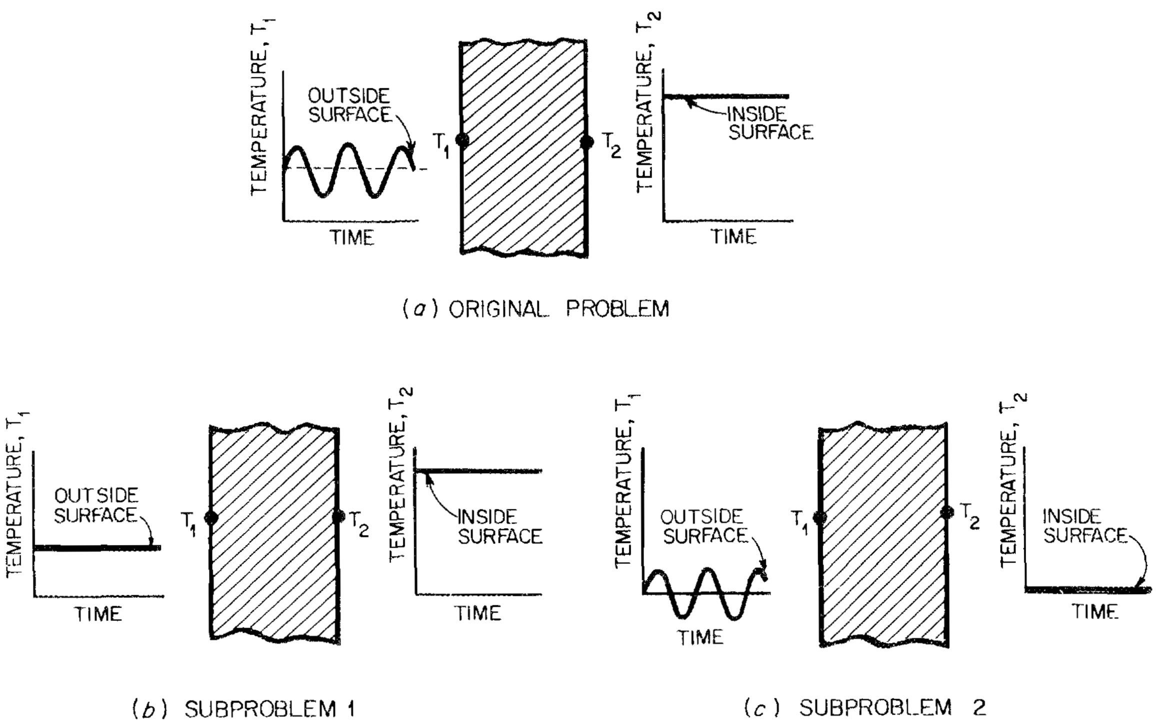

Fig. 2.17. Illustration of superposition principle for dividing a problem into two simpler problems.

The heat flux at the inside surface is made up of two components: a constant heat flux which depends only on the R-value and the average temperature difference across the slab, and a fluctuating heat flux. It has already been noted that over an entire cycle there is no net energy flow at this inside surface due to the fluctuating component of the outside surface temperature. Thus, the total heat flow at the inside surface of a wall over a cycle is not influenced by the mass of the wall, but only by its R-value. The peak heat flux and the lag time are influenced by both the R-value and the thermal mass of the wall.

The lag time is not influenced by the steady-state portion of the problem. Thus, the lag time is the same as it would have been if only the fluctuating portions were present. As before, the lag time increases when either the thermal mass or R-value of the wall is increased.

The peak value of heat flux is influenced by both the steady-state and fluctuating portions of the problem. The peak heat flux is the sum of the steady-state component and the amplitude of the fluctuating component. The influence of the R-value and thermal mass on the amplitude of the fluctuating component has already been addressed. The steady-state portion of the heat flux is proportional to the R-value and is not affected by the thermal mass. Two slabs of equal thickness, composed of different materials having the same value of thermal diffusivity, will experience the same time lag, but different average and peak heat fluxes. A material with lower conductivity (consequently, a lower ρc product since $k/\rho c$ is constant) will experience both a lower average and a lower peak heat flux.

The R-value of a wall has a greater impact than does its thermal mass on the heat flux at the inside surface. This is because the thermal mass influences only the fluctuating component of this heat flux, whereas the R-value influences both the average and fluctuating components and has a greater impact on the fluctuating component than does the thermal mass.

2.2.4 Multilayer Slabs

For steady-state heat flow through a slab, going from a single layer to multiple layers does not greatly complicate matters. The steady-state equation for heat flow through the slab is still valid except the R-value for the entire slab must be used. The R-value for the entire slab is simply the sum of the R-values for the individual layers.

For a fluctuating temperature on one side of the slab, the phase lag and the heat flux amplitude ratio depend on the dimensionless grouping $\sqrt{L^2/\alpha P}$. Unfortunately, when going to a multiple layer slab, there is not a simple grouping such as this which determines the phase lag and amplitude reduction. The sum of this dimensionless group for all of the layers can, however, be used to arrive at an approximate value of lag and amplitude reduction. Arumi, of the University of Texas, has done work in this area. His work is discussed in Appendix A.

2.3 Recoverable Energy Storage

When there are changes in the interior conditions of a building, heat can flow into and be stored in the building envelope or interior partitions or other mass in contact with the interior air space. Under certain circumstances this energy can later be recovered by the interior air space. Thus, the "recoverable energy storage," is energy storage and subsequent recovery produced by variations in the interior conditions of a building.

In the discussion of heat flow through a wall, it was mentioned that energy was stored in the mass, and this influenced the heat flow through the wall. This was a situation where the energy storage resulted from changing conditions on the outside of the wall.

Energy can be transferred to mass for storage only when some temperature in its surroundings is higher than the surface temperature of the mass. When the surrounding air is at a higher temperature than the mass, heat is transferred from the air to the mass by convective heat transfer. When there is a surface at a higher temperature within line-of-sight of the mass, heat is transferred from the hotter surface to the mass by radiative heat transfer. This surface need not be inside the building. In fact, the sun shining through a window may be the most important source of radiative heat transfer. Air is virtually transparent to radiative heat transfer and is, thus, not heated by it.

Interior air can recover energy from the mass by convection when the air temperature is lower than the mass temperature. The mass can also lose energy by radiation when there is another surface at a lower temperature. However, since this radiative energy does not heat the air, this energy is not immediately recovered by the interior air. There is a further discussion of the differences between convectively coupled and radiatively coupled mass in Sect. 2.3.2. In Sect. 2.3.1 the primary concern will be with the conduction of energy within the mass and not the mechanism by which it arrives at the surface of the mass.

The recoverable energy storage can have an effect on the energy usage of a building since the energy gains and losses may not have an immediate impact on the interior air temperature. This is discussed in Chap. 3.

2.3.1 Heat Conduction in Storage Mass

Figure 2.18 shows how the temperature profile develops with time in a wall when the temperature on one surface undergoes a step change in temperature at time t_0 and the other surface is insulated so that heat is not lost through it. The amount of energy stored at a temperature above the initial temperature is indicated by the shaded areas in Fig. 2.18. The stored energy per unit surface area is proportional to this shaded area and to the ρc product for the wall. The shaded area is equal to the average temperature rise times the wall thickness. As has already been noted, the speed at which the temperature profile develops is determined by the thermal diffusivity, α, of the material. In a material with a large thermal diffusivity, the temperature profile will develop quickly. Since the thermal diffusivity is $k/\rho c$, the temperature profile will develop more quickly in a material with a small ρc product. However, a material with a small ρc product will not store as much energy per unit volume as one with a large ρc for a given temperature rise. Thus, the thermal diffusivity is not a good indicator of how rapidly thermal energy penetrates the wall. Another parameter, which does indicate the speed at which energy penetrates the wall during a transient, is given by the product $k\rho c$ and is called the thermal penetration property.

A wall will not complete the transient shown in Fig. 2.18 under normal circumstances since surface conditions will probably change before this occurs. Thus, the speed at which energy can get into the mass is of primary importance since there is limited time to accomplish this energy storage. A material with the largest thermal penetration property will usually store the most energy.

If, at time t_2 [Fig. 2.18, part (*c*)], the surface temperature were to drop back to its original value, the transient of Fig. 2.19 would ensue. At time t_3 heat is flowing out of the surface. Because heat flows down the temperature gradient (from higher temperature to lower),

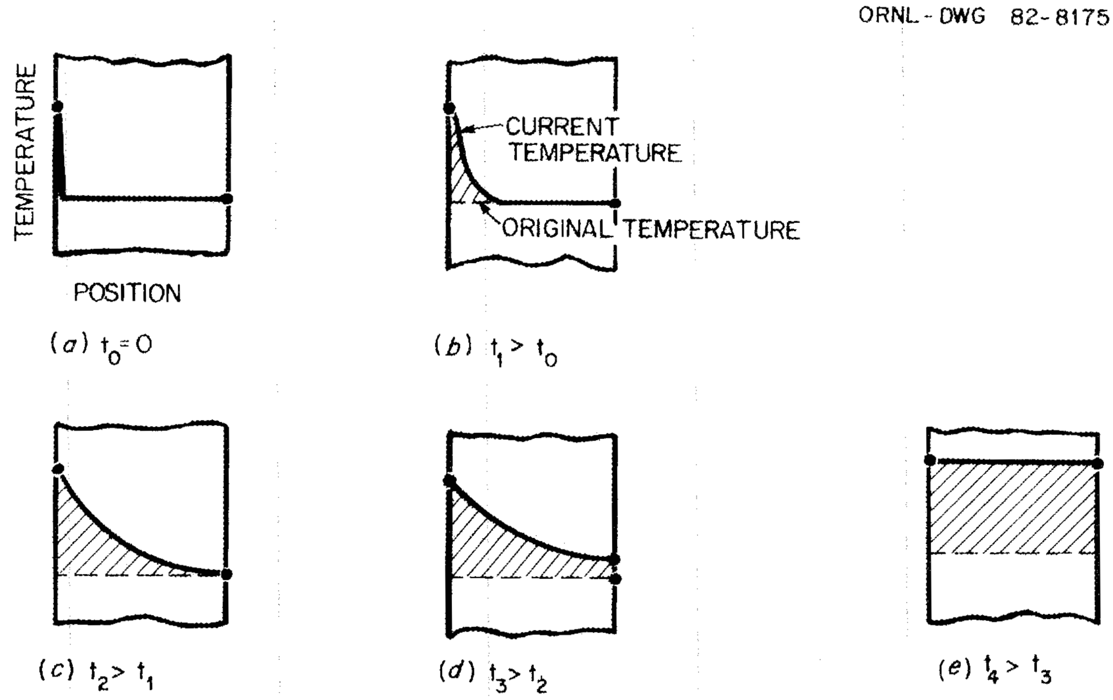

Fig. 2.18. Development of temperature profile in a wall used for energy storage.

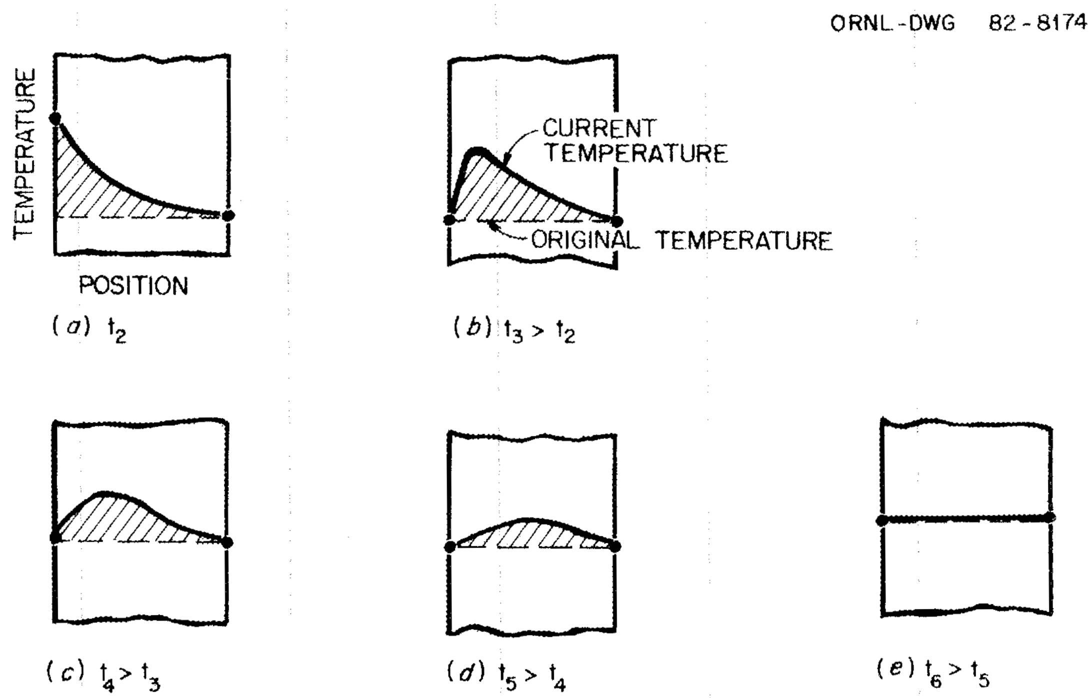

Fig. 2.19. Development of temperature profile in a wall used for energy storage.

there is still heat flowing into the wall from the location of maximum temperature. At time t_4 more energy has flowed out of the wall. The temperature profile still contains a hump, but it is smaller than previously and has moved further into the wall. At time t_5 the transient is complete. When the temperature profile in the wall is viewed with passing time, it appears that a temperature wave begins at the surface and travels through the wall, decreasing in amplitude as it goes.

The maximum energy which can be stored in a wall per unit surface area is

$$Q_{\text{stored}} = \rho C_p L \Delta T_{\text{surface}} \ ,$$

where L is the wall thickness and $\Delta T_{\text{surface}}$ is the rise in the wall surface temperature above some reference temperature. However, this amount of energy storage can occur only if there is sufficient time for the temperature change to fully penetrate the wall (refer to Fig. 2.18). Of greater concern is the amount of energy that actually will be stored in a wall and subsequently recovered when the surface experiences a continually changing temperature.

A simple model helps explain the actual energy stored in a wall under dynamic conditions. This model consists of a wall made up of a single layer of a homogeneous material. The back surface is insulated, and the front surface undergoes a sinusoidally varying temperature change with period. Under these conditions, heat goes into the wall during half of each period and flows back out during the other half. This problem, fortunately, has an exact analytical solution. This solution is, however, rather complicated, so only the results of the solution will be presented.

Of primary interest is energy storage for a diurnal (24-h) cycle. In Fig. 2.20, the actual energy storage for a diurnal cycle with a 1° change in surface temperature is presented for eleven different materials for varying wall thickness. The effect of wall thickness on the amount of energy stored is surprising. With a thin wall, increasing the wall thickness increases the energy stored almost linearly, as expected. However, with further increases in thickness, the energy stored goes through a maximum value and then actually decreases slightly. The maximum energy storage occurs when $L = 1.2\sqrt{\alpha P/\pi}$. Wall thickness greater than this gives no additional energy storage benefit and actually reduces energy storage. The physical explanation for this is that heat stored in this wall from previous days is trying to flow out of the wall and interferes with current heat flow into the wall.

Another interesting point is that for thin walls, the wall having the largest ρC_p product stores the most energy, but for thicker walls, the wall having the largest $k\rho C_p$ product stores the most energy. In Fig. 2.20, this is illustrated by comparing the wall of normal weight concrete and the wall of face brick. A thin wall of face brick, which has the higher ρC_p, stores more energy than the normal weight concrete wall. However, a thick concrete wall, which has the higher $k\rho C_p$, stores more energy than a face brick wall.

Also of interest is the energy stored in walls over intervals shorter than diurnal cycles. Fig. 2.21 shows energy stored in various walls for a sinusoidal temperature variation with a period of 1 h. The shape of the curves is the same as for diurnal variations, but the peak energy stored is less and occurs at a lesser wall thickness.

Table 2.5 gives the thickness which gives the maximum energy stored for 24- and 1-h cycles. This gives the maximum thickness which one would want for a storage wall. To use Fig. 2.20 or 2.21 for walls where both surfaces are used for energy storage, use the following

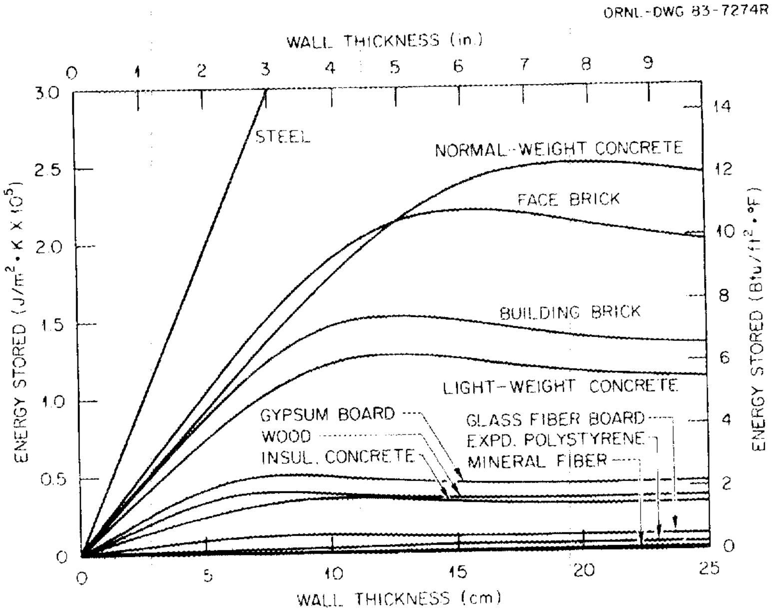

Fig. 2.20. Energy stored in walls of various materials for a 1° change in surface temperature—sinusoidal variation with a 24-h period.

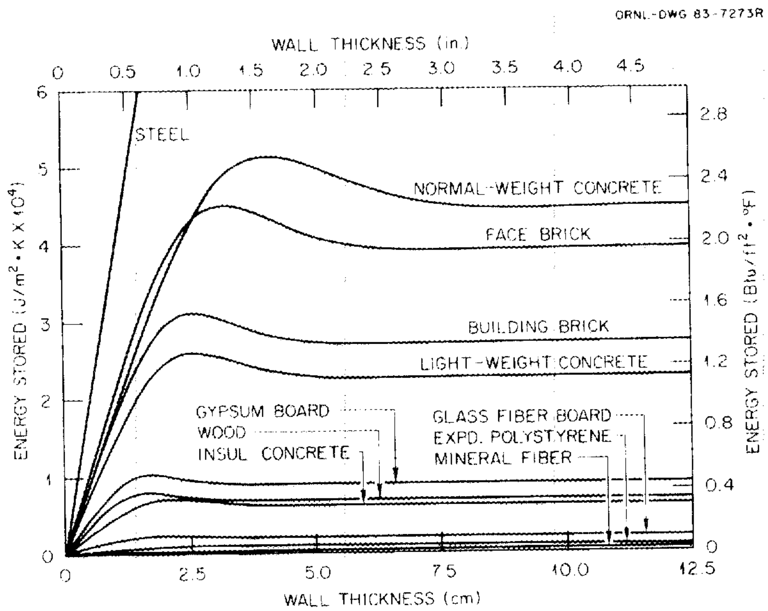

Fig. 2.21 Energy stored in walls of various materials for a 1° change in surface temperature—sinusoidal variation with a 1-h period.

Table 2.5. Wall thickness that gives maximum energy storage for walls with a sinusoidally varying surface temperature for periods of 24 and 1 h

Material	Thickness 24 h cm	Thickness 24 h in.	Thickness 1 h cm	Thickness 1 h in.
Normal weight concrete	20.2	8.0	4.1	1.6
Structural lightweight concrete	12.8	5.0	2.6	1.0
Insulating lightweight concrete	10.7	4.2	2.2	0.9
Building brick	12.8	5.0	2.6	1.0
Face brick	15.7	6.2	3.2	1.3
Mineral fiber[a] (loosefill)	52.7	20.8	10.8	4.2
Glass fiberboard[a] (resin binder)	9.9	3.9	2.0	0.8
Expanded polystyrene[a]	16.4	6.5	3.4	1.3
Steel	67.6	26.6	13.8	5.4
Wood	8.2	3.2	1.7	0.7
Gypsum board	8.5	3.4	1.7	0.7

[a]Meaningless since these materials would never be used for energy storage.

procedure. Take half the wall thickness, read energy stored from Fig. 2.20 or 2.21, and double this value. In Table 2.5, simply double the values listed.

Generally speaking, the best allocation of energy storage mass is to maximize the surface area and minimize the thickness. It should be pointed out that any mass in contact with the interior air of a building is utilized for energy storage. This includes interior partitions, furnishings, any mass included expressly for this purpose, and mass in the building envelope, if it is not isolated from the interior by insulation.

2.3.2 Implications of Radiatively and Convectively Coupled Mass

When a heat source directly heats the air, and the air, in turn, heats the mass by convective heat transfer, the mass is said to be convectively coupled to the heat source. Examples of heat sources in which this is the primary mechanism of transferring heat to the mass are people, appliances, electronic equipment, and, to a large degree, incandescent lights.

The transfer of energy from the air to the mass is described by Newton's law:

$$q = hA(T_{\text{air}} - T_{\text{surface}}) \ ,$$

where

q = rate at which energy is transferred to the mass, W (Btu/h),

h = convective heat transfer coefficient, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 {}^\circ F$),

A = surface area of mass, m^2 (ft^2),

T_{air} = air temperature, K (°F),
$T_{surface}$ = surface temperature of the mass, K (°F).

The heat transfer coefficient, h, depends on several quantities including air velocity near the surface; the surface orientation, texture, and size; and the temperature difference between the surface and the air. For vertical walls in a room with still air, the value will be of the order of 6 $W/m^2 \cdot K$ (1 $Btu/h \cdot ft^2 \cdot °F$) or less.

For a room which contains a constant uniform heat source, an exact analytical solution can be obtained for the temperature of the mass and air. Some simplifying assumptions are made in obtaining this solution. They are: (1) all of the energy supplied by the source is stored as sensible heat in either the mass or the air; (2) the air temperature is constant throughout the room, but varies with time; (3) the mass temperature is constant throughout the entire mass, but varies with time; and (4) the heat transfer coefficient is constant.

The rise in the air temperature and the mass temperature obtained from the exact solutions is plotted as a function of time in Fig. 2.22. The units were intentionally omitted from both axes since it is the general behavior which is being examined rather than a specific case. The shape of the curves is the same for all cases. Initially, what is observed is a rapid rise in the air temperature. The rate of rise in the air temperature then drops dramatically until the rate of rise becomes a constant value. From this time on, the temperature difference between the air and the mass is a constant amount.

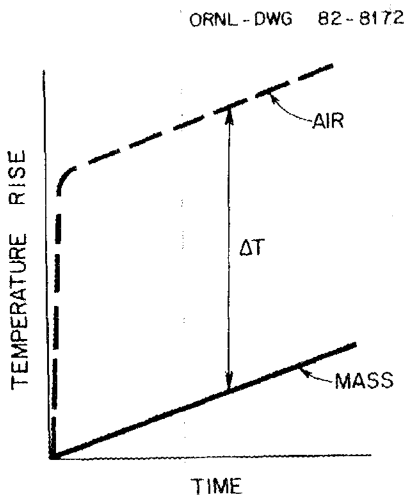

Fig. 2.22. Rise in air and mass temperature for convectively coupled mass.

A physical explanation of this behavior is that initially the air temperature rises rapidly because of its low heat storage capacity and the fact that a disproportionate amount of the energy is absorbed by the air. The mass absorbs very little of the energy initially because the temperature difference between the mass and the air is not great enough to transfer a large amount of heat to the mass. As the air temperature rises, this temperature difference increases and a larger portion of the heat is stored in the mass, which decreases the rate of rise of the air temperature. At some point, the temperature difference between the mass and air becomes such that the energy storage split between the air and mass matches their abilities to store energy. From this point on the rate of temperature rise of both the air and mass will be the same. The fraction of the energy stored in the air will be

$$\frac{q_{\text{air}}}{q_{\text{source}}} = \frac{(\rho c V)_{\text{air}}}{(\rho c V)_{\text{air}} + (\rho c V)_{\text{mass}}} ,$$

and the fraction stored in the mass will be

$$\frac{q_{\text{mass}}}{q_{\text{source}}} = \frac{(\rho c V)_{\text{mass}}}{(\rho c V)_{\text{air}} + (\rho c V)_{\text{mass}}} .$$

The temperature difference necessary for this to occur is

$$\Delta T = \frac{q_{\text{source}}}{hA} \frac{(\rho c V)_{\text{mass}}}{(\rho c V)_{\text{mass}} + (\rho c V)_{\text{air}}} .$$

Since $(\rho c V)_{\text{mass}}$ is much, much greater than $(\rho c V)_{\text{air}}$, this can be approximated as

$$\Delta T \simeq \frac{q_{\text{source}}}{hA} .$$

By examining the curve (Fig. 2.22), it is clear that a good estimate of the length of time during which the air experiences the rapid, initial temperature rise can be arrived at by assuming that all of the heat from the source is stored in the air and none in the mass until the previously discussed temperature difference is reached. Thus,

$$t = \frac{(\rho c V)_{\text{air}} \ \Delta T}{q_{\text{source}}} ,$$

or, substituting for ΔT,

$$t = \frac{(\rho c V)_{\text{air}}}{q_{\text{source}}} \frac{q_{\text{source}}}{hA} \frac{(\rho c V)_{\text{mass}}}{(\rho c V)_{m} + (\rho c V)_{\text{air}}}$$

$$= \frac{(\rho c V)_{\text{air}}}{hA} \frac{(\rho c V)_{\text{mass}}}{(\rho c V)_{\text{mass}} + (\rho c V)_{\text{air}}}$$

$$t \simeq \frac{(\rho c V)_{\text{air}}}{hA} .$$

An interesting result is that the time period during which the initial, rapid temperature rise occurs is not influenced by the rate at which energy is supplied by the source. Of course, the magnitude of the temperature rise is directly proportional to this rate. For a typical building, this time is of the order of a few minutes.

Some conclusions can be drawn about thermal mass that is convectively coupled to a heat source.

1. There is a period immediately following the initiation of the heat source when the temperature rise of the air is virtually unaffected by the presence of mass. This time can be estimated as

$$t \simeq \frac{(\rho c V)_{\text{air}}}{hA} .$$

2. The temperature rise experienced by the air during this period is approximately $\frac{q_{\text{source}}}{hA}$.

   Thus, the presence of mass does not moderate short-term temperature rises of this magnitude or less, but does moderate larger temperature rises.

3. This initial air temperature rise occurs before there is any significant energy storage in the mass.

4. The rate of air temperature rise after the initial jump is

$$\frac{dT}{dt} = \frac{q_{\text{source}}}{(\rho c V)_{\text{air}} + (\rho c V)_{\text{mass}}} \simeq \frac{q_{\text{source}}}{(\rho c V)_{\text{mass}}} .$$

When energy is transferred directly to the mass from a high-temperature source by radiation heat transfer, the mass is said to be radiatively coupled to the source. As the temperature of the mass rises, it heats the surrounding air by convection. The most obvious example of this type of source is solar gain through windows. As with the convectively coupled mass, an exact analytical solution is possible when a similar set of assumptions is made.

The rise in the air and mass temperatures obtained from the exact solution are plotted as a function of time in Fig. 2.23. In this case the mass temperature increases at a fairly constant rate, and the air temperature follows the mass temperature very closely. There is no dramatic, initial air temperature rise as with the convectively coupled mass. After the initial part of the transient, the temperature difference between the mass and the air is constant.

A physical explanation of this behavior is very similar to that for the convectively coupled case. The mass is heated directly, but its temperature rises slowly because of its large capacity for energy storage. Very little energy is transferred to the air initially because of the small temperature difference between the mass and air. As more energy is stored in the mass, this temperature difference increases until it reaches a value where an energy flow balance occurs. Thus, the rates of energy storage in the mass and air are proportional to their abilities to store energy, and their rates of temperature increase will be the same.

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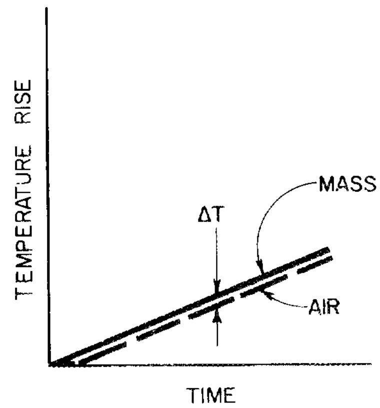

Fig. 2.23. Rise in air and mass temperature for radiatively coupled mass.

However, since the air's ability to store energy is small, a large air-mass temperature difference is not required to obtain this energy flow balance. The value of this temperature difference is

$$\Delta T = \frac{q_{\mathrm{source}}}{hA} \frac{(\rho c V)_{\mathrm{air}}}{(\rho c V)_{\mathrm{mass}} + (\rho c V)_{\mathrm{air}}} .$$

By assuming that all of the energy is stored in the mass and none in the air until this temperature is reached, an approximation of the time required can be made. Doing this yields

$$t = \frac{(\rho c V)_{\mathrm{air}} (\rho c V)_{\mathrm{mass}}}{hA (\rho c V)_{\mathrm{mass}} + (\rho c V)_{\mathrm{air}}} ,$$

or

$$t \simeq \frac{(\rho c V)_{\mathrm{air}}}{hA} .$$

This is the same time estimate arrived at for the initial, rapid temperature rise for the convectively coupled mass.

The mass and the air are essentially at the same temperature since ΔT is so small. The rate of temperature rise for the mass and air can be estimated as

$$\frac{dT}{dt} = \frac{q_{\text{source}}}{(\rho c V)_{\text{air}} + (\rho c V)_{\text{mass}}} \simeq \frac{q_{\text{source}}}{(\rho c V)_{\text{mass}}} .$$

Some conclusions can be drawn about mass that is radiatively coupled to a heat source.

1. The temperature of the mass rises at a relatively constant rate and the air temperature closely tracks it. The rate of temperature rise is

$$\frac{dT}{dt} \simeq \frac{q_{\text{source}}}{(\rho c V)_{\text{mass}}} ,$$

and the temperature difference between the mass and air is

$$\Delta T = \frac{q_{\text{source}}}{hA} \frac{(\rho c V)_{\text{air}}}{(\rho c V)_{\text{mass}} + (\rho c V)_{\text{air}}} .$$

2. Radiatively coupled mass is effective at moderating short-term increases in air temperature.

If the amount of energy emanating from a radiatively coupled source and a convectively coupled source is the same, then the quantity of energy stored will be equal in both cases. However, the case with the convectively coupled source will experience a greater increase in air temperature than the case with a radiatively coupled source. A greater air temperature rise has implications affecting both comfort and energy usage. These are also addressed in subsequent sections.

3. HEATING AND COOLING LOADS

The preceding chapter discussed the influences that mass in the building envelope and in the interior of a building have on energy flow and energy storage. This chapter will discuss how this behavior influences the amount of energy needed to maintain the desired conditions inside a building.

Several points should be made prior to beginning the discussion so that confusion on the part of the reader may be avoided.

1. It is assumed that the average daily outdoor temperature remains fairly constant for a period of at least a few days. Thus, the environment that the building is exposed to can be assumed to be reasonably periodic. Nonperiodic conditions (e.g., warming or cooling trend, cold snap, heat wave) will be briefly discussed later.
2. "Heating/cooling energy or load" refers to the amount of energy which must be supplied to or removed from the interior of a building in order to maintain the desired interior temperature. This can differ significantly from the amount of energy which is used by the heating/cooling system to accomplish this purpose. The amount of energy used by the heating/cooling system is influenced by the efficiency of the equipment under different conditions and is beyond the scope of the current discussion.
3. In the following discussion, the terms "envelope mass" and "interior mass" are used. Envelope mass is, as its name implies, the mass in the envelope of the building (i.e., the walls, floor, ceiling). This mass produces an amplitude reduction and time lag in the heat flux at the interior surface of the building envelope due to varying outdoor conditions. Interior mass is any mass in the interior of a building (e.g., interior partitions, furnishings, etc.) which can be utilized for energy storage. Mass in the building envelope can also act as interior mass if it is not isolated from the interior by insulation.
4. In this discussion, the interior conditions are assumed to be described simply by the air temperature. Other factors such as the humidity and the mean radiant temperature also are a part of the interior conditions and can influence the comfort of building occupants and thus have a bearing on energy requirements. This is well illustrated by a building in a warm, humid climate where dehumidification is as important, or even more important, than temperature control. There is a section on comfort in the next chapter in which this issue is briefly addressed.

3.1 Energy Gains and Losses by a Building

At any particular time the rate of energy gain or loss by the interior of a building is the result of several phenomena taking place simultaneously. These individual gains and losses may include:

Internal gains — People, appliances, electronic equipment, and lighting all produce heat. Thus, all of these result in energy gain by the interior.

Solar gain through windows — The sun shining through windows results in energy gain by the interior.

Infiltration/exfiltration — Whenever inside air escapes from a building, it is replaced by an equal amount of outside air. If the outside air is at a lower temperature than the inside air, the interior loses energy because the energy content of the cold outside air is less than that of the warmer inside air. On the other hand, if the outside air is warmer than the inside air, this process causes an energy gain by the interior.

Heat transmission through the building envelope — Heat transmission through the envelope can result in either a gain or a loss by the interior at a particular time, depending on the inside and outside conditions at that and prior times. The most important factors are inside and outside temperatures, radiation effects on the outside surface (solar gain, radiation to night sky, etc.), and the properties of the portion of the envelope of interest (R-value, mass, etc.).

Energy storage in interior mass — Any energy going into storage mass represents a loss of energy by the interior air. When energy is transferred from the mass to the air, energy is gained by the interior air.

The instantaneous sum of these rates of gains and losses gives the rate at which energy must be supplied to or removed from the interior of a building to maintain a constant interior air temperature.

A discussion of the influence of mass on total energy requirements can become quite complicated. Therefore, the discussion will begin with a simple case in which no heating or cooling is supplied and the interior air temperature is allowed to float freely. Then, a case in which the interior air temperature is held constant will be examined. Finally, a case is discussed in which the interior air temperature is controlled so that it does not go outside a specified band of temperature, but it is allowed to float within this band.

3.2 Free-Floating Interior Air Temperature

Obviously, if the interior air temperature is allowed to float freely, mass cannot affect energy usage since energy is neither supplied to nor removed from the interior by the heating/cooling system. Nonetheless, the effect of mass on the variation in the floating interior air temperature is of interest in itself, as well as being a good foundation for the subsequent development of the discussion for the cases where heating or cooling is supplied.

Any net energy gain will result in a rise in the interior air temperature of a building. Similarly, a net energy loss results in a drop in the interior air temperature. Although this may appear to be stating the obvious, the important point is that interior air temperature changes are the result of instantaneous net energy gains or losses by the interior. Envelope mass influences the instantaneous energy flow through the envelope, and interior mass can influence instantaneous energy gains and losses by the air. Thus, mass has an influence on the temperature swings experienced by a building with a free-floating interior air temperature.

As a point of reference, consider a very light building that does not have a mass effect. The interior air temperature will fluctuate about some mean value. This mean interior air temperature will normally be above the average outdoor temperature due to internal gains and solar effects. Under usual conditions, solar gain through windows, infiltration, and heat transmission through the building envelope will all represent energy gains by the interior during the daytime. At night the outdoor temperature drops, and the windows now allow, by conduction, a net loss by the interior. Infiltration is now a net loss by the interior as is heat transmission through the envelope. Internal gains also normally result in more energy gain in the daytime than at night.

The result of this is that all of the major sources of energy gain or loss by the interior are in phase with each other. That is, they all produce an energy gain by the interior during the daytime, and at night they all result in an energy loss (or at least a lesser energy gain).

Figures 2.14, 2.15, and 2.16 show that mass in the envelope can shift the occurrence of the maximum heat flux through the envelope, thus making it out of phase with the other gains and losses. There is less energy gain by the interior during the daytime and less energy loss by the interior at night. Since these energy gains and losses cause the temperature swing, a building with a more massive envelope will have less variation in the interior air temperature.

Interior mass can have a further effect on the temperature swings. During periods of net energy gain, the interior air temperature will rise above the temperature of the interior mass. Energy will be transferred from the air to the mass, limiting the air temperature rise to a lesser amount than if no interior mass were present. When a following period of net energy loss by the interior is encountered, the air temperature will drop below the mass temperature. Energy transferred from the mass will limit the temperature drop to less than would have occurred if the interior mass were not present.

If, during a period of net energy gain by the interior, the interior mass is radiatively heated (for example, by solar gain), the mass will absorb some of the energy which would otherwise have heated the air. The behavior of the radiatively heated mass is similar to that just discussed, but it is more effective at reducing temperature increases. This is because in convectively coupled mass the interior air temperature must rise before energy can be transferred to the storage mass.

Both envelope mass and interior mass have the capability of reducing temperature swings in a building whose interior air temperature is allowed to float.

3.3 Fixed Interior Air Temperature

In this section the influence of mass on energy usage is discussed for the case in which the interior air temperature is maintained at a constant value. At any time it is unlikely that the sum of all of the energy flow rates will result in no net energy gain or loss by the interior. Therefore, the building heating/cooling system must either supply energy to or remove energy from the interior to bring about the energy balance required to maintain a constant interior temperature.

Once again, it is convenient to use a hypothetical lightweight building which has no mass effect as a base case for comparison. If the sum of all the individual rates of energy gain and loss for such a building is plotted as a function of time, a graph similar to Fig. 3.1, part (*a*), may result. At any time, the distance between the curve and the line of zero rate of energy transfer represents the rate at which energy must be supplied to or removed from the interior to maintain a constant temperature. The area on the graph below zero and bounded by the curve represents the total amount of energy which must be supplied by the heating system. The area above zero and bounded by the curve represents the total amount of energy which must be removed by the cooling system.

It has already been noted that the inclusion of mass in the envelope can change the instantaneous heat flow through the envelope. Mass in the envelope does not change the average heat flow through the envelope nor does it change any other gain or loss experienced by the building. Figures 2.14, part (*b*), 2.15, part (*b*), and 2.16, part (*b*), show the change in the instantaneous heat flux through the envelope that can result from mass. If the exterior walls of the lightweight building were replaced with walls of equal R-value but of sufficient mass to produce a 12-h lag, the building load of Fig. 3.1, part (*b*), results. This modified building load is determined by adding the change in heat flux through the envelope for a 12-h lag [Fig. 2.16, part (*b*)] to the total building load of Fig. 3.1, part (*b*). Note that both the heating and cooling loads have been reduced.

Since envelope mass does not change the average heat flow through the envelope or affect any other gain or loss experienced by a building, the average rate of energy gain or loss by the building as a whole is unchanged by the inclusion of mass in the envelope, or, put another way, the net amount of energy supplied to or removed from the interior air is

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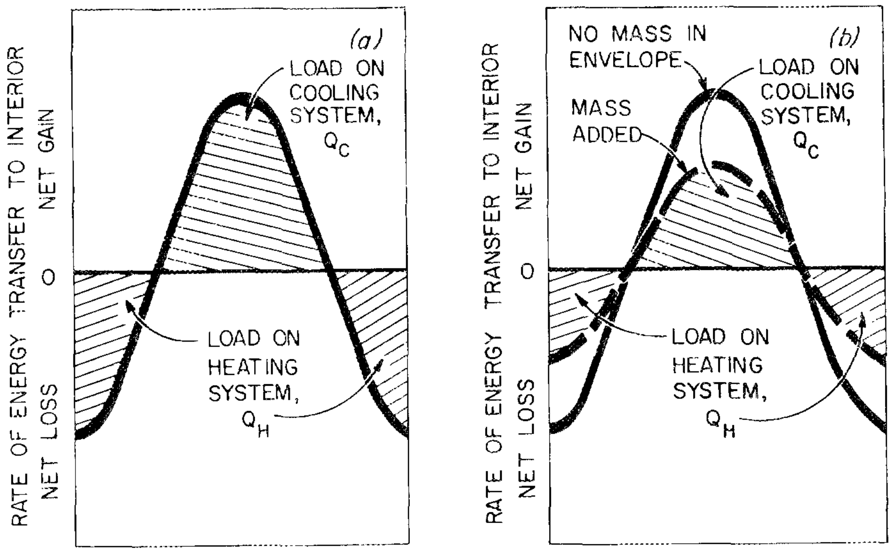

Fig. 3.1. Change in heating and cooling load produced by envelope mass—fixed interior temperature.

not influenced by the mass of the envelope. While this might seem to contradict the previous conclusion, it does not. The net amount of energy supplied to or removed from the interior during one cycle, Q_{net}, can be written as

$$Q_{net} = Q_H - Q_C = \text{constant} ,$$

where Q_H is the total heating energy supplied and Q_C is the total cooling energy removed. The total amount of energy which the heating/cooling system must transfer to or from the interior is

$$Q_{total} = Q_H + Q_C .$$

This total energy is a better indication of the energy usage of the building, and it is influenced by the mass of the envelope. The minimum value of Q_{total} will occur when either Q_C or Q_H is zero. Since Q_{net} is a constant, any change in Q_H produced by the mass in the envelope must be accompanied by an equal change in Q_C. Thus, the most that mass in the envelope can do is to eliminate the smaller of the two values, Q_H or Q_C. When this occurs, Q_{total} will equal Q_{net}.

However, the ability of mass in the envelope to accomplish this is limited. Envelope mass only influences the fluctuating portion of the heat flux through the envelope. The maximum change in the instantaneous heat flux through the envelope that can be accomplished occurs when enough mass is present to produce a time lag of 12 h. For a homogeneous wall exposed to sinusoidal conditions, this means a maximum change in the instantaneous heat flux through the wall equal to 122% of the amplitude of the fluctuations in the heat flux. If in a lightweight building the maximum heating or cooling load exceeds 122% of the amplitude of fluctuation of heat flow through the envelope, adding mass to the envelope cannot eliminate either Q_H or Q_C. In this case Q_{total} will be greater than Q_{net}.

For the addition of envelope mass to be effective in reducing loads in a lightweight building, the heat flux through the envelope must be in phase with the total load on the building.

It has already been pointed out that the minimum possible value for Q_{total} is Q_{net}. In a lightweight building experiencing a continuous energy loss rather than alternating periods of gain and loss, the cooling load Q_C is zero. Thus,

$$Q_{total} = Q_{net} = Q_H \ .$$

The addition of mass to the envelope cannot reduce the total energy requirement since it is already at its minimum possible value. It is possible that the addition of mass can even increase Q_{total} in this case.

In a lightweight building experiencing a continuous energy gain, Q_H is zero. This means that

$$Q_{total} = Q_{net} = Q_C \ .$$

Once again, adding mass to the envelope cannot reduce the total energy requirement since it is already at its minimum possible value.

Now consider the influence of interior mass on total energy requirements. Since the interior air temperature is held constant, there is never an opportunity to store energy in interior mass by convection. Thus, convectively coupled mass cannot influence the total energy requirements. Radiatively coupled mass can still store energy since it is not dependent on the air temperature. However, with the air temperature held constant, the amount of energy that can be stored in interior mass is limited. This is because, as the mass temperature rises above the air temperature, heat is transferred from the mass to the air by convection. As with envelope mass, radiatively coupled interior mass can only result in a reduction in total energy usage if there are alternating periods of net energy gain and loss by the building. However, due to the limited energy storage achievable, the impact of radiatively coupled mass will be minor even then.

3.4 Interior Air Temperature Maintained in Comfort Zone

In reality the interior air temperature of a building is neither allowed to float freely nor held fixed. What is often done is a combination of these two modes of operation. There is a band of temperature referred to as the comfort zone in which the temperature is allowed to float freely, but the temperature is not allowed to go outside the limits of this band.

To simplify the discussion of building energy usage under these operating conditions, two categories of weather are introduced: severe and moderate. Severe weather is defined as those periods during which a building experiences a continuous net heat loss (severe winter weather) or a continuous net heat gain (severe summer weather). The periods of moderate weather include the rest of the year.

During severe weather periods either continuous heating or cooling is required to maintain the temperature in the comfort zone. In this situation, the interior air temperature will remain fixed at either the lower or upper limit of the comfort zone. This is exactly the case of a fixed interior temperature with either a continuous energy loss or continuous energy gain by the interior. It has already been concluded that the addition of mass does not influence the total heating or cooling load in this case.

For the moderate weather periods, first consider the case in which the building requires heating some, but not all, of the time. Assume that the interior air temperature is held fixed at the lower limit of the comfort zone; the required heating and cooling will be similar to that shown in Fig. 3.2, part (*a*). Since, on the average, some heating is required, the area Q_H is larger than Q_C. In Fig. 3.2, part (*b*), an optimum result for the addition of mass in the envelope is shown where the cooling load is totally eliminated. As previously discussed, this gives the minimum possible heating load. The ability of mass in the envelope to accomplish this is subject to the same limitations as those previously discussed.

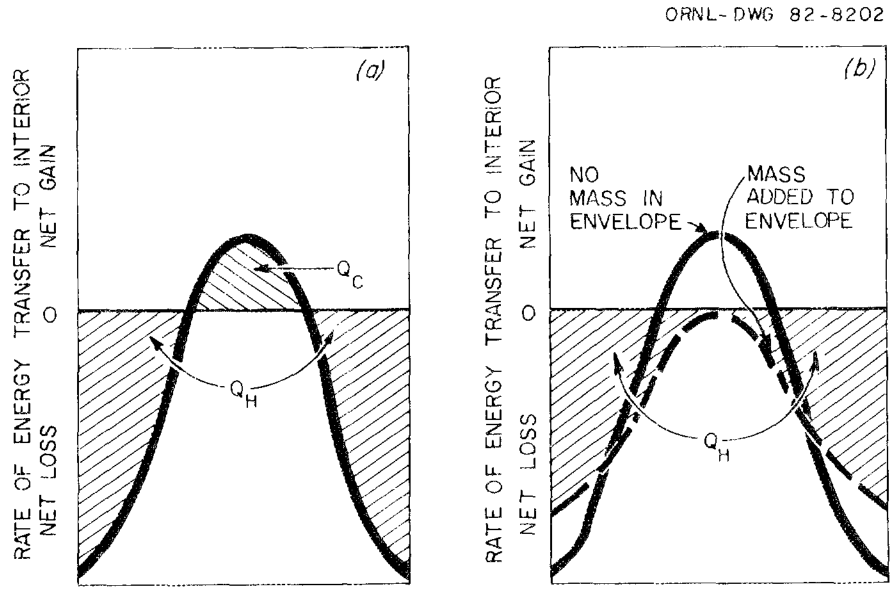

Fig. 3.2. Change in heating load produced by envelope mass—interior temperature maintained in comfort zone.

In this case, however, the area Q_C does not actually represent a cooling load since the interior air temperature can rise above the lower limit of the comfort zone. This area represents energy which is available for storage in interior mass. The discussion of this storage on heating load makes use of Fig. 3.3.

During the period of net energy gain (A to B), there is, of course, no load placed on the heating system. This net energy gain is stored as sensible heat in the air and in other mass

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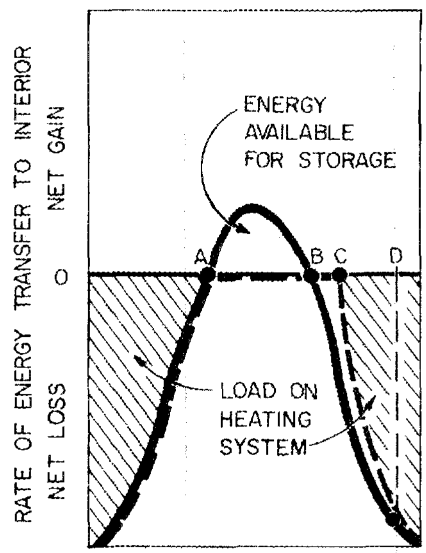

Fig. 3.3. Change in heating load produced by interior mass.

in the interior of the building. When there is once again a net energy loss (point B), the interior temperature is above the heating setpoint temperature, and there is no load immediately placed on the heating system. There will be no load placed on the heating system until the net energy loss by the building removes enough energy to lower the air temperature to the thermostat setpoint (C). At this time there is, once again, a load placed on the heating system since energy must be supplied to prevent the air temperature from dropping below the setpoint.

The mass in the interior may still be at a higher temperature than the air since it releases its stored heat slowly. This heat is therefore still being released to the air, offsetting some of the net energy loss and reducing the load placed on the heating system. The heat load will not match the net energy loss until all of the stored energy is removed from the mass and its temperature has dropped to the setpoint temperature (D).

The result of this is that the heating load is reduced. Ideally, it would be reduced by an amount equal to Q_C. However, when the interior air temperature rises, the energy flows to or from the interior are altered (e.g., conduction through the envelope and energy transfer by infiltration are affected by the inside-outside temperature difference). Thus, the amount by which the heating load is reduced is less than Q_C. A building with greater interior mass will experience a smaller air temperature rise and will thus be able to store more of the available energy. A very similar explanation to the preceding one applies to a period requiring cooling, but not continuous cooling.

There are, of course, periods during which no heating or cooling is required, even in low mass buildings. During these periods, the interior temperature floats freely, but does not go outside the range of the comfort zone. As discussed in Sect. 3.2, the addition of mass can reduce the interior temperature swing. This reduced temperature swing in more massive buildings extends the period during which no heating or cooling is required.

3.5 Conclusions

From the preceding discussion, the following conclusions can be reached about the conditions necessary for mass to reduce total energy requirements of a building exposed to periodic outside conditions.

If a building initially satisfies the following criteria, the addition of envelope mass can result in reduced energy usage. Criterion 1 must be satisfied before any energy savings can result. Criteria 2 and 3 must be satisfied before this savings can be significant.

1. The building, as a whole, must experience periods of both net energy gain and net energy loss during the cycle.

2. The heat flow through the envelope must be in phase with the total building load.

3. The amplitude of the fluctuations in heat flow through the envelope must be a significant fraction of the maximum heating or cooling load.

For the addition of interior mass in a building to reduce total energy requirements, the following conditions are necessary.

1. The building, as a whole, must experience periods of both net energy gain and net energy loss during the cycle.

2. The interior air temperature must be allowed to float.

While these conditions do not allow one to predict the magnitude of any possible energy savings, they do allow one to identify cases where mass can or cannot result in energy savings. The magnitude of the possible energy savings is largely dependent on how much of a building's annual energy use occurs in moderate weather conditions since this is the only energy use influenced by the mass of the building. However, one should not lose sight of the fact that, as defined here, moderate and severe weather conditions are relative to the thermal behavior of a particular building. Therefore, the proper design and operation of a building can extend the moderate weather period. If one understands this and that a building must experience alternating periods of net energy gain and loss to benefit from mass, one can operate a building to better utilize available energy sources or sinks to bring about these periods of net gain and loss. This is discussed further in Sect. 4.6.

4. OTHER POTENTIAL IMPACTS OF THERMAL MASS

4.1 Effect of Mass on Peak Loads

As evidenced in Chap. 3, both envelope mass and interior mass can influence the instantaneous load on the heating or cooling systems. If this change in instantaneous load results in a reduction in the seasonal peak heating or cooling load, equipment capacity can be reduced accordingly. This not only can mean a reduction in the initial cost of the heating/cooling plant, but can also result in an energy savings. The energy savings is brought about by the smaller equipment operating at a higher fraction of its capacity much of the time, resulting in reduced cycling.

It is obvious from Fig. 3.1 that mass can reduce the daily peak load for certain days, but the seasonal peak load is of interest here. For a region having significant heating loads, the peak heating load would be expected to occur during a period of continuous energy loss by a building. Under these conditions, the interior air temperature would remain constant, and any interior mass would not affect the heating load. Even if there is a short period of net energy gain by the building during the daytime, the energy stored is small compared to the net loss during subsequent times. Thus, this stored energy will be largely dissipated by the time of peak heating load (usually early in the morning) and will have little or no impact on the peak load. This is illustrated by Fig. 3.1.

Mass in the envelope can still influence the peak load. However, as discussed in Chaps. 2 and 3, the maximum change that can be produced in the peak load is limited to approximately or less than the amplitude of the variation in energy flow through the envelope. For a region experiencing a significant heating season, the amplitude of variation of heat flow through the envelope will be small compared to the average heat flow through the envelope at the time of occurrence of the seasonal peak heating load. Thus, envelope mass will have only a small impact on the seasonal peak heating load.

The case of seasonal peak cooling load is somewhat different. Even in regions of the country experiencing significant cooling seasons, it is not unusual for buildings to experience periods of net energy loss at night. Thus, interior mass can possibly influence the peak cooling load. Also, the amplitude of the variation in heat flow through the envelope can often be significant, and envelope mass can influence the seasonal peak cooling load. However, this reduction can be obscured by the fact that in some regions having significant cooling loads dehumidification is a large contributor to the total cooling load.

4.2 Effect of Internal Thermal Mass on Equipment Cycling

Most heating or cooling equipment cannot vary its output to exactly match the instantaneous load; it is either on or off. A thermostat controls the equipment, turning it on or off as required to maintain the desired temperature. With this on-off type of operation, the interior temperature cannot be maintained exactly constant. In the heating season the temperature will rise while the heating system is on and fall when it is turned off. In order to avoid switching the equipment on and off in rapid succession, the temperature is allowed to float slightly about the setpoint by having the temperatures at which the thermostat turns the equipment on and off differ by a small amount. For instance, in the heating season, the heating system is turned on when the temperature drops below some selected temperature and continues to operate until the temperature exceeds some other higher temperature. This difference in temperature is typically on the order of 1 to 2°C (2 to 3°F).

When the heating equipment begins operating, the air temperature is at the lower temperature limit. The heat output offsets the heat loss by the structure and also raises the air temperature. In the process, the temperature of any mass in the structure is also raised.

When the air temperature reaches its upper limit, some amount of energy will have been stored as sensible heat in the air and in any mass in the interior. The heating system will then shut off and the structure will gradually lose this stored energy until the air temperature reaches the lower limit, at which point the cycle will repeat itself.

The time that is required to complete a single cycle is dependent on the heating equipment capacity, the rate of heat loss by the building, and the amount of energy stored and released during each cycle. We can write

$$Q_s = (q_e - q_l)\, t_{\text{on}} ,$$

where

Q_s	=	amount of energy stored during "on" period,
q_e	=	heating equipment output rate,
q_l	=	rate of energy loss by building,
$(q_e - q_l)$	=	rate of energy gain by building during "on" period,
t_{on}	=	time that heating equipment is on.

Thus,

$$t_{\text{on}} = \frac{Q_s}{q_e - q_l} .$$

The length of time the equipment is off can be determined as

$$Q_s = q_l\, t_{\text{off}} ,$$

$$t_{\text{off}} = \frac{Q_s}{q_l} .$$

The time for one complete cycle is

$$t_{\text{cycle}} = t_{\text{on}} + t_{\text{off}} = \frac{Q_s}{q_e - q_l} + \frac{Q_s}{q_l} .$$

The cycling frequency is the reciprocal of the time for one cycle.

$$f = \frac{1}{t} = \frac{1}{\dfrac{Q_s}{q_e - q_l} + \dfrac{Q_s}{q_l}} = \frac{q_e\left[1 - (q_l/q_e)\right]}{Q_s} .$$

It is apparent from the preceding equation that the cycling time is increased (cycling frequency decreased) when the energy stored in the structure is increased. Since thermal mass adds to heat storage capacity of a structure, this would seem to imply that thermal mass could significantly influence cycling frequency. However, the storage capacity of the thermal mass is not fully utilized, so the effect is somewhat diminished.

In a forced-air type of heating system, the air is heated directly, and the air then convectively warms any mass present. The amount of energy transferred to the mass is controlled by the value of the heat transfer coefficient on the surface and temperature difference between the mass and the air. Since both the heat transfer coefficient and the temperature difference are relatively small, there is not a great deal of heat transferred to and stored in the mass. Since the storage capacity of the mass is not being utilized, more mass will have little additional effect. In fact, the mass normally present in a "lightweight" building (furnishings, partitions, etc.) may already be all the mass that can effectively be utilized to decrease equipment cycling.

A different type of heating system in which the mass is heated directly could probably make better use of thermal mass to reduce equipment cycling. However, thermal mass would probably not be included in a structure for this reason. Any benefit gained would be relatively minor, and modifications to heating equipment (e.g., flue dampers) can reduce energy loss due to cycling at lower costs.

4.3 Effect of Mass on Thermostat Setback

One criticism of massive structures is that one loses the energy saving potential of thermostat setback. If this is indeed the case, any energy advantage that a massive building may otherwise have may be more than offset by this loss. If a building's usage pattern permits thermostat setback, then any energy usage comparison between a light and heavy building should utilize setback.

In order to understand the impact of mass on the energy savings due to setback, it is first necessary to review why an energy savings results from thermostat setback. When the thermostat setpoint is reduced at night, the building loses energy until the interior temperature reaches the new setpoint. This interior temperature is maintained by the heating system.

When the thermostat setpoint is again raised to its original value, the heating system supplies energy to raise the interior air temperature to the original value. Recall from the previous discussion that the total energy flow through the building envelope over a period of time is determined solely by the R-value of the envelope and the time-averaged inside-outside temperature difference. Thus, by reducing this average temperature difference by the use of setback, the energy loss through the envelope is reduced, resulting in a smaller cumulative load on the heating system. The amount of energy lost due to infiltration is also reduced since it, too, is almost directly proportional to the inside-outside temperature difference.

A more massive structure means that more energy is stored in the structure, and, thus, a longer time is required for the interior temperature to change (this applies during both cool down and recovery periods). Therefore, the inside-outside temperature difference during setback will be greater for massive buildings than for lightweight buildings. The average inside-outside temperature difference for the entire cycle is greater for a more massive building. The more massive the building, the less effective thermostat setback will be.

Another difficulty arises during the recovery from setback. Three options may be followed at recovery. First, recovery can be started at the same time as it would have been in a lightweight building. Since a massive building will not recover as fast as a lightweight building, the massive building may remain uncomfortably cool well into the day. Second, a larger heating plant can be installed to speed recovery. This has the disadvantages of higher initial cost and possibly higher operating cost, resulting from inefficient operation of the oversized heating plant. Third, recovery can be initiated earlier so that the daytime setpoint can be reached earlier. This reduces potential energy savings by effectively shortening the setback period.

In conclusion, setback is more effective in less massive buildings, but it can produce some energy savings even in massive buildings.

4.4 Effect of Mass on In Situ Measurements of Wall R-Values

An important consideration in building energy conservation is how well building components perform in actual buildings. Onsite inspections repeatedly show that actual construction practices commonly deviate from design. Also, functional modifications and component deterioration contribute to performance that differs markedly from that predicted by reviewing the design aspects of a building. Because of this, some effort has been expended to determine in situ R-values for building components such as walls and roofs, which, in turn, can be used to more accurately predict actual building performance. These are not simple measurements, particularly for high mass components. As discussed in Sects. 2.2.2 and 2.2.3, the combination of mass in building components and changing temperatures on either side of these components causes the simple proportional relationship between heat flow and interior/exterior temperature difference to become invalid as an indicator of the component R-value.

Two basic techniques are currently in use to provide R-values from in situ measurements. One approach attempts to control conditions on both sides of the wall. For instance, a constant temperature is maintained at each wall surface by some means, and the heat flux is measured on one or both sides. Once steady-state conditions have been established, it is a simple matter to determine the R-value of the wall. It is simply

$$R = \frac{\Delta T}{q} ,$$

where

ΔT	=	temperature difference across wall,
q	=	heat flux through wall.

There are two drawbacks to this approach: the size and expense of the equipment involved, and if the wall is massive, hours or even days may be required to reach steady-state conditions.

A variation of this approach involves imposing a transient on one side of the wall and observing the response on the other side. This may shorten the time required compared to the steady-state analysis, but the equipment must be much more sophisticated, and data collection and analyses capabilities are required. A massive wall still presents problems in that it may take some time for the transient to penetrate the wall, and the signal may be greatly attenuated. Also, not knowing the initial conditions within the wall, either the transient must be periodic in nature and repeated enough times so that the initial conditions no longer have an influence, or known initial conditions must be established before the transient is initiated.

In another approach, the inside air temperature is held constant by the building's heating, ventilating, and air-conditioning system, and the outdoor conditions are determined by the weather. The temperature is measured on both sides of the wall, and the heat flux is measured on either one or both surfaces. By taking measurements over a long enough period, the R-value of the wall can be determined as

$$R = \frac{\int_o^t \left(T_{\text{in}} - T_{\text{out}}\right) \, dt}{\int_o^t q \, dt} ,$$

where T_{in}, T_{out}, and q are the instantaneous values of inside wall temperature, outside wall temperature, and heat flux, respectively. The time over which measurements are made is t. In this approach, the investigator is entirely at the mercy of the weather. The average temperature difference must be significantly different from zero over the test period. Also, in order to minimize the time necessary to obtain accurate results, it is desirable for the weather conditions to be reasonably periodic for a few days prior to and including the test period. If the weather conditions were exactly periodic within a 24-h period, the R-value could be determined exactly in a test of 24 h even for a very massive wall. Fairly accurate values could be determined in shorter periods. The less massive the wall, the shorter the required measurement time. However, if weather conditions are not periodic, longer measurement times would be required. For a very lightweight wall, it would not matter as much whether the weather were periodic. For a massive wall, required measurement times could become on the order of several days.

4.5 Effect of Mass on Comfort

Comfort is primarily a function of a person's body temperature, which results from an energy balance between the body and its surroundings. The amount of internal heat generated by the body must be balanced by heat loss from the body by convection to the air, thermal radiation to surrounding objects, and evaporative cooling of the skin. Radiation may actually be an energy gain rather than a loss if you are in direct sunlight or near a hot object. If heat cannot be dissipated as fast as it is being generated by the body, the body temperature will rise to a point where there is an energy balance. Similarly, if the body is losing heat at a faster rate than it is being generated, the body temperature will fall to the point where this energy balance is re-established.

Important factors affecting comfort are the air temperature and velocity which affect convective losses, the humidity which affects evaporative losses, and the temperature of the surroundings which affects radiative gains or losses. Another important factor is the type and amount of clothing worn. Also, if a person is engaged in physical activity, the body's internal heat generation is affected, which influences comfort.

The width of the comfort zone [20 to 27°C (68 to 80°F)] seems to imply that a person would be comfortable anywhere within this range. However, to be comfortable at the extremes of this zone requires different types of clothing as well as some acclimation by the body. Such a wide temperature variation over a short period of time would not be comfortable. During the transition season, thermal mass can reduce the variations in temperature and can thus increase comfort.

Also, when a structure undergoes a large internal heat gain which greatly exceeds the capacity of the cooling equipment in the short run, thermal mass can increase comfort for the occupants. For instance, if a large number of people entered a room at the same time, the heat source (the people in this case) would raise the air temperature, and the air, in turn, would convectively heat the thermal mass. In this situation, thermal mass may not be very effective at moderating short-term temperature increases. The convective heat transfer coefficient is relatively small, so a large temperature difference is required between the air and thermal mass to transfer the heat. Due to the small convective heat transfer coefficient and the large capacity to store heat of the thermal mass, its temperature rises slowly. Thus, even though the air temperature may rise almost as rapidly in a massive building as in a lighter one, the people will be more comfortable in the more massive building because of radiation to the relatively cool thermal mass.

If the large short-term heat gain were to transfer heat directly to the thermal mass by radiation rather than indirectly through convection, the behavior would be quite different. An example of this is the sun shining through a window onto the thermal mass. Thermal mass absorbs this energy with a relatively small increase in temperature. Heat is transferred from the thermal mass to the air by natural convection. Both the surface and air temperatures are less with thermal mass present than without it; thus, comfort is improved by the presence of thermal mass.

During periods when the interior air temperature is thermostatically controlled and maintained at a constant value, thermal mass may still have an influence on comfort. Thermal mass in the building envelope reduces the temperature variations on the inside surface of the envelope due to exterior weather variations. Heat loss from the body to this surface because of radiation is, thus, more nearly constant, which might imply a more comfortable condition.

During the heating season, thermal mass might influence comfort when thermostat setback is used. During recovery from setback, both the air temperature and the thermal mass temperature are below desired levels for comfort. The mass may remain cold for several hours, causing some discomfort for the occupants. Starting the recovery from setback earlier or installing oversized heating equipment could remedy this, but both have adverse effects on energy usage.

4.6 Strategies to Maximize Benefits from Mass

Thermal mass is effective when a building experiences alternate periods of net energy gain and loss during each day. During periods of continuous energy loss (continuous heating required) or continuous energy gain (continuous cooling required), thermal mass does not influence the cumulative load placed on the heating/cooling system. The maximum benefit occurs when the alternating losses and gains average near zero. When this occurs, thermal mass can potentially eliminate heating and cooling loads.

The net energy loss or gain is greatly influenced by the design of the structure. In the heating season, losses can be controlled by varying the amount of insulation in the walls, ceiling, and floor; by varying window area and insulating value; by reducing infiltration; and by other means. Most internal gains are not influenced by building design; however, one very important factor which is influenced is solar gain through windows. Thus, by properly designing a building, the average net energy flow can often be made to fluctuate about zero for the heating season. When the average is near zero, thermal mass can reduce the variation to the point that little heating or cooling is required. Similarly, measures could possibly be taken to design the structure so that energy flow in the cooling season fluctuates around zero.

Some difficulties arise in that a design arrived at to save energy during one period may actually increase energy use in another period. For example, adding insulation to reduce energy losses during winter may actually be harmful during another period. During milder weather, the outside temperature could be in the comfort zone, but the inside temperature might be too warm because the well-insulated envelope prevents internal heat gain from escaping.

The design of the building presents opportunities for passive measures to control energy use. There are also active measures that can be taken, including controlled ventilation of the structure to use advantageous outdoor temperatures to control energy gain or loss and control of windows so that solar gain can be taken advantage of when needed. In addition, energy losses can be reduced by movable insulation.

Ventilation of the structure could be used to efficiently remove energy from the structure. During the cooling season, nighttime outdoor temperatures may drop below the indoor temperature. When this occurs, ventilating of the structure can lower the interior temperature to near the outdoor value. Thus, the mass in the structure, which is cooled during the night, can absorb heat gain during the next day. Ventilation of the structure at night has resulted in the average energy flow being near zero. It should be noted that the normal thermostat strategy for cooling must be altered in this case to allow cooling below the setpoint temperature.

By using a combination of the above passive and active strategies, it may be possible to cause the energy flow for a building to alternate between gains and losses during each day throughout much of the year. If this can be done, the use of thermal mass can reduce the variation in internal conditions due to this fluctuation so that they remain in the comfort zone.

5. OBSERVATIONS AND FUTURE DIRECTIONS

From the discussion to this point, it is obvious that there is a definite mass effect on the thermal behavior of buildings. For a lightweight wood frame building, ignoring this effect may not cause significant errors in predicting building performance; for a massive building, however, the errors can be very significant.

As an example of one such effect, for a 20-cm (8-in.) thick concrete wall exposed to a diurnal cycle, a lag of approximately 4.5 h will be experienced between the time of maximum temperature difference across the wall and the time of maximum heat flux at the inside surface. The amplitude of the variation in the inside surface temperature and the heat flux will be 25% less than those predicted by steady state. (The values were arrived at by use of Figs. 2.12 and 2.13.)

The discussion to this point has handled energy savings resulting from mass effects in a qualitative manner. That is, the phenomena have been explained without attempting to put numerical values on their magnitude. The next step of arriving at such values is extremely complicated and has been very controversial. Most investigators put the savings in energy due to thermal mass on the order of a few percent, but even this does not have universal agreement. Generally, the colder the climate, the less the savings that can result from mass. Also, as alluded to earlier, mass on the inside of insulation is more effective at reducing energy use than is mass on the exterior. There are, however, a plethora of other factors which influence any mass effect.

To a large degree, the disagreement in the effect of mass on building energy usage is a result of the extreme complexity of the problem and the many simplifying assumptions which must be made in order to handle it. It appears that the current applications of theory are not adequate to accurately predict individual building behavior and to generalize design criteria, which will give optimum performance.

Some areas in which future work should be directed include:

1. further laboratory and field data collection;
2. verification of assumptions, inputs, and models used in computer programs;
3. investigation of the effect of control strategies;
4. investigation of comfort implications; and
5. development of guidelines not requiring the use of large computer programs.

Work in many of these areas has already commenced, as is evident from the review of previous work, shown in Appendix A. However, additional investigation of each of these areas is still required.

APPENDIX A — PREVIOUS WORK

This chapter gives synopses of a few significant papers which have been written on thermal mass.

These particular papers were chosen because they put numbers on the savings which can result from thermal mass. Their appearance here does not imply that the authors of this report are in agreement with the conclusions reached in the various papers. In fact, the task of evaluating what each paper presents would be monumental and was not even attempted. The results appearing in this appendix should not be used to draw general conclusions about thermal mass.

A.1 Computer Simulations

This section contains papers in which computer simulations are used to determine the effect of building mass on energy usage.

A.1.1 Arumi

Arumi, of the University of Texas, investigated the effect of the thermal inertia of walls on the energy consumption for space heating and cooling.[1] The analyses were done using the computer program DEROB.[2] Arumi used a dimensionless number, γ, which is an indication of the thermal inertia of a wall exposed to diurnal cycles:

$$\gamma = \sqrt{\pi \frac{L^2}{24} \alpha} \ .$$

Note that when considering a 24-h cycle, the dimensionless grouping used earlier in this report to characterize time lag and amplitude reduction is

$$\sqrt{\frac{L^2}{24} \alpha} \ .$$

This grouping differs from Arumi's γ only by a factor of $\sqrt{\pi}$.

The effect of the thermal inertia of the walls on annual energy consumption for four cities is given in Fig. A.1. The conclusion of the report is that walls having greater thermal inertia use less energy. The effect of the thermal inertia lessens with decreasing wall conductance (increasing R-value). The relative importance of thermal inertia in reducing energy consumption is less in climates where total energy use is more, but the absolute importance is of the same order of magnitude for all climates.

There is an appendix to the report that outlines a manual method to calculate peak loads and annual energy consumption associated with the wall.

A.1.2 Brown

Gosta Brown, of the Royal Institute of Technology in Sweden, used a computer program to study the effect of thermal mass on cooling energy requirements of office buildings.[3] He demonstrates that the heat storage effect of the external wall in a room cannot have an

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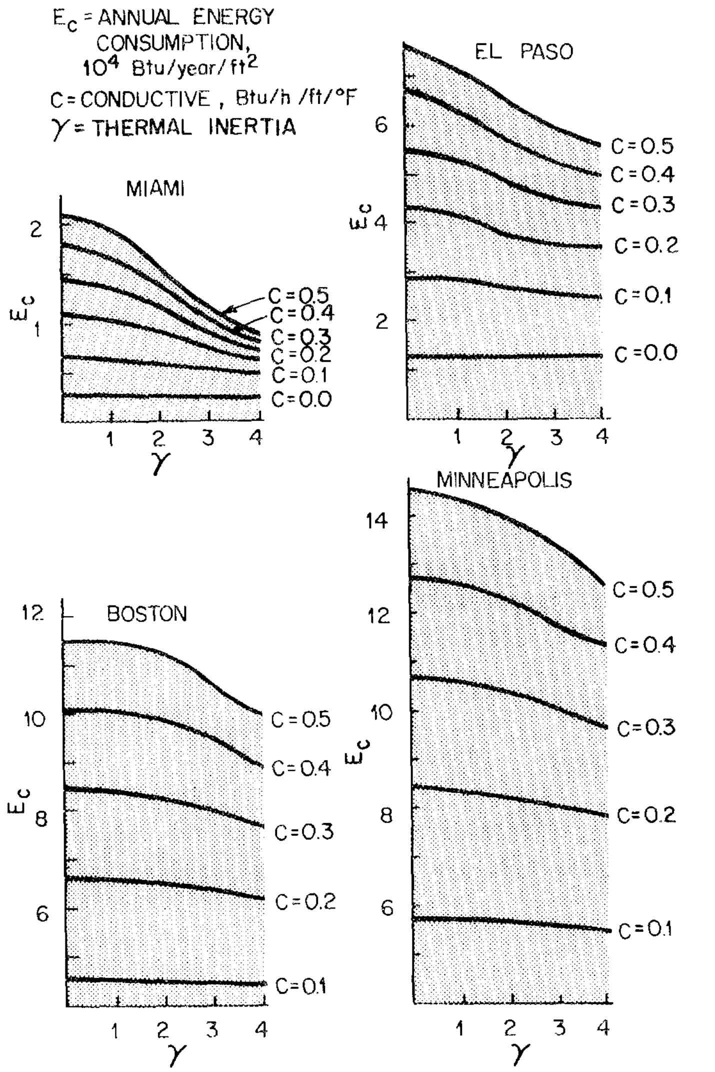

Fig. A.1. Annual energy consumption dependence on conductance and thermal inertia.

appreciable influence on room temperature since its surface area is small compared to the total surface area of the room.

Floors and partition walls must not be insulated if they are to effectively damp variations in room temperature. However, direct air contact with covered concrete floors can be achieved by conveying air through ducts in a hollow core floor.

If the maximum output of the cooling equipment is too low to maintain the setpoint temperature, the temperature rise may be relatively moderated by the heat storage which occurs in the building structure. The question of rather more massive partition walls resulting in lower annual energy costs of cooling was examined. Using assumed values for the cost of cooling and relationship between the cost and weight of the walls, it was concluded that the lightest possible partition walls were the most economical.

A.1.3 Leslie

The annual heating energy requirements for several slab-on-grade dwellings were calculated for four different climate regions in New Zealand.[4] The effect of the thermal capacitance was examined by artificially setting the capacitance equal to zero in the computer program, without altering other factors. Leslie's conclusions regarding the effect of capacitance on annual heating energy requirements include:

1. Calculations which consider thermal capacitance can result in annual heating requirements 20% larger or smaller than would be obtained by neglecting these effects.
2. The effect of thermal capacitance on annual heating requirements cannot be separated from heating regime (continuous or intermittent) and climate. In the mild climate of Mangere, annual heating energy requirements decreased with increasing building capacitance, for both intermittent and continuous heating, but in colder Christchurch, heating energy decreased with increasing capacitance in the continuously heated case, but increased in the intermittent case.
3. The effects due to the thermal capacitance of the floor and ground are greater than those due to the walls and roof.
4. For continuously heated buildings, insulation outside of thermal capacitance offers energy savings, while for the intermittent heating, inside placement is preferable.
5. The three prime factors affecting annual heating energy requirements in New Zealand are climatic severity, heating regime, and insulation. Change in energy requirements due to thermal capacitance are less important than changes in these factors.

A.1.4 Catani and Goodwin

Three walls with equal U-factors, but different mass, were studied.[5] For a temperature range similar to that used in the National Bureau of Standards (NBS) experimental study, peak heating loads through the lightweight walls were 33% greater than through the heavier masonry wall. When subjected to sol-air temperature ranges recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), peak cooling load through the lightweight walls is 38 to 65% higher than for the heavy walls. For two roofs considered, a light roof had twice the peak heat gain of a heavy roof.

Since the envelope accounts for only a portion of the total heating or cooling load, the study also considered the effect on all of the loads on a building. A one-story commercial building in a rather moderate climate was analyzed using the ASHRAE transfer function method. Four different building envelope types are examined. The lightest envelope had a 12.3% higher peak heating load and a 17.4% higher peak cooling load than the heaviest envelope considered. The heavier envelope had a higher U-factor.

In another study the National Bureau of Standards Load Determination program (NBSLD) was used to study three hypothetical buildings in ten cities across the country.[6] The buildings considered were of all-metal construction. Walls and roofs were insulated to give the same U-factors for all buildings. The results are tabulated in Table A.1. The most massive building required the least heating and cooling energy in all ten cities.

Table A.1. Annual heating and cooling loads for the one-story nonresidential buildings studied

	Degree days C	Degree days F	Concrete walls, concrete roof (A) J × 10^9	Concrete walls, concrete roof (A) Btu × 10^6	Metal roof, concrete walls (B) J × 10^9	Metal roof, concrete walls (B) Btu × 10^6	Metal roof, metal walls (C) J × 10^9	Metal roof, metal walls (C) Btu × 10^6
			Annual heating					
Chicago	3,670	6,600	389	369	411	390	423	401
Cleveland	3,560	6,400	258	245	275	261	184	274
Denver	3,440	6,200	353	335	381	361	298	377
Boston	3,110	5,600	236	224	257	244	268	254
Seattle	2,890	5,200	153	145	181	172	193	183
Washington, D.C.	2,330	4,200	75	71	93	88	102	97
Atlanta	1,670	3,000	43	41	60	57	68	64
Fort Worth	1,330	2,400	15	14	24	23	30	28
Los Angeles	1,110	2,000	0	0	0	0	0	0
Tampa	210	680	0	0	0	0	0	0
			Annual cooling					
Tampa			591	560	644	610	664	629
Fort Worth			486	461	545	517	567	537
Los Angeles			378	358	459	435	483	458
Atlanta			361	342	427	405	450	427
Washington, D.C.			246	233	310	294	334	317
Chicago			175	166	222	210	241	228
Denver			173	164	227	215	253	240
Boston			156	148	206	195	223	211
Cleveland			169	160	227	215	237	225
Seattle			113	107	171	162	189	179

A.1.5 Dougall, Goldthwait, Rudoy, and Dougall

Dougall and Goldthwait[7] used NBSLD to evaluate the effect of the mass of exterior wall construction on the peak loads and energy requirements for the heating and cooling of single-family residential buildings. Three building types (insulated wood frame, uninsulated masonry, and insulated masonry) were studied in two locations (Tampa and Atlanta). Rudoy and Dougall extended the study to include an additional wall type (uninsulated wood frame) and three additional locations (Phoenix, Chicago, and Sacramento).[8] Calculated peak loads and energy requirements are shown in Figs. A.2 and A.3. The wall mass had little effect on peak heating or cooling loads for insulated buildings. For uninsulated buildings, mass in the walls reduced peak heating loads in all locations, but only slightly. Peak cooling loads were actually increased slightly by the addition of mass in some locations.

The masonry structures required slightly less annual heating energy than the wood frame structures at all five locations. However, the cooling energy requirements were either the same or slightly greater for the masonry buildings at all locations.

A.1.6 Mitalas

Mitalas used computer simulations to determine the change in annual heating energy requirements for buildings in the Canadian climate resulting from changes in the thermal

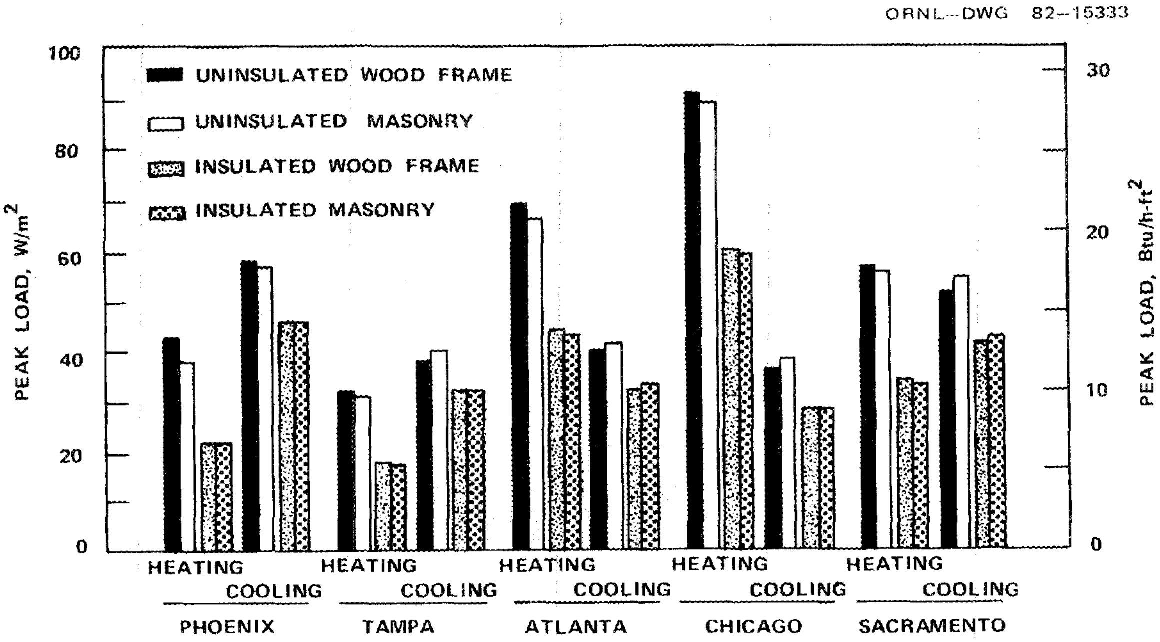

Fig. A.2. Effect of mass and insulation on peak load.

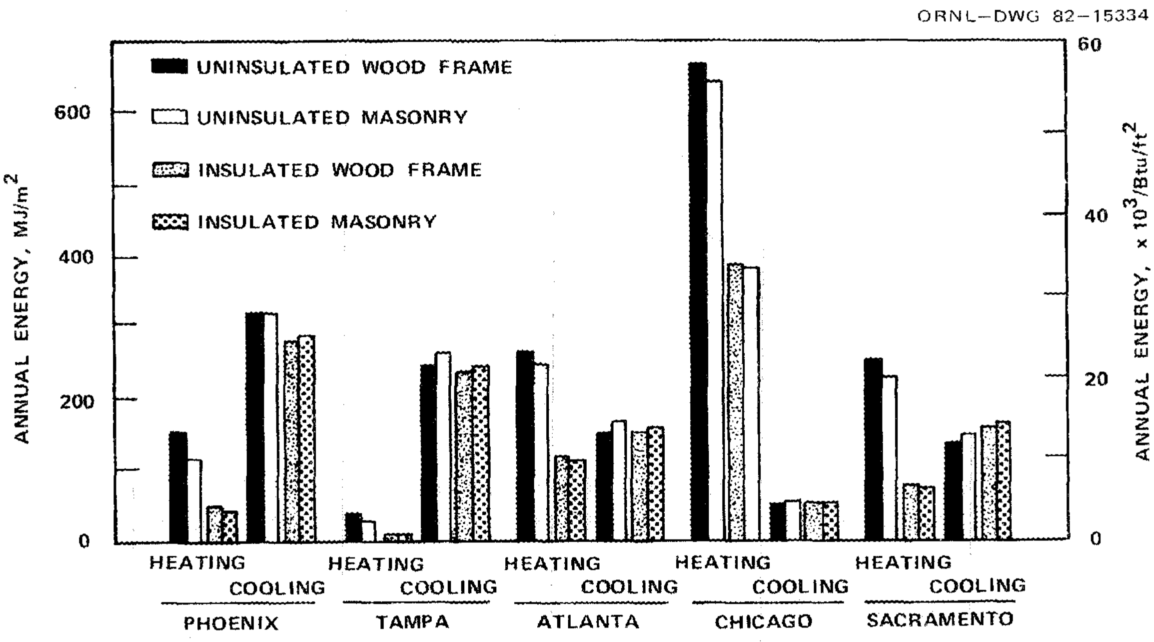

Fig. A.3. Effect of mass and insulation on annual energy consumption.

storage of the building enclosure.[9] Based on these calculations, a relationship was developed which gave the permitted reduction in the thermal resistance of a massive building enclosure component that would still maintain the same annual heating energy requirement. The two factors which most influence the mass effect are the location of the mass relative to the insulation and the rate of heat loss relative to internal heat gains by a building. A mass layer on the inside permitted a greater reduction in the thermal resistance than did one on the outside. A building with a low rate of heat loss relative to internal gains allowed a greater reduction than a building with a high relative loss. The thermal resistance/mass relationship for the case allowing the greatest reduction in thermal resistance (inside mass and low relative heat loss) is given in Fig. A.4. A building with light walls with an R-value of 5 $m^2 \cdot K/W$ and a similar building with wall mass of 600 kg/m^2 and an R-value of 3 $m^2 \cdot K/W$ (ΔR of 2 from Fig. A.4) will have the same annual heating energy requirement.

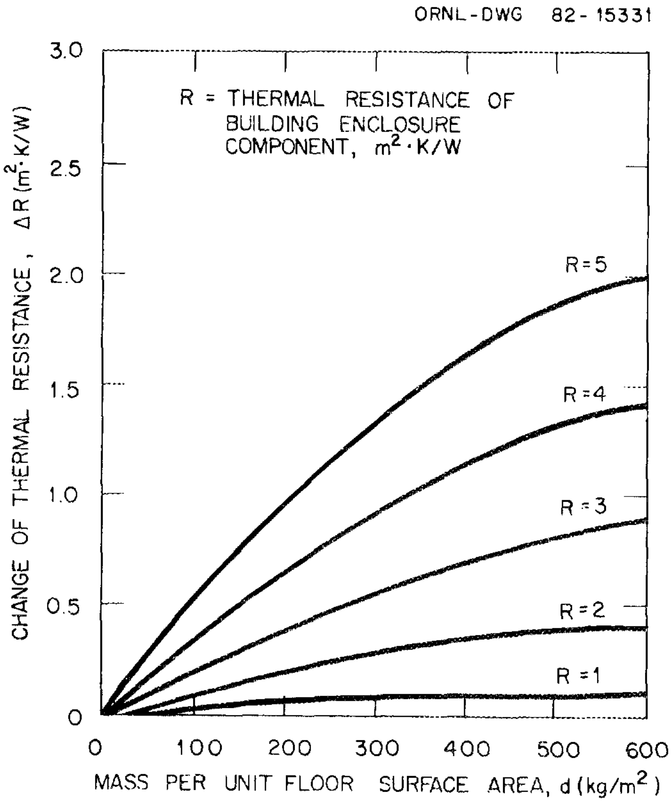

Fig. A.4. Relation between thermal resistance and mass of building envelope — mass in direct contact with interior air, low rate of heat loss relative to gain.

A.1.7 Hopkins, Gross, and Ellifritt

Hopkins, Gross, and Ellifritt used the E-CUBE 75 computer program to study the effect of envelope mass on peak heating and cooling loads as well as annual heating and cooling loads.[10] They also examined the effectiveness of temperature setback during heating and setup during cooling with a massive structure.

A one-story contemporary office building was examined in three different locations. Peak and annual heating and cooling loads for a light and a heavy version of the building are given in Table A.2. The buildings differ only in the mass of the envelope. The density of the heavy structure was 464 kg/m^2 (95 lb/ft^2) for exterior walls and 376 kg/m^2 (77 lb/ft^2) in the roof vs 18.3 kg/m^2 (3.75 lb/ft^2) and 24.4 kg/m^2 (5 lb/ft^2) for the light structure. The heavy structure had 4 to 6% higher peak heating loads than the light structure, but from 0 to 6% lower peak cooling loads. Annual heating loads were from 3 to 12% lower for the heavy structure and annual cooling loads were 2 to 3% lower for the heavy structure. The effects of temperature setback and setup were examined. However, due to unacceptable 8:00 a.m. temperature drifts for the light buildings, simulations for the heavy buildings were not run.

Table A.2. Peak and annual energy loads for three-story office buildings

	Peak energy load[a]		Annual energy load[b]	
	Light envelope	Heavy envelope	Light envelope	Heavy envelope
		Minneapolis		
Heating	1.000	1.006	1.000	0.960
Cooling	1.000	0.970	1.000	0.925
Total			1.000	0.946
		Kansas City		
Heating	1.000	1.008	1.000	0.931
Cooling	1.000	0.970	1.000	0.952
Total			1.000	0.945
		Birmingham		
Heating	1.000	1.005	1.000	0.894
Cooling	1.000	0.974	1.000	0.961
Total			1.000	0.945

[a]Normalized to peak energy load for light envelope.
[b]Normalized to annual energy load for light envelope.

A similar analysis was carried out for a three-story commercial office building. The results are given in Table A.3. Trends in annual and peak energy loads are similar to the one-story building. The use of setback resulted in identical peak heating loads for both the light and heavy construction, but setup during cooling produced approximately 3% lower peak cooling loads.

The light structure with setback consistently had the lowest annual heating loads (in the one exception, temperature drift was considered unacceptable) when compared to the heavy structures. However, the massive structures with setup consistently had lower annual cooling energy usage (see Table A.4).

Table A.3. Peak and annual energy loads for one-story office buildings

	Peak energy load[a]		Annual energy load[b]	
	Light envelope	Heavy envelope	Light envelope	Heavy envelope
		Minneapolis		
Heating	1.000	1.035	1.000	0.965
Cooling	1.000	0.993	1.000	0.973
Total			1.000	0.971
		Kansas City		
Heating	1.000	1.047	1.000	0.930
Cooling	1.000	0.945	1.000	0.976
Total			1.000	0.969
		Birmingham		
Heating	1.000	1.058	1.000	0.883
Cooling	1.000	0.947	1.000	0.961
Total			1.000	0.969

[a]Normalized to peak energy load for light envelope.
[b]Normalized to annual energy load for light envelope.

Table A.4. Annual energy loads for a three-story office building

	Light envelope		Heavy envelope	
	6 a.m. reset	6 a.m. reset	Midnight reset	No setback
		Minneapolis		
Heating	1.000	1.030	1.074	1.216
Cooling	1.000	0.879	0.896	1.010
Total	1.000	0.965	0.997	1.127
		Kansas City		
Heating	1.000	1.025	1.087	1.274
Cooling	1.000	0.921	0.933	1.066
Total	1.000	0.953	0.980	1.129
		Birmingham		
Heating	1.000	0.975	1.098	1.396
Cooling	1.000	0.918	0.938	1.094
Total	1.000	0.928	0.968	1.150
Density per unit of floor area	273 kg/m^2 (56 lb/ft^2)		834 kg/m^2 (171 lb/ft^2)	

A.1.8 Petersen

Petersen used the NBSLD computer program to perform a large number of simulations of the annual heating and cooling requirements of a prototypical single-story house.[11] This information was then used to determine the economically optimum levels of insulation for masonry and wood frame walls based on life-cycle cost analysis. The conclusions of the study are given below.

> In general, insulation costs for masonry walls are considerably higher than those for wood frame walls, especially if rigid foam insulation is used in the masonry walls. In addition, equal reductions in U-

value tend to save less energy in masonry walls than in wood frame walls, especially in the southern and southwestern regions of the United States. As a result, the maximum economic level of insulation tends to be lower for masonry walls than for wood frame walls, at least in the milder heating regions. Where a minimum R-metric 1.94 (R-11) mineral wool insulation in wood frame walls is cost-effective in nearly every region of the continental U.S. (except southern Florida), the equivalent level of rigid foam insulation in masonry walls is not generally cost-effective anywhere in the southern half of the United States.

The use of free-standing 38 x 64 mm (2 x 3 in.) framing on the inside surface of masonry walls, together with conventional fiberglass insulation, is a cost-effective alternative to rigid foam insulation. While the cost of the framing is substantial, the expense of furring strips is avoided. Moreover, the framing can be moved out farther from the wall to accommodate more insulation at little increase in carpentry costs. Equivalent interior areas can be maintained by extending the end walls slightly during construction. With the use of this mineral wool insulating system, higher R-values than were found for rigid foam insulation are cost-effective. Still, the maximum economic level of insulation in masonry walls in southern, southwestern, and west coast regions tends to be significantly lower [often R-metric 0.53 (R-3)] than that for wood frame walls, especially where natural gas or heat pumps are used in heating.

It was found that the addition of insulation to either wood frame or masonry walls reduced cooling loads insignificantly, except in the case of the Phoenix climatic region.

...While the insulation of the inside wall surfaces negates some of the beneficial effects of thermal mass on exterior walls, the reduced rate of heat loss through those walls more than compensates for this negative effect. Since insulation on inside surfaces can be significantly less expensive than exterior insulation, serious doubts about the economic efficiency of exterior insulation are raised.

A.1.9 Brookhaven Study

Under contract to Brookhaven National Laboratory, a study was conducted by Total Environment Action, Inc., to determine the feasibility of reducing energy usage by the incorporation of additional thermal storage capacity to a building.[12] This study made use of the TRNSYS and DEROB computer programs for building energy analyses. The abstract from the report is included below.

The thermal storage capacity found in the materials of conventional building construction affect the heating and cooling requirements of buildings and the long-term efficiency of the space conditioning equipment used to meet these demands. The quantity of this natural thermal storage (NTS) can be increased through architectural design to improve overall building thermal performance and decrease the consumption of conventional fuels used by space conditioning.

> Improvements in performance come about when (1) heating or cooling peak loads are reduced, (2) previously, poorly used, natural energy sources are tapped, or (3) conventional system efficiencies are increased. The capability of NTS materials to absorb, store, and release thermal energies can be used advantageously to bring about these improvements.
>
> The technical and economic feasibility of these uses of NTS in residential construction in the north central and northeast U.S. is examined. For many NTS applications, the percentage savings in heating and cooling are impressive, but the actual value of the energy saved is found to be insufficient to justify the incremental cost of NTS over reasonable levels of insulation and other energy strategies. NTS in the form of modified Trombe walls, when combined with energy conserving construction methods, is found to be an effective, available, and marketable system. A prototypical residence incorporating this NTS system is designed for instrumentation and as a demonstration of NTS principles. Annual space conditioning costs are reduced to one-third of those found in new construction built to current codes, and less than one-fifth the costs found in typical existing homes.

This study culminated in the design of the Brookhaven House, an energy-saving residence that demonstrates how thermal mass can be used to cut heating costs in conventional single-family housing.

A.2 Experimental Studies

This section reviews previous as well as ongoing experimental work on the effects of thermal mass. There is, of course, much experimental work currently being done at universities and in industry from which results are not yet available.

A.2.1 NBS Experimental Masonry Building

In 1973 the National Bureau of Standards conducted experimental studies on a 6.1-m (20-ft) square, single room, concrete block house in a large environmental chamber.[13] The building was subjected to a simulated sol-air temperature cycle which ranged from 4.4 to 38°C (40 to 100°F). The sol-air temperature is the hypothetical air temperature which produces the same heat flow through the envelope as the combined effects of solar radiation and the actual air temperature.

Tests were conducted in which the interior air temperature was allowed to float (no heating or cooling supplied). For the uninsulated structure, this resulted in an inside air temperature variation of about 5.8°C (10.5°F). Placement of insulation inside reduced this variation to about 3°C (5.5°F). When insulation was placed on the outside surface instead of the inside, this variation was reduced to about 1°C (2°F).

The addition of interior mass to the building [1180 kg (2600 lbs) of concrete blocks stacked inside the building] resulted in a slight reduction in the variation in inside air temperature for the uninsulated case, but for the insulated cases, the effect was negligible.

A second series of tests was conducted in which the interior air temperature was thermostatically controlled. It was observed that the minimum heating load usually occurred later in the day than the peak outside air temperature because of the effect of building mass and insulations. As expected, the effect of placing insulation on either the inside or outside was to substantially reduce the amount of heating required to maintain a constant interior temperature. These tests were conducted primarily to help validate the NBSLD simulation computer program.

A.2.2 National Forest Products Association

The National Forest Products Association has conducted two experimental studies comparing the energy performance of wood frame and masonry structures. In 1960-61, tests were conducted on test houses in Beltsville, Maryland,[14] and in 1968 on houses in Tempe, Arizona.[15] The interior dimensions of each single-room house are approximately 3.40 m (11 ft 2 in.) wide by 4.62 m (15 ft 2 in.) long by 2.44 m (8 ft) high. The wood frame structure had a crawl space, and the masonry structure was slab-on-grade. The buildings were oriented the same and had the same window and door arrangement. The wood frame structure had wood window frames, while the masonry structure had aluminum windows. All buildings were insulated to levels which were typical at the time of their construction. Because of this, the wood structures are better insulated than are the masonry structures. In the Maryland study, the wood frame house required 26% less energy for heating and 18% less for cooling than did the masonry structure. In the Arizona test, the energy savings were 23% less for heating and 30% less for cooling. It should be pointed out that these savings are largely attributable to the difference in insulation between the houses. However, the Arizona study showed that during transition periods (October-November and March-April), when both heating and cooling were required, the masonry house used less energy than did the wood frame house.

A.2.3 NBS Research Study

Six 6.1 m (20 ft) square one-room test buildings have been constructed outdoors at the National Bureau of Standards located at Gaithersburg, Maryland.[16] These test buildings have the same floor plan and orientation. They are identical except for the walls, which are as follows:

1. insulated lightweight wood frame;
2. uninsulated lightweight wood frame;
3. conventional insulated masonry (masonry positioned predominantly on the exterior);
4. conventional uninsulated masonry (masonry positioned predominantly on the exterior);
5. log; and
6. unconventional insulated masonry (masonry positioned predominantly on the interior).

A detailed description of the walls of the test buildings is given in Table A.5. The steady-state thermal resistances of the insulated walls (1, 3, and 6) and the uninsulated walls (2 and 4) are designed to be approximately equivalent.

Space cooling for the test buildings is provided by individual split-vapor-compression air conditioners with the indoor units centrally located within each test building. The indoor units are equipped with electric-resistance heating elements for providing space heating during the winter season.

Each of the test buildings has two north-facing and two south-facing double hung windows and an insulated door. The total window area is approximately 12% of the floor area, which is considered to be representative of residential construction.

The floors of the test buildings consist of slab-on-grade. The ceilings of the test buildings are insulated to an R-value of 6.7 $m^2 \cdot K/W$ (38 $h \cdot ft^2 \cdot °F/Btu$).

The buildings are extensively instrumented to measure wall heat transmission, heating and cooling energy requirements, air infiltration rate, and the indoor comfort condition. The test buildings were exposed to outdoor weather conditions for one calendar year, thereby permitting evaluation of seasonal variations in the thermal benefits of wall mass. Separate tests will later be carried out with an interior partition dividing each test building into a

Table A.5. Description of wall of test buildings

1. Insulated lightweight wood frame
   1.6 cm (5/8 in.) exterior plywood
   5 x 10 cm (2 x 4 in.) stud with R-1.9 (R-11) insulation installed in cavity
   1.3 cm (1/2 in.) gypsum board

2. Uninsulated lightweight wood frame
   same as above, except that the insulation is not installed within the cavity

3. Conventional insulated masonry
   10.2 cm (4 in.) brick
   10.2 cm (4 in.) concrete block
   5.1 x 5.1 cm (2 x 2 in.) furring strips placed 16-in. o.c.
   polystyrene insulation installed in cavity
   1.3 cm (1/2 in.) gypsum board

4. Conventional uninsulated masonry
   20.3 cm (8 in.) concrete block
   1.9 cm (3/4 in.) air space
   1.9 x 5.1 cm (3/4 x 2 in.) furring strips placed 16-in. o.c.
   1.3 cm (1/2 in.) gypsum board

5. Log
   20.3 cm (8 in.) lodgepole pine square logs

6. Unconventional insulated masonry
   10.2 cm (4 in.) nominal block
   8.9 cm (3 1/2 in.) perlite insulated cavity
   20.3 cm (8 in.) nominal concrete block
   0.3 cm (1/8 in.) plaster covering

two-room test module. Differences in wall heat transmission, heating and cooling energy consumption, and indoor comfort attributed to variations in wall thermal mass will be quantified and correlated with respect to the outdoor climatic conditions.

Data collection began at the site early in 1981. This study and the Southwest Thermal Mass Study are coordinated efforts. A Thermal Mass Review Panel acts in an advisory role for both projects.

The results for the 14-week winter heating season are presented in Fig. A.5. Here the winter heating season is defined as that portion of the winter during which the heating system operated some during each hour of every day. There is no thermal mass effect illustrated by these results. The energy consumption for each building was accurately predicted by steady-state methods using component R-values and average outdoor temperatures.

The results for the intermediate heating season (heating was not required during every hour) are presented in Fig. A.6. A very definite thermal mass effect is shown here. The more massive buildings use less energy. Mass on the inside of insulation performs better. However, to put things in perspective, even though there is a significant reduction in heating requirements during the intermediate heating season, this season does not represent a very substantial portion of the annual heating load.

The results for the summer cooling season are given in Fig. A.7. (To be consistent, this should probably be called the intermediate cooling season since cooling was never required during every hour of the day.) Here, again, a definite thermal mass effect is evident. As in the intermediate heating season, the presence of mass reduces energy consumption. Also, mass inside insulation is preferable.

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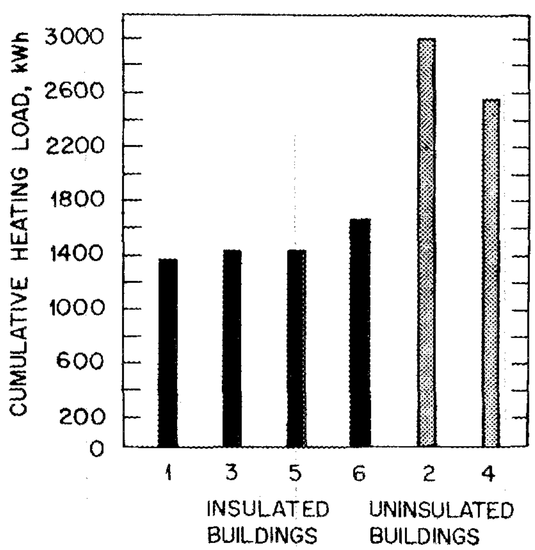

Fig. A.5. Cumulative heating loads for the NBS test buildings during winter heating season.

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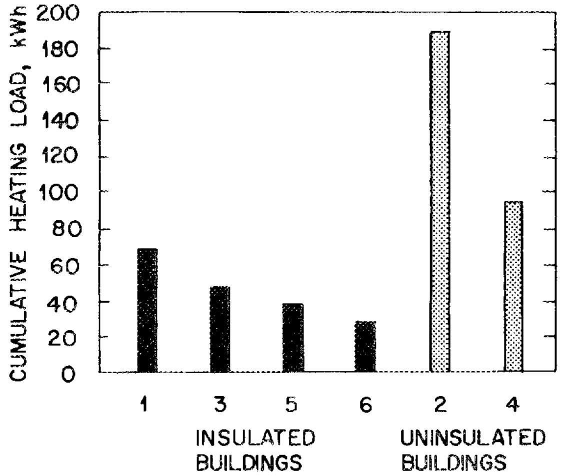

Fig. A.6. Cumulative heating loads for the NBS test buildings during intermediate heating season.

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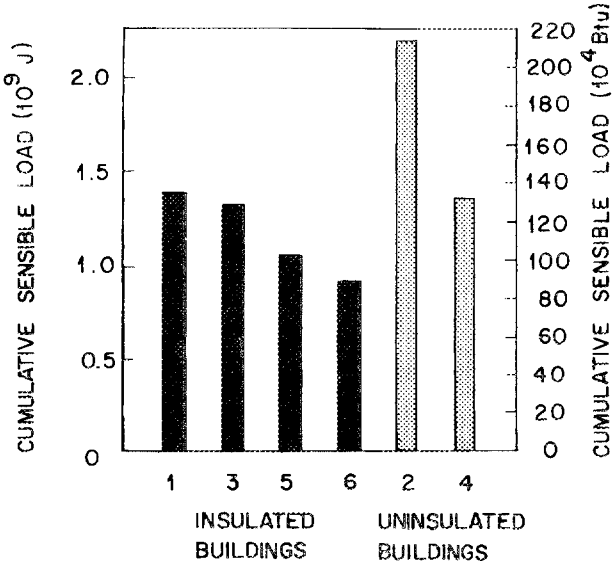

Fig. A.7. Cumulative cooling loads for the NBS test buildings during the cooling season.

A.2.4 The Southwest Thermal Mass Study

This project consists of a study to identify the characteristics of thermal mass with emphasis on adobe.[17] Objectives of the project are: (1) to measure thermal performance of mass walls as components in buildings; (2) to measure effects of energy consumption of the mass wall coupling with thermostat setpoints and ventilation; (3) to measure U-values of stabilized and traditional adobe, including changes due to curing effects; and (4) to compare experimental results with predictions from techniques such as effective U-values, M-factors, and steady-state U-values.

The proposed facility will consist of eight test structures, each with inside dimensions of 6.1 m by 6.1 m (20 ft by 20 ft). The structures all have the same orientation and are spaced to eliminate any shading. The eight structures consist of five adobe structures, one concrete block structure, a log wall structure, and an insulated frame wall structure. The five adobe structures consist of three 25.4-cm-thick (10-in.) adobe walls, one 35.6-cm-thick (14-in.) wall structure, and one 61.0-cm-thick (24-in.) wall structure. Of the three 25.4-cm-thick (10-in.) structures, two will be identical. These will be used to do side-by-side tests of various parameters. The other 25.4-cm (10-in.) structure will be made out of stabilized adobe to identify effects of stabilization on thermal performance.

The test site is located on land owned by the Tesuque Pueblo and is approximately 9 miles north of Santa Fe, off U.S. 84-285. The weather in the area is very similar to that of Santa Fe. There are about 3330°C (6000°F) heating degree days and very few cooling degree days. For this reason, the main emphasis of the tests will be on the heating implications of the thermal mass. Tests will be run with constant thermostat settings, with night setback, and with changes in parameters such as surface absorptivity and use of internal partitions to eliminate radiation exchange between the walls.

Using the frame wall insulated structure as the base, the performance of the other seven cells will be compared on the basis of overall energy requirements, inside air temperature profiles, and dynamic requirements of energy vs probable residential load patterns. From this information, it will be possible to assess the effects of thermal mass on energy consumption. In their present configuration, the test cells are without doors, windows, or internal heat sources other than the heating system. This is done to isolate the thermal mass and to identify the effects of thermal mass without including the effects of interaction with other components in the building. If it is determined that the use of mass walls does not have an effect on energy savings over that which would be predicted through the steady-state U-calculations, then internal heat sources and solar gains will be added to the cells. Tests will then be run on these configurations to isolate the interactions occurring and the mechanisms through which mass reduces overall energy requirements in a building. Data collection began in late 1981 and early 1982. This study and the NBS Research Study are coordinated efforts. A Thermal Mass Review Panel acts in an advisory role for both projects.

A.3 Simplified Design Calculations

Since traditional steady-state calculations do not accurately predict annual energy usage by a building, and the use of large computer simulation programs is impractical for designers to use because of high cost, there is a need for simplified design calculation techniques. This section reviews some of these techniques.

A.3.1 M-Factor

The Masonry Industry Liaison Committee developed the M-factor concept to account for the mass effect in exterior walls of buildings.[18-20] The M-factor is a correction to conventional steady-state U-values (or R-values) which results in less insulation being required for heavy buildings than for lightweight buildings. The M-factors were developed using subroutines from the NBSLD computer program. The M-factor correction is less in regions having large heating degree day values. The M-factor chart is given in Fig. A.8.

The validity of the M-factors has been questioned because of the theoretical basis of its development.[21,22] However, defenders of the M-factor claim that the results agree with actual experience.

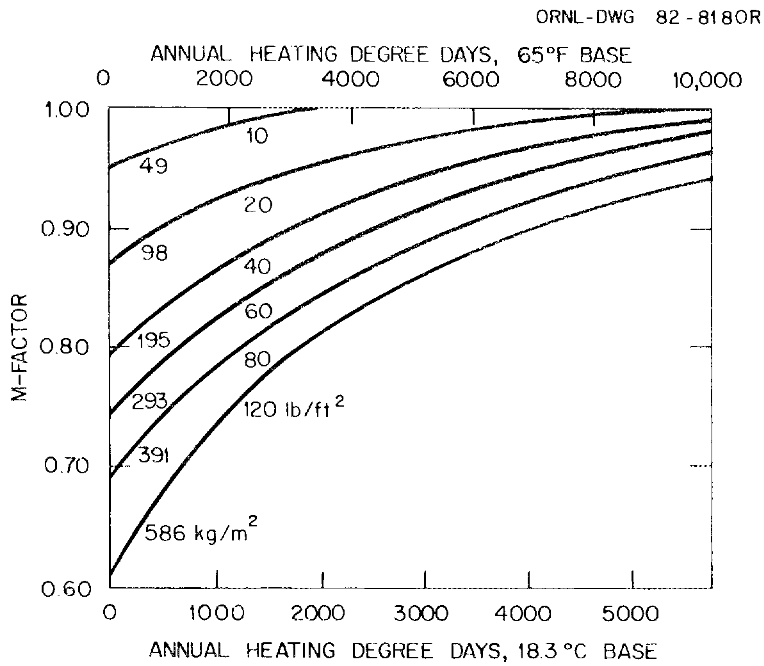

Fig. A.8. M-factor curves for various weight walls.

A.3.2 Effective U-value

Steady-state U-values, as already indicated, are not necessarily a good indication of energy consumption by a building. This is because of two primary factors: (1) walls are seldom, if ever, in a steady-state condition; and (2) solar input is a crucial factor in determining energy usage, yet this is usually ignored in steady-state analyses. Therefore, the state of New Mexico developed an effective U-value which accounts for these factors.[23,24] The effective U-values were determined by use of computer analysis, a specific wall construction, orientation, and color exposed to an average week of winter weather in a specific location.

There were 27 wall types, four orientations, and three colors considered. New Mexico was divided into eleven climatic regions. The effective U-values were also experimentally checked and corrected where necessary. A sample table is given as Table A.6.

Some conclusions that were reached by the study are:

1. In some cases, U-values are quite different from steady-state U-values. Thermal storage and solar effects are included in effective U-value calculations.
2. Effective U-values for east, west, and south walls are affected strongly by color. In some instances, it may be more cost-effective to paint than to insulate.
3. Generally speaking, effective U-values indicate that less insulation is needed than is suggested by steady-state U-values. This is substantiated in a separate study of energy (NMEI Report No. 76-163, Energy Conservation Housing for New Mexico) used by buildings constructed according to FHA standards. It would appear that houses built to conform to old FHA standards, using less insulation, are more energy conservative than houses built to the newer standards, although further statistical analysis is needed to verify this observation.
4. Some wall-climate combinations have negative effective U-values. This indicates that the wall acts as a solar collector and is a net energy gainer.
5. Properly oriented and treated windows are energy gainers. Steady-state U-values erroneously indicate the opposite.
6. Effective U-values can be easily substituted into codes such as ASHRAE 90-75 and UBC. The result is a "performance" code that allows a broader range of construction and focuses on average energy use rather than peak energy use. This provides a more energy conservative code.

A.3.3 ΔR Concept

Since it is claimed that heavier building construction can result in a reduced energy consumption in winter weather, codes requiring equal R-values (U-values) for both lightweight and heavy walls are actually more strict for the heavy wall. The goal of the building codes is to have equal performance. Therefore, the heavier wall should be allowed a reduced R-value. This has led to a ΔR concept (pronounced "delta R" and meaning change in R-value).

As discussed in Sect. A.1.6, Mitalas has developed a ΔR correction for buildings in the Canadian climate. Also, based on the work of Petersen (see Sect. A.1.8), the Department of Housing and Urban Development (HUD) has proposed a similar correction for the United States. The HUD proposal has correction graphs for specific wall types in different climate regions (based on number of heating degree days). HUD uses U-values rather than R-values. (The R-value is the reciprocal of the U-value.) A typical graph is shown in Fig. A.9.

Table A.6. Effective U-values for heating

Wall type 10 — 20.3 cm (8 in.) standard concrete block (unfilled)
ASHRAE steady-state U-value: 3.19 $W/m^2 \cdot K$ (0.526 $Btu/ft^2 \cdot h \cdot °F$)

New Mexico climatic region	Wall orientation and color											
	North			East			South			West		
	Light	Medium	Dark	Light	Medium	Dark	Light	Medium	Dark	Light	Medium	Dark
1	2.51 (0.442)	2.12 (0.374)	1.74 (0.306)	2.42 (0.427)	1.92 (0.339)	1.40 (0.246)	2.35 (0.414)	1.65 (0.291)	0.90 (0.158)	2.45 (0.431)	1.92 (0.339)	1.41 (0.249)
2	2.37 (0.417)	2.16 (0.381)	1.95 (0.344)	2.31 (0.407)	2.02 (0.355)	1.72 (0.303)	2.24 (0.394)	1.82 (0.320)	1.39 (0.245)	2.32 (0.409)	2.04 (0.359)	1.76 (0.310)
3	2.34 (0.412)	2.17 (0.383)	2.00 (0.353)	2.38 (0.420)	2.03 (0.357)	1.77 (0.312)	2.20 (0.388)	1.83 (0.322)	1.46 (0.257)	2.29 (0.404)	2.06 (0.362)	1.83 (0.322)
4	2.32 (0.408)	2.18 (0.384)	2.05 (0.361)	2.25 (0.396)	2.01 (0.354)	1.78 (0.314)	2.15 (0.379)	1.79 (0.315)	1.43 (0.252)	2.27 (0.399)	2.06 (0.363)	1.86 (0.327)
5	2.32 (0.408)	2.19 (0.385)	2.06 (0.362)	2.24 (0.395)	2.00 (0.352)	1.77 (0.311)	2.14 (0.377)	1.76 (0.310)	1.39 (0.245)	2.27 (0.399)	2.06 (0.362)	1.85 (0.325)
6	2.32 (0.409)	2.19 (0.385)	2.05 (0.361)	2.24 (0.394)	1.98 (0.348)	1.73 (0.305)	2.12 (0.374)	1.71 (0.302)	1.31 (0.231)	2.26 (0.398)	2.04 (0.359)	1.82 (0.321)
7	2.33 (0.411)	2.19 (0.385)	2.04 (0.360)	2.24 (0.394)	1.95 (0.344)	1.68 (0.296)	2.11 (0.372)	1.66 (0.292)	1.21 (0.213)	2.27 (0.399)	2.02 (0.356)	1.78 (0.314)
8	2.35 (0.414)	2.19 (0.385)	2.02 (0.356)	2.24 (0.394)	1.91 (0.337)	1.60 (0.282)	2.10 (0.369)	1.57 (0.277)	1.04 (0.183)	2.27 (0.400)	1.99 (0.350)	1.71 (0.301)
9	2.38 (0.419)	2.18 (0.384)	1.99 (0.350)	2.24 (0.395)	1.86 (0.328)	1.49 (0.262)	2.08 (0.367)	1.46 (0.258)	0.82 (0.145)	2.29 (0.403)	1.95 (0.343)	1.61 (0.284)
10	2.43 (0.428)	2.17 (0.383)	1.92 (0.338)	2.27 (0.399)	1.78 (0.313)	1.29 (0.228)	2.07 (0.365)	1.28 (0.226)	0.45 (0.080)	2.73 (0.480)	1.88 (0.331)	1.43 (0.252)
11	2.47 (0.435)	2.17 (0.382)	1.87 (0.330)	2.28 (0.402)	1.72 (0.303)	1.16 (0.205)	2.07 (0.364)	1.16 (0.205)	0.20 (0.036)	2.34 (0.412)	1.83 (0.322)	1.31 (0.231)

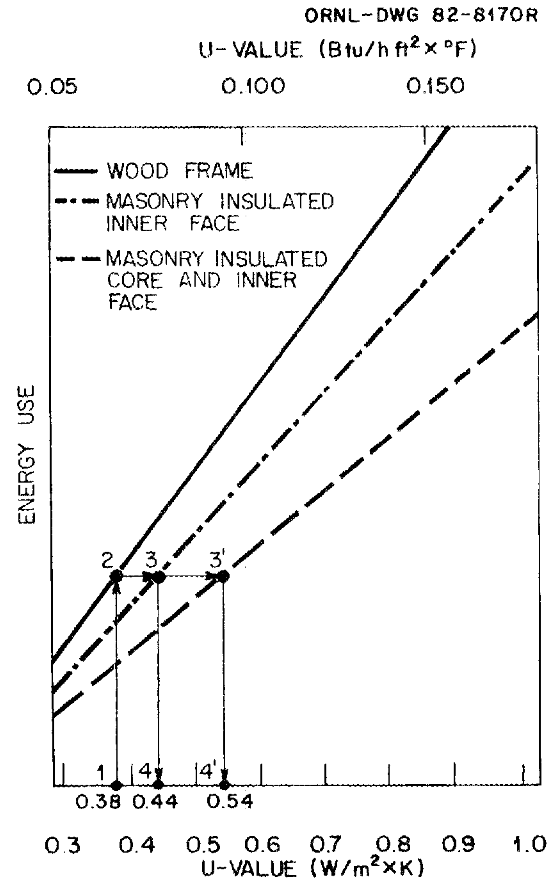

Fig. A.9. Chart for determining U-values that give equivalent energy use for region experiencing 1390–1945 (2501–3500) heating degree days [18.3°C (65°F) base].

As an example of how to use the graphs, assume that we wish to determine U-values necessary for masonry walls to perform equivalent to a wood frame wall with a U-value of 0.38 $W/m^2 \cdot K$ (0.067 $Btu/h \cdot ft^2 \cdot °F$). This is equivalent to an R-value of 2.6 $m^2 \cdot K/W$ (15 $h \cdot ft^2 \cdot °F/Btu$). Step 1: locate 0.38 on the abscissa and move straight up until the curve for a wood frame wall is intersected. Step 2: move horizontally to the right until the curve for the desired masonry wall is intersected. Step 3: move straight down. The intersection point with the abscissa gives the necessary U-value for the masonry wall. In the example given, the U-values, which will result in equal energy usage for three wall types in a location having between 1390 and 1945°C (2501 and 3500°F) heating degree days, are 0.38, 0.44, and 0.54 (0.067, 0.078, and 0.095). These U-values correspond to R-values of 2.6, 2.25, and 1.85 $m^2 \cdot K/W$ (15, 12.8, and 10.5 $h \cdot ft^2 \cdot °F/Btu$) for a wood frame wall, concrete masonry unit with insulated inner face, and concrete masonry units with insulated core and insulated interface, respectively.

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