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HEAT STORAGE AND DISTRIBUTION INSIDE PASSIVE-SOLAR BUILDINGS*

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ABSTRACT

Passive-solar buildings are investigated from the viewpoint of the storage of solar heat in materials of the building: walls, floors, ceilings, and furniture. The effects of the location, material, thickness, and orientation of each internal building surface are investigated. The concept of diurnal heat capacity is introduced and a method of using this parameter to estimate clear-day temperature swings is developed. Convective coupling to remote rooms within a building is discussed, including both convection through single doorways and convective loops that may exist involving a sunspace. Design guidelines are given.

KEYWORDS

Passive solar heating, heat storage, heat distribution, diurnal heat capacity, convection.

INTRODUCTION

Necessity for Heat Storage

There are three key physical processes that make passive solar heating possible: solar gain, heat storage, and heat distribution. A key difference between active and passive approaches to solar heating is that passive designs rely almost totally on natural processes for these phenomena. There is little, if any, exercise of control over the way they take place. The building works well or poorly, depending primarily on how it is designed; that is, it is the design that determines whether the natural processes will conform to the needs of the building at any particular time. Solar gains are controlled primarily by the location, orientation, and shading of the apertures (windows) in the building. Heat storage is in the normal materials of the building, and distribution is by radiation and convection.

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Heat storage becomes more essential as the dependence of the building on solar gains increases. If the building is only solar tempered, which means that the solar contribution is relatively small (usually less than about 40%), solar gains primarily offset the needs for daytime heating. Some heat storage will take place, but requirements for building heat at night and during cloudy periods are met primarily by auxiliary sources.

In a well-designed passive solar building tho situation is quite different. Typically, no auxiliary heating is required in sunny winter weather. This means that all of the nighttime heating must come from heat stored within the building. Normally some auxiliary heat is still required, but it is needed only during cloudy periods when there has been less than full sun for one or more days. The need for auxiliary heat increases gradually as the heat stored in the building is gradually depleted. It is not very useful to talk in terms of a "heat storage carry-over time," as is often done, because of this gradual transition. Also, the carry-over time would depend on the particular heating requirements for the building. During mild, cloudy weather the carry-over time would be longer and during severe weather it would be shorter. For both reasons, carry-over time is not a particularly helpful concept.

In no small part, the economy of passive solar heating stems from the dual use of most of the construction and furnishing materials. Windows serve for light and view as well as for solar gain. Heat is stored in ordinary walls, floor, and, indeed, in all of the materials of the building. Although one may alter the construction techniques of the building to enhance the amount of heat storage available, in almost all cases heat storage serves multiple functions.

Natural convection within buildings is a very effective mechanism for heat distribution. Convective flow through doorways can be used to heat remote rooms if the heat loss of the space is not too large. A convective loop can also be set up within the building, greatly increasing the heat exchange. Such a loop may, for example, involve a sunspace, a doorway opening into the sunspace at the second level, upper rooms and hallways, a stairway, lower rooms and hallways, and a doorway opening at the lower level. Such loops have been shown to be very effective for heat distribution and make dual use of architectural features.

HEAT STORAGE IN PASSIVE SOLAR BUILDINGS

Direct Gain Situations

Direct gain is by far the most widely used passive solar strategy. It occurs to one extent or another in almost all passive solar buildings. It occurs with all windows, whether they are south facing or not, and storage of most of the heat associated with the solar gains occurs whether we plan for it or not. If the materials of the building interior are very lightweight, heat storage might be quite temporary, and transfer of the heat to the air in the room may take place quite soon. In more massive materials, the heat diffuses to the interior and is returned only at a later time when the room temperature drops somewhat, allowing for a reversal of temperature gradients so that the heat can rediffuse slowly to the surface.

The mechanisms of heat distribution within a direct gain room, after the short-wave solar radiation has entered the window, are very complex. Fortunately, we are not required to model all of these phenomena in great detail to obtain a reasonably good understanding of how heat storage takes place. Depending on sun angles, sunlight shines on a particular spot in the room with some energy being absorbed, some being converted to heat, and some being reflected, depending on the color of the surface. But if the surfaces are all light in color, the heat may be distributed rather uniformly around the room by short-wave solar radiation. If the angle of incidence of the sun at the light surface is acute, the sun may be reflected deep within the space, facilitating both natural lighting and heat distribution. If the surface is dark in color, there will be a concentration in conversion of light to heat at the region of first solar incidence.

Once the short-wave radiation is turned into heat at one or another of the building's internal surfaces, one of three actions occurs: (1) the heat migrates into the material, (2) the heat is transferred to the room air by convection, or (3) the heat is reradiated as infrared energy to all of the surfaces within the room that can be viewed from that location. Most of the energy that flows outward from the surface does so by infrared radiation with convection to room air being the smaller component. Thus, each surface in the room is continually bombarded by infrared radiation from every other surface within view. Except for surfaces that are in the direct sun, this inflow of infrared energy constitutes the major heat source. The fact that this infrared radiation transport within the space is so dominant is the primary reason that direct gain is a viable solar strategy. Understanding this fact is a great aid in direct gain design.

Only an area approximately the size of the window receives direct-beam solar radiation, depending on the angles. On a sunny day, the rate of energy inflow at this point is much greater than most masonry materials can accommodate for very long. Thus, most of the energy will be redistributed by convection and infrared radiation. Mazria (1979) has shown clearly that it is better to distribute the energy uniformly over a large surface area than to attempt to absorb it at the point of first incidence. This strategy results in much smaller temperature swings within the space. It is fortunate that infrared energy flow is such a good ally in accomplishing this redistribution. Although surfaces in the sun may be temporarily significantly warmer than other surfaces, the energy is quickly redistributed, and within a few hours most of the surfaces enclosing the space will be at similar temperatures.

Diffusion of heat into massive materials is a very slow process, affected little by the temporary shadows and other short-term variations in incident energy. We are more concerned with the gradual behavior of these materials over a period of a day or more than we are with the short-term effects occurring near the surface.

Convective Situations

It is usually better to maintain solar energy as radiant energy (either short wave or infrared) or stored heat as long as possible. Inevitably, however, some energy is transferred to the room air causing its temperature to increase. Air has a small heat capacity, typically about 1/1400th that of solid materials (on a volumetric basis). It is also quite mobile and tends to rise as heating decreases its density. This phenomenon displaces cooler air at some other location within the building and results in the establishment of convective loops. It is also possible for the hot air simply to collect at the top of the room, resulting in temperature stratification.

Usually about 1/3 of the solar gain entering the room results in heating of the room air. The warm air can then either convect to other spaces within the building that are cooler, flow out of the building by exfiltration (to be replaced by cooler infiltration air that dilutes its temperature), or rise in temperature until the energy flows balance. Controlling this temperature rise is a key factor in maintaining comfort in passive solar buildings. Normally the day/night temperature swing of the room is cited as a measure of the designer's success. Temperature swings above about 6°C are normally considered uncomfortable.

Distribution of heat by convection to cooler places within the building is a major mechanism of heat distribution during the day and a major source of energy for heat storage within the walls of these spaces. Because of the small thermal conductivity of air, the heat flux at these mass surfaces is substantially less than at surfaces within the direct gain space. Thus, it is convenient to distinguish between surfaces that are radiatively coupled to the source and those that are convectively coupled. Radiative coupling is much more effective and occurs at surfaces that are within the direct gain space. Convective coupling is the primary heat transport mechanism to remote spaces. Heat storage in materials in convectively coupled situations is usually less than in radiatively coupled situations. Nonetheless, convective coupling can constitute an important part of the heat storage in the building.

In the situation of a passive solar sunspace, convective coupling may be a major mechanism for energy transport. Temperature swings in the sunspace are large because the ratio of mass surface to glazing surface is small (typically 3:1). Thus, there are large temperature differences to drive convective exchange to the rest of the building. Because the living portions of the building have large interior surface areas, there can be extensive storage of heat in these rooms even though the heat fluxes at the surfaces are relatively small.

Importance of diurnal heat storage. It is convenient to distinguish between three time domains of heat storage: short-term heat storage, which lasts for a few hours; diurnal heat storage, which consists of heat stored during the day that is returned at night; and long-term heat storage, which refers to storage durations longer than one day. Of these phenomena, diurnal heat storage is the most significant to passive solar design. If one designs on the basis of diurnal storage, long-term storage will usually be adequate.

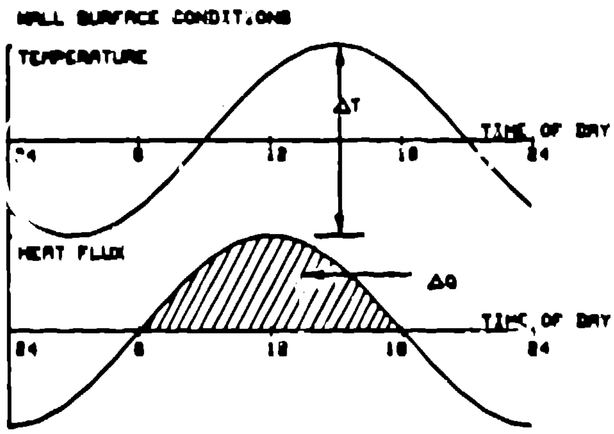

Fig. 1. Diurnal component of wall surface temperature and heat flux into the wall for a very thick wall. The crosshatched area is the heat stored during a half day (equal to the heat released during the other half day). The diurnal heat capacity is $\Delta Q/\Delta T$.

Diurnal heat capacity. Because of the importance of diurnal solar and outside temperature inputs, it is important to characterize the building's response at this 24-hour frequency. This has lead to the concept of a diurnal heat capacity, which, in simple terms, is the amount of heat that can be stored in building thermal mass during the first half of a 24-hour cycle and returned to the space during the second half of the cycle. This is shown in Fig. 1 for the case of a wall with a sinusoidal heat flux introduced into the wall surface. The curve shows that the typical response of the surface temperature to this sinusoidal input is also a sinusoid shifted 3 hours later. This time shift of 1/8 of a cycle (45^o phase shift) is characteristic of the response of very thick masonry walls. For thinner walls, the time shift is usually longer and may be up to 6 hours.

Diurnal heat capacity is the amount of heat that is stored per degree of temperature swing. This amount of heat is equal to the integral under the top half of the heat flux curve, which is marked ΔQ on the figure. The diurnal heat capacity is simply the ratio, $\Delta Q/\Delta T$. Diurnal heat capacity is given per unit of surface area and thus the units are Wh/^oC m^2 day. Because the day unit is implied in the term diurnal, it is usually omitted, and the units are given as Wh/^oC m^2. In this paper, diurnal heat capacity is referred to by the symbol dhc.

The dhc of a wall is a measure of the ability of the wall to absorb and store heat during one part of a periodic 24-hour cycle and then release the heat back through the same surface during the second part of the cycle. This 24-hour give-and-take at the wall surface is the most important heat storage that occurs in the passive solar building.

Diurnal heat capacities of various materials. Diurnal heat capacities of different materials can be tabulated as a function of the material thickness if the properties are known. Properties used for various materials are listed in Table 1.

TABLE 1 Properties of Materials

Material	Density	Specific Heat	Thermal Conductivity	dhc_∞*
	kg/m^3	kCal/^oC kg	W/^oC m	Wh/^oC m^2
Granite	2675	0.20	1.82	65.1
Concrete	2290	0.21	1.73	60.2
Concrete Masonry	2242	0.21	1.42	54.0
Limestone	2451	0.22	0.93	46.9
Builder Brick	1922	0.22	0.72	36.5
Adobe	1922	0.20	0.56	31.1
Hardwood	720	0.30	0.16	12.3
Softwood	512	0.33	0.12	7.8

*dhc of an infinitely thick wall.

Diurnal heat capacities for different wall thicknesses are shown in Fig. 2. Relationships needed to calculate the dhc of layered wall situations or situations with convective coupling from the room to the wall surface are given by Davies (1973) and Balcomb (1983).

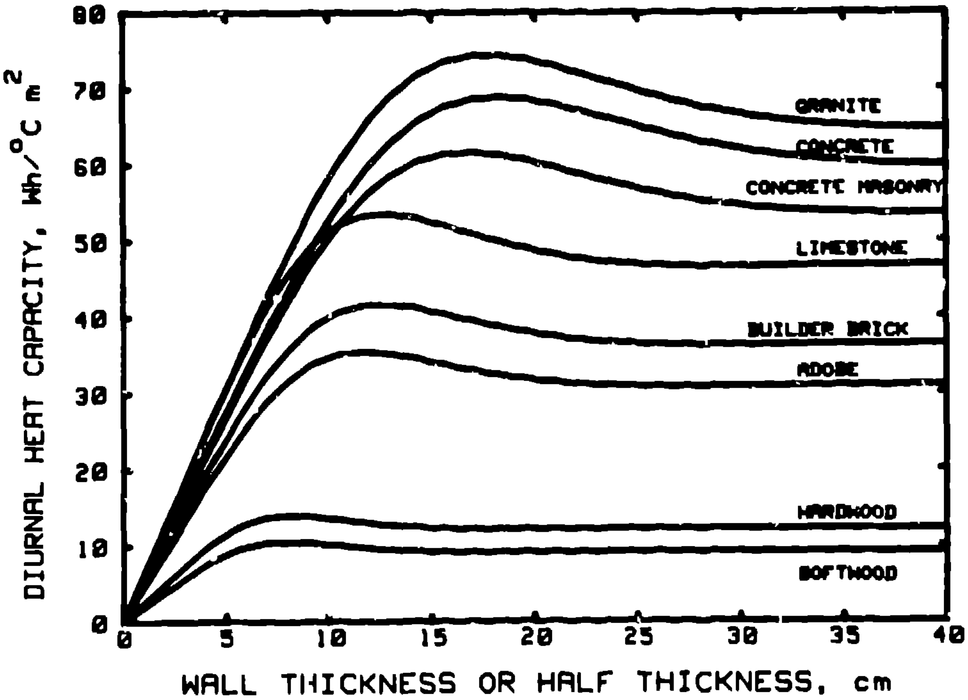

Fig. 2. Diurnal heat capacities of various materials as a function of thickness. Material properties used to generate these curves are given in Table 1. For interior partition walls, use 1/2 the total wall thickness to determine the diurnal heat capacity for each of the two surfaces. These curves apply to radiatively coupled mass.

Diurnal heat capacity of a whole room. The diurnal heat capacity of a whole room or a whole building can be determined by aggregating the effect of all surfaces acting in parallel. This will be called DHC. It is the vector sum of all the DHC values for all the various surfaces that enclose the room.

$$DHC = \sum_i A_i \, dhc_i \quad , \qquad (1)$$

where A_i is the area of the i^{th} surface, m^2, and
dhc_i is the dhc of the i^{th} surface, $Wh/^{o}C\ m^2$,

so that DHC has units of $Wh/^{o}C$.

It is first necessary to classify each inside surface of the building or room according to the coupling between the surface and the solar gain. It is useful to distinguish the following two major categories.

Radiation-coupled mass. Solar energy is transferred to the storage mass by either solar or thermal radiation. The mass must be either within the space that the sunshine enters or form an enclosing surface of the space. It is not necessary for the mass to be in the direct sun, but there must be a direct line of sight between the mass surface and absorbing or reflecting surfaces that are in direct sun.

Natural-convection-coupled mass. Solar energy is transferred to the storage mass by natural convection of warm air. Doorway or other convection openings must be provided with a total open area of at least 4% of the storage mass surface, or 2% of the storage mass surface if the openings are spaced more than 2 vertical meters apart.

Categorizing surfaces. We identify four types of surfaces as follows:

Type 1. Surfaces in the direct sun (radiation coupled),
Type 2. Other enclosing surfaces of a direct gain room (radiation coupled),
Type 3. Surfaces that are convectively coupled only, and
Type 4. Surfaces with zero coupling (zero dhc).

Exceptions are the following: (1) all ceilings, because of the excellent heat exchange with room air, are classified Type 2 even if they are in remote rooms, provided there is a suitable convective connection, and (2) floors not in the direct sun, because of the poor convective coupling and the lack of line-of-sight direct coupling, are downgraded one type number.

The following list gives further advice on assigning surface type:

Location	Type
The surface of any massive material that receives some direct sun, except covered floor.	1
Covered floor (or any covered surface).	4
Walls that enclose a direct gain room.	2
All ceilings, except in closed-off rooms (such as closets).	2
Walls that enclose other rooms that communicate by convection with direct gain rooms.	3
Uncovered floor in direct gain rooms (not directly sunlit).	3
Floors other than in direct gain rooms.	4
All surfaces in closed-off rooms.	4

In this listing, include gypsum-board surfaces and wood surfaces more than 1 cm thick. Do not include insulating materials such as fiber glass ceiling panels and walls or floors covered with heavy fabric, rugs, or other insulation. The next step is to estimate the area of each Type 1, Type 2, and Type 3 surface. For Type 1 surfaces, estimate the fraction of the solar day that the surface is sunlit, f, and the absorptance of the surface, α.

The estimates need not be very precise. Absorptance values can be estimated visually using the following guide:

Very dark surfaces	α = 0.8 to 0.9
Most surfaces	α = 0.5 to 0.6
Light colored surfaces	α = 0.3 to 0.4

Rough estimates are also adequate for f. Next determine the dhc of each surface using the following:

Type 1:	dhc = (radiation-coupled dhc) · (1 + αf)
Type 2:	dhc = radiation-coupled dhc
Type 3:	dhc = convectively-coupled dhc
Type 4:	dhc = 0

By radiation-coupled dhc we mean dhc calculated in terms of surface temperature swing. By convectively-coupled dhc we mean dhc calculated in terms of room temperature swing using a convective coupling; a value of 0.26 $W/^{o}C\ m^2$ is normally used as the coupling coefficient.

Next calculate the DHC of the furniture and room air. This can be estimated as 11 $Wh/^{o}C$ for each m^2 of floor area for normal furnishings.

Next add the DHC = (A) · (dhc) for each surface to determine the whole building DHC. It is somewhat more accurate if this is a vector addition, accounting for the phase of each component, but the extra effort required is great and the improvement in accuracy is small.

Estimation of Room Temperature Swing

A major use of diurnal heat capacity is in estimating room temperature swing. This is relatively simple because DHC gives the amount of heat stored per degree of room temperature swing. It remains only to compute the amount of heat that is stored and divide this by the DHC to obtain the peak-to-peak amplitude of the 24-hour sinusoidal room temperature swing. A correction can then be made to account for higher harmonics.

The amount of heat that is stored in the building during clear winter days can be estimated knowing the direct gain glazing area, the solar penetration per square meter of glazing area, and the heat loss characteristics of the building. A heat balance is calculated over the 12-hour period from 0600 to 1800, accounting for solar gains plus internal heat minus heat losses. The heat losses are calculated based on the total heat loss coefficient of the building (TLC) and the difference between average inside temperature and average outside temperature.

The energy balance stated above in words can be put in equation form as follows:

$$\Delta T\ (\text{swing}) = \frac{Q_s \cdot A - (T_r - T_a)TLC/2 + Q_i/2}{DHC} \quad , \qquad (2)$$

where
ΔT(swing) = peak-to-peak room temperature swing,
T_r = daily average room temperature,
T_a = daily average ambient temperature,
Q_s = daily solar gains per unit area of direct gain glazing,
Q_i = daily internal heat (assumed uniform), and
A = direct gain glazing area.

Although one could account for the detailed structure of the inside and outside hourly temperature profiles in determining T_r and T_a, this is not done for this analysis. The primary reason is that we wish to keep the analysis fairly simple and little accuracy would be gained by the complication. A second reason is that both inside and outside temperatures will be higher than average during the daytime (both due to solar gains) so that there is a tendency for these effects to cancel one another. Whether they would cancel exactly, of course, depends on the exact magnitude of the two swings. If the building uses no auxiliary heat, then

$$Q_s \cdot A = (T_{i^-} - T_a)\ TLC - Q_i \quad , \tag{3}$$

$$\Delta T\ (\text{swing}) = \frac{Q_s \cdot A}{2\ DHC} \quad . \tag{4}$$

A factor can be used to account for higher harmonics. From study of typical profiles we find:

$$\Delta T\ (\text{swing, actual}) = 1.22 \cdot \Delta T\ (\text{swing, diurnal}) \quad . \tag{5}$$

$$\text{Thus, } \Delta T\ (\text{swing}) = 0.61\ Q_s \cdot A/DHC \quad . \tag{6}$$

Design Guidelines for Direct Gain

A design guideline can be determined based on limiting temperature swings in direct gain situations. This leads to a minimum required diurnal heat capacity per unit area of south-facing direct gain glazing. From Eq. (6) we obtain:

$$DHC/A \geq 0.61 \cdot Q_s/\Delta T\ (\text{swing, maximum}) \tag{7}$$

Other passive solar heating design guidelines for direct gain can be given.

- One should achieve an extensive distribution of heat storing mass within the building and use materials that have a high density. A rough rule is to make the surface area of mass located somewhere within the direct gain space at least 6 times larger than the direct gain window area.

- Surfaces within the room, with the exception of the floor, should be light in color. This refers to both lightweight elements, for which it is essential, and massive elements. One reason for this guideline is to aid in distribution of energy to all surfaces of the room; by making the surfaces light in color, short-wave solar radiation is more liberally scattered throughout the space. Another reason for this is to aid in balancing the daylight within the space. Light surfaces, and especially mat white surfaces, greatly aid in daylight distribution.

- One exception to the above consideration is the color of the floor. If the floor is massive, it should be dark in color (Mazria, 1979). This is to maintain heat storage at the lowest possible level within the space to counteract the inevitable tendency for stratification. Comfort is enhanced by keeping the radiant temperature near the floor, the space people occupy, as high as possible. However, if the floor is of low-mass construction or if it is covered with carpeting, it would undoubtedly be better to make it light in color to scatter the light to other locations where it can be better stored.

- The appropriate color of mass walls will depend somewhat on the total amount of heat storage in the room. If there is only one massive element, and all the rest are lightweight, it may be desirable to make this mass element darker in color to better absorb the energy. If all of the surfaces are massive, the use of light-colored surfaces greatly aids in distributing the energy to all of the mass.

- If mass added in construction increases the cost of the project, as is usually the case, there is a definite limit to the thickness that should economically be used. Although some long-term heat storage capacity is achieved by making the mass thicker, this is not of great importance to the overall performance of the building. There is little to be gained by increasing the thickness beyond the amount required by structural requirements or the thickness determined to give the maximum diurnal heat capacity, whichever is greater. The latter is typically about 10 cm for lower density masonry materials and about 18 cm for high-density materials.

All of the above guidelines lead strongly to one conclusion: if there is a limited amount of mass that can be put in a space, it is much better to spread that mass thinly to achieve as large a surface area as possible.

CONVECTION

Simple Doorway Convection

Convection through doorways can be estimated from the following relation (Weber and Kearney, 1980):

$$Q = 63.5\, w(d\Delta T)^{3/2} \quad . \tag{8}$$

where
Q = heat flow, W,
w = doorway width, m,
d = doorway height, m, and
ΔT = room-to-room temperature difference, °C.

Based on this equation, we can develop a relationship for the steady-state temperature difference between one room and an adjacent room. Consider the simple case of a room that is heated only by convection through a doorway from an adjacent space at a steady temperature. The room loses heat to a steady outside temperature through a fixed loss coefficient. In this case the solution is very simple. The energy balance is as follows:

$$Q = 63.5\, w[d(T_d - T_r)]^{3/2} = LC\,(T_r - T_a) \quad , \tag{9}$$

LC = loss coefficient, W/°C; T_d = driving temp., and

T_a = ambient temp.; T_r = room temp.

The solution to this equation gives the room-to-room temperature difference as a function of the room-to-outside temperature difference for different values of the load/door ratio (LDR).

$$\Delta T = T_d - T_r = \left|[LDR\,(T_r - T_a)/63.5]^2/d\right|^{1/3} \quad , \tag{10}$$

$LDR = LC/(wd)$, the load/door ratio (W/°C m²) .

If the door height is specified, the equation can be represented graphically as shown in Fig 3. This graph can be used as a design aid for determining the necessary door size for a particular given inside/outside temperature difference. Equation (10) is not very sensitive to door height.

Detailed numerical experiments were carried out to determine the validity of Eq. (10) under time-varying conditions. The conclusions (Balcomb, 1981) are as follows:

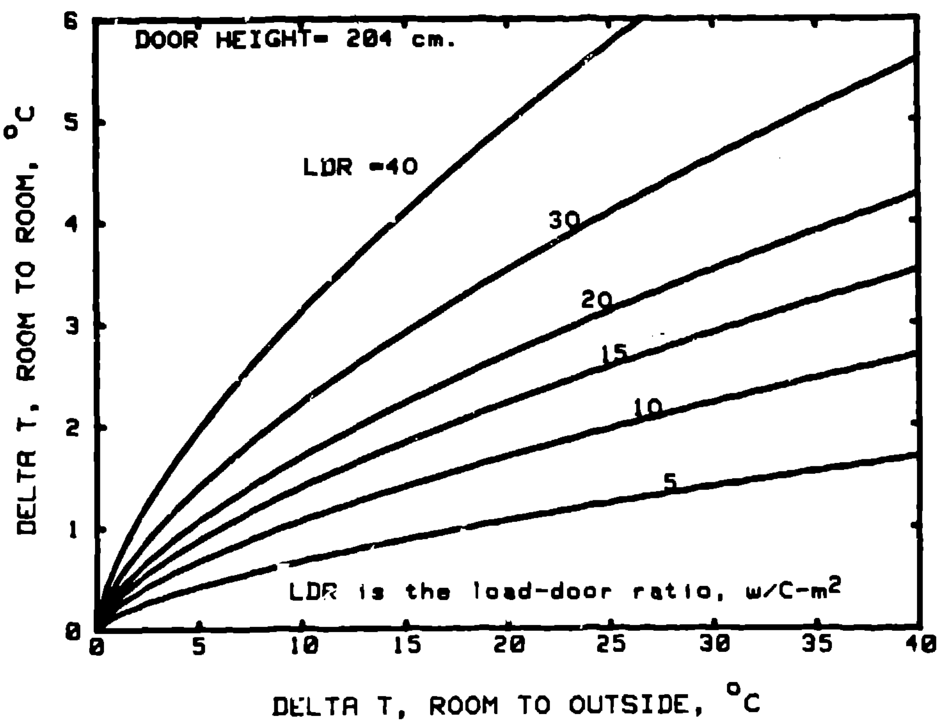

Fig. 3. Steady-state results for air flow through a doorway to a remote room. The curve shows the average temperature difference between the driving room and the remote room as a function of the average temperature difference between the remote room and the outside and the load/door ratio (LDR). The LDR is the ratio of the heat loss coefficient of the room to the door area. The curves are drawn for a standard height door.

- Convection through doorways is a very effective way of heating remote rooms. Quite reasonable temperature differences between the driving room and the remote room can be maintained.
- The steady-state solution given in Eq. (10) or Fig. 3 gives good indication of the 24-h average temperature differences that can be expected under most conditions.
- The effect of large variations in the driving temperature is advantageous, generally decreasing the difference between the average temperature in the driving room and in the remote room. Temperature swings in the remote room are always less than the driving room.
- If the temperature swing in the driving room is quite large, as in the case of an attached sunspace, properly operating the door can improve the situation, decreasing the ΔT. The door should be open during the day and closed at night.
- Heat storage in the remote room is quite important if the driving temperature swing is large. Insufficient mass will lead to excessive temperature swings.

Convective Loops

Discussion of Principles. Up to this point the discussion has concerned simple convection through doorways into rooms with a single opening. In this case, all of the air that enters the room through the top of the doorway must exit through the bottom of the same doorway.

Convective loops can also involve several rooms in the building. It is the purpose of this section to discuss this type of loop, especially in situations of multistory buildings with a sunspace.

A simple convective loop is shown in Fig. 4. In this example, a two-story sunspace is attached to a two-story house. The convective loop is made up of air that flows through openings into the sunspace at the upper level, down the stairway from the upper level to the lower level, and back into the sunspace at the lower level.

One way to describe such a loop is as a "heat engine." Figure 5 shows this schematically. Heat is added in the south side of the loop, and the same amount of heat is withdrawn on the north side. Air flows around the loop because of the difference in densities between the south leg and the north leg. In fact, we can calculate the flow rate based on the difference in average temperatures between the two legs. It is also possible for heat to be removed along the top leg of the loop; this is particularly effective in driving the loop because it increases

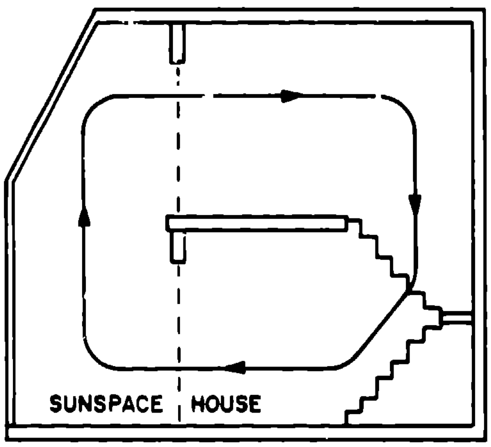

Fig. 4. Typical convective loop in a two-story house with a sunspace and stairway.

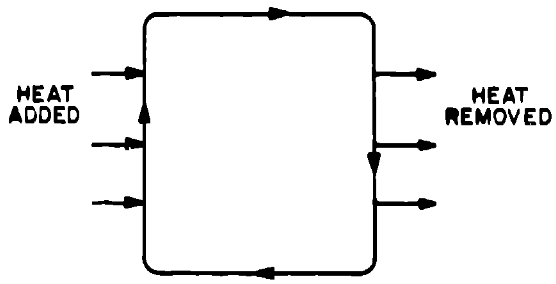

Fig. 5. "Heat engine" representation of a convective loop. The "engine" is the air motion and the mechanism driving the engine is heat added on one side and heat removed on the other side. Note that this heat engine is as dependent on the heat removal as on the heat addition.

the average density along the vertical north leg. Lastly, it is possible for heat to be removed along the bottom return leg; this is not very effective in driving the loop because it does not contribute to the increased density in the north vertical leg.

Although most convective loops that exist in present-day buildings are inadvertent (that is, they were not purposely designed into the building to cause convective heat exchange), it is certainly possible for the designer to consciously arrange the layout of internal spaces to aid in heat distribution. As in most design situations, this will probably result in a better functioning building than if the designer relies on luck.

The normal ingredients in a building convective loop are hallways, stairways, other rooms in the building, and doorways connecting these spaces. It is usually desirable to be able to stop the convective loop to prevent reverse flow at night. This is particularly true in sunspace situations; it is easily accomplished by providing a closable door in the openings at the top and bottom of the sunspace.

Convective loop results. Air velocity and temperature measurements have been made in six buildings that incorporate natural convective loops involving a sunspace and other architectural features. These measurements have been made near midday during relatively sunny weather. The results are still being analyzed and will be reported in detail in future Los Alamos reports. Balcomb (1983) shows the results from one building.

The results have been very encouraging, indicating large convective energy exchange. A summary of these results for a few houses is given in Table 2.

TABLE 2 Summary Convection Data

Sunspace Height	Sunspace Glazed Area	Sunspace-to-House			
		Connecting Doorway Area	Typical ΔT	Total Air Flow	Energy Transport by Convection
# of Stories	m^2	m^2	°C	m^3/min	kW
2	37	7.4	3.3	47	5.18
1	17	2.9	1.7	19	0.17
2	38	10.6	2.8	63	4.54
2	53	4.5	5.6	47	6.18
1.5	29	5.9	2.2	29	1.50

Design Guidelines. Although the work described here is still in progress and certainly far from complete, certain design guidelines emerge clearly. It is evident that a major amount of heat can be stored inside a house resulting from convection from a sunspace. The major driving mechanism for this convection is the heat engine, driven by heat from the sun on one side and heat removed by the walls on the opposite side. If the designer is fully aware of the principles involved, the design can benefit most from effective convective exchange.

The key design factor is to lay out the building so that the convective loops can operate effectively. This can usually be done without architectural compromise.

In fact, in most cases studied, no conscious attempt to achieve a convective loop was made; it resulted, strictly in serendipitous fashion, from architectural considerations.

In designing for a convective loop within the building, the designer should try to use natural elements of the building as much as possible. Do not try to contrive a convective loop for its own sake but rather try to work it in with normal architectural considerations. The following list gives design hints for the convective loop, starting with the source of heat and moving around in the same direction as the air flow.

- A sunspace makes an excellent heat source to drive the convective loop. Because the flow velocity varies as the square root of the height, it is desirable to make the space as high as practical. A two-story building with a two-story sunspace has been found to work very effectively; even greater heights would probably work even better, although the tendency for temperature to stratify in the top of the building might be exacerbated. A dark-colored mass wall at the back of the greenhouse will aid in absorbing the sun and will heat the air as it rises.

- Provide a large opening at the top of the sunspace for the air to enter the upper story. Doors are excellent for this purpose, although large operable windows can also be used. Doors are preferable because they are larger and are more apt to be used. A shallow balcony opening out into the top level of the sunspace is excellent for this purpose. During sunny weather it will probably not be necessary to close these openings during the night because closing other openings at the return end will effectively shut off the convective loop.

- Provide for air flow across the upper level of the house from the south side to the north side of the building. This is most conveniently done using a hallway, although other rooms can also be used.

- Provide for downflow of air in the north part of the house. A stairwell serves this purpose ideally. The fact that the air may have to bend around corners to get across the building and down the stairs and into the lower portions of the building is of no great concern so long as the flow area is adequate. In fact, the scrubbing action of the air against the surfaces may increase the heat transfer. It is desirable for this path to be against the north wall of the house so that the convective loop can effectively supply the heat lost.

- Arrange for return of the air flow through the lower floor of the house and back into the solar heat source room. Again, this might be through a hallway or simply across a room. It is essential to provide an operable doorway or other opening that can be closed in this portion of the path. This prevents cool air from the sunspace from flowing back into the building, tending to reverse the loop at night.

- Provide one or more level changes at the ground floor, stepping down from the north side of the house toward the south. This makes the floor level of the solar gain room (sunspace) the lowest point in the ground-floor level of the building. One or two steps should be sufficient.

CONCLUSIONS

Diurnal heat capacity provides a useful measure of the heat storage capacity of a direct gain room during periodic clear-day weather. It can be used to estimate temperature swings yielding answers in good agreement with simulation analysis.

Closed-form solutions for the diurnal heat capacity of layered walls can be obtained. Methods of categorizing room internal wall surfaces and computing the diurnal heat capacity of an entire room are given.

Convection, either through single doorways or through interconnected building spaces, is a predictable and effective means of distributing heat to remote spaces. Mass within those spaces can be used effectively for storing this heat. However, air convection is nonlinear and, therefore, estimation of the diurnal heat capacity of remote spaces must be done cautiously; it may be that such estimation will require simulation analysis.

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