Thermal Mass

The use of thermal mass in passive solar houses is conceptually simple: mass materials, such as brick or concrete, store and later release heat energy entering through the passive aperture (south-facing glazing area). When properly used, thermal mass prevents stifling daytime overheating and chilly nighttime temperatures in the living space. Improperly used, however, thermal mass may be ineffective.
Total Environmental Action, Inc. (TEA) has discovered through consulting and reviews of hundreds of passive solar homes that, while designers often incorporate correct total quantities of mass, the location and configuration is often not adequately treated. In order to help architects, designers, and builders create more efficient passive solar homes, TEA has brought together a number of existing rules-of-thumb for sizing thermal mass and prepared them as architectural patterns.

How to Use This Booklet

Five patterns are shown. Each is a basic architectural configuration of thermal mass often found in passive solar homes. For each of these patterns, four interrelated factors describing the sizing characteristics of the thermal mass system are given in a mass sizing table:

1. The passive solar aperture area
2. The mass surface area
3. The mass material type
4. The mass thickness

Depending on which of these variables is assumed fixed, the designer can use the patterns in a number of ways. Turn to Pattern 1 on page 3. In this configuration, for example, 3-inch thick concrete requires 5 square feet of surface area for each square foot of aperture area. If the aperture area is known, it can be multiplied by that number to identify the total mass surface area required. For example, if the total aperture area is fixed at 100 square feet, then 500 square feet (5 x 100) of 3-inch thick concrete would be necessary.

Conversely, if the total surface area of the mass is fixed, it could be divided by the number in the table to determine the allowed aperture. In this instance, if you plan to use 500 square feet of 3-inch concrete in a Pattern 1 configuration, then the total allowed aperture area will be 100 square feet. Thus, the tables can be used to make trade-offs between aperture area and mass surface area, or to try out optional configurations for the system by using a different pattern.

Finally, the type and thickness of various mass materials for each configuration and aperture size can be evaluated. In this way; a number of complete systems can be quickly sized so that cost and other design implications can be seen. Note that the term "allowed aperture area" refers only to the mass configuration being analyzed.

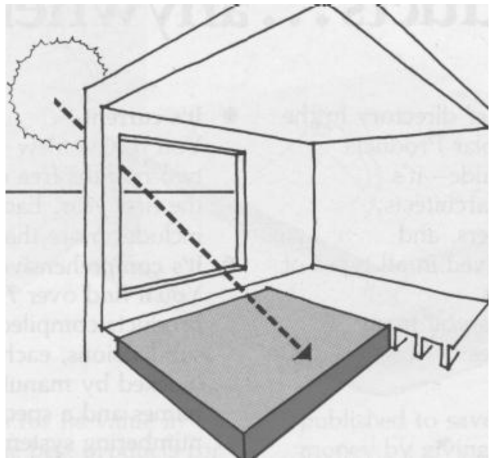
In an actual passive building, several types and configurations of mass combine to store heat and prevent overheating. Using the patterns, each of these can be analyzed separately and a total "allowed aperture" for the building derived. Later in this booklet, a simplifying assumption to account for normal residential wall finishes, furniture, etc. is given so that in preliminary analysis the designer can focus on the specific house elements that are used for heat storage.

Note also that these tables were developed for an assumed optimal performance for the thermal mass. The penalty for using more than the allowed aperture area is some degree of overheating. This can result in reduced efficiency of the passive system if the overheating causes the occupants to open windows and vent heat that might otherwise be stored to offset nighttime heating loads.

In some situations it may be necessary to interpolate between Patterns 1 and 2 to determine the amount of mass area. It is important to note whether each type and configuration of mass is exposed to sunlight all day long or for only part of the day. If it is exposed all day (i.e., about six hours), Pattern 1 numbers apply. If it is exposed none of day, Pattern 2 applies. If, however, the mass is exposed for only a fraction of the day, follow these steps:

Interpolation procedure	**Example**
1. Determine the mass material and thickness	Assume 6-inch thick concrete
2. Identify the required surface area from Pattern 1.	3
3. Identify the required surface area from Pattern 2.	5
4. Subtract the Pattern 1 number from the Pattern 2 number.	5 – 3 = 2
5. Determine the fraction of the day the mass is exposed to the sun.	Assume $^{1}/3$ of the day (i.e., about 2 hours)
6. Multiply that fraction by the result	2 x $^{1}/3$ = $^{2}/3$ in Step 4.
7. Subtract the number identified in Step 6 from the number identified in Step 3	5-(2/3) = 4$^{1}/3$
8. The resulting number equals the square feet of mass surface area required for each square foot of passive aperture.	4$^{1}/3$ square feet of 6-inch thick concrete are needed for each square foot of passive aperture

Pattern 1: Floor or wall in Direct Sunlight.

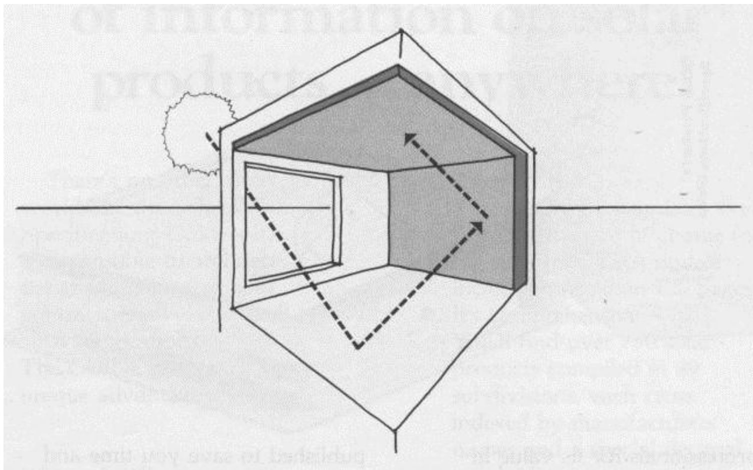


This pattern is defined as thermal mass that has one surface exposed to the living space and a "back surface that is insulated. The exposed surface is further defined as being in direct sunlight for at least six hours a day. Architecturally, this pattern combined with Pattern 2 is useful for direct gain passive rooms. The mass can be either a directly irradiated floor slab as shown, or a directly irradiated exterior wall. As with Patterns 2 and 3, the mass element is one-sided, that is, heat moves into and out of the mass from the same surface.

Mass Sizing Table

Material Thickness	Directly Irradiated Mass Surface Area to Passive Aperture Area Ratio				
	Concrete	Brick	Gypsum	Oak	Pine
1/2 "			76		
1"	14	17	38	17	21
1 1/2 "			26		
2"	7	8	20	10	12
3”	5	6		10	12
4"	4	5		11	12
6"	3	5		11	13
8"	3	5		11	13

Pattern 2: Floor, Wall or Ceiling in Indirect Sunlight.



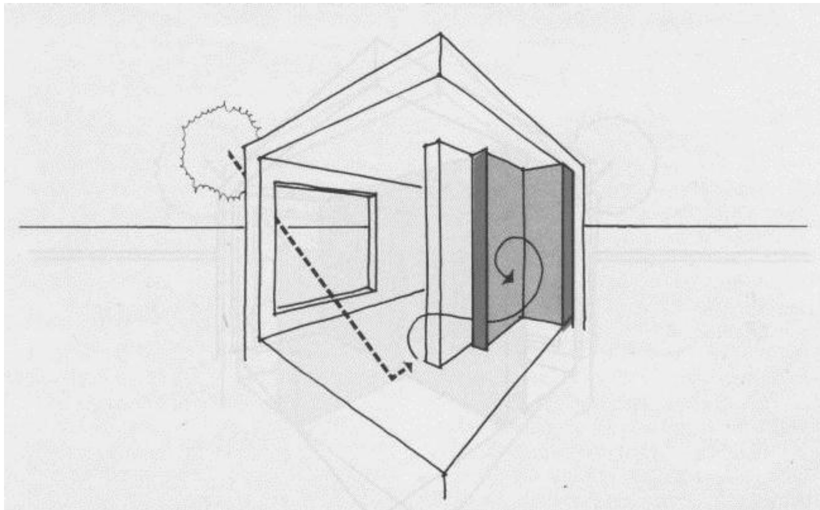
The mass in this pattern is defined in the same way as in Pattern 1, that is, the mass is one-sided and insulated on the back side. The distinction here is that the mass is not receiving direct beam radiation, but rather reflected sunlight. In a simple direct gain space, some of the mass will be a Pattern 1 case (perhaps a floor slab near the aperture, for example), and some mass will be a Pattern 2 case (perhaps the ceiling, for example). Much of the mass in such a space will be directly irradiated some of the time and indirectly sunlit for the rest of the day. In these cases an interpolation between Patterns 1 and 2 must be carried out, as described earlier.

Mass Sizing Table

Indirectly Irradiated Mass Surface Area to Material Passive Aperture Area Ratio

Thickness	Concrete	Brick	Gypsum	Oak	Pine
1/2"			114		
1"	25	30	57	28	36
1 1/2"			39		
2"	12	15	31	17	21
3"	8	11		17	20
4"	7	9		19	21
6"	5	9		19	22
8"	5	10		19	22

Pattern 3: Floor, Wall or Ceiling Remote from Sunlight.

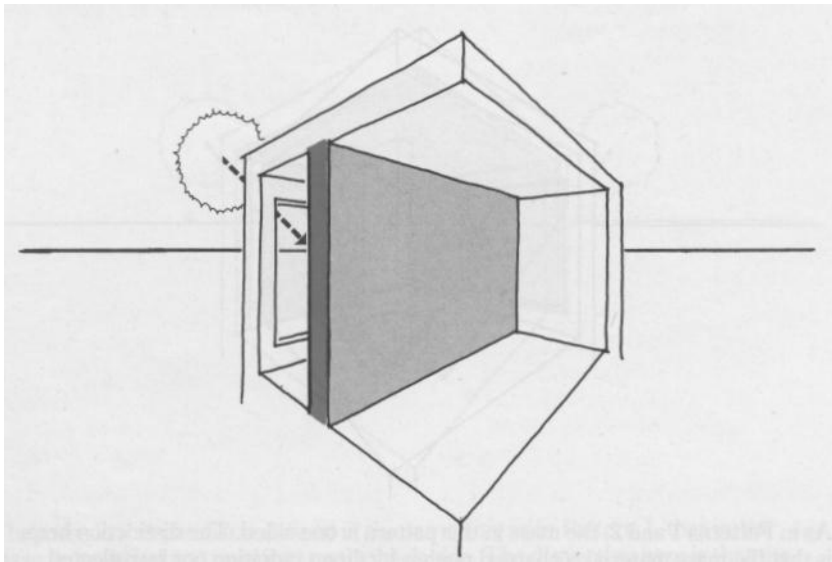


As in Patterns 1 and 2, the mass in this pattern is one-sided. The distinction here is that the mass material is charged neither by direct radiation nor by reflected radiation, but rather is heated by the room air that is warmed as a result of solar gains elsewhere in the building. Architecturally, this pattern is useful for mass materials in spaces deeper within a passive building, away from the rooms receiving solar gains. However, the solar-heated air must reach the remote mass either by natural or forced convection. Reasonable judgement is required here-a hallway open to a south room could be included; a back room totally closed off from the solar heated spaces could not be included.

Mass Sizing Table

Material Thickness	Remote Mass Surface Area to Passive Aperture Area Ratio				
	Concrete	Brick	Gypsum	Oak	Pine
1/2"			114		
1"	27	32	57	32	39
1 1/2 "			42		
2"	17	20	35	24	27
3"	15	17		26	28
4"	14	17		24	30
6"	14	18		28	31
8"	15	19		28	31

Pattern 4: Mass Wall or Waterwall in Direct Sunlight

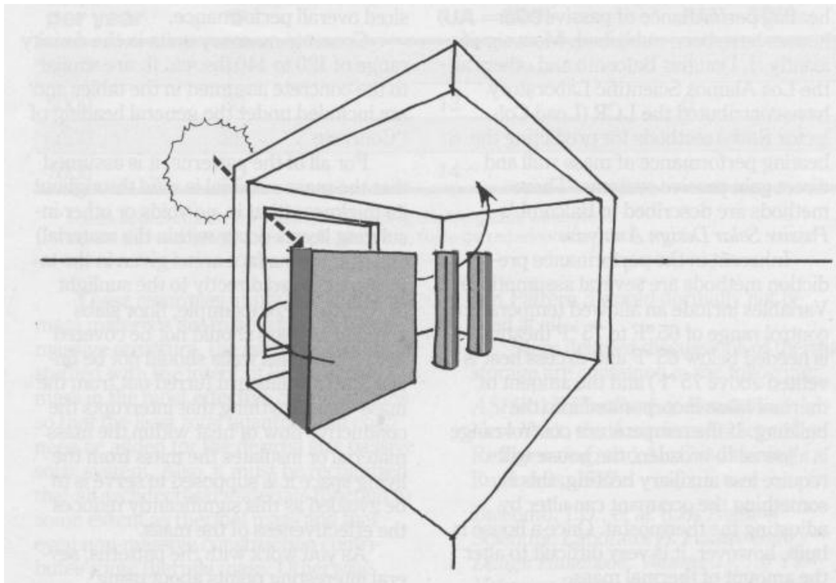


This pattern is defined as a wall of massive material that is directly irradiated on one side and exposed to the living space on the other side. Further, the wall is defined as being continuous from sidewalk to sidewall and from floor to ceiling; the sunlit side is isolated from the living space side. This pattern is useful for Trombe walls where a high temperature on the sunlit side causes no discomfort since the space between the wall and the aperture is not a living space. The mass wall may have high and low vents or be unvented as shown without affecting the values in the table. Generally, the performance of the wall improves with thickness up to about 18" but is not very sensitive to variations in thickness within normal buildable ranges. For sunlit mass walls of brick, higher density bricks (water absorption less than 6%) are recommended over bricks of lower density. Note that the "mass surface area" refers to the sunlit side only.

Mass Sizing Table

Material	Irradiated Mass Surface Area to Passive Aperture Area Ratio
Brick 8" Thick	1
Concrete 12" Thick	1
Waterwall 8" Thick	1

Pattern 5:
Partial Mass Wall or Water Containers in Direct Sunlight.



This pattern is similar to Pattern 4 in that the mass is directly irradiated on one side and exposed to the living space on the other side. The distinction in this pattern is that there is free air circulation around the mass material so that heat may be gained to the living space from either side of the partial wall (or from all sides of a water container). Architecturally, this may represent a freestanding mass wall or a series of water containers located within a direct gain space. Unlike Pattern 4, the space between the mass element and the aperture is considered part of the living space of the room. The mass is assumed to be directly irradiated for the entire solar day (6 hours). Like Pattern 4, the wall thicknesses listed are not very sensitive to variations, and the wall surface area listed is for one side of the wall only. Water containers are listed as gallons per square foot of aperture.

Mass Sizing Table

Irradiated Mass Surface Area Material to Passive Aperture Area Ratio

Brick	2
8" Thick Concrete	2
6" Thick Watertubes or Drums	At least 7 gallons of water per square foot of passive aperture.

Notes and Assumptions

Several methods for predicting the heating performance of passive solar houses have been published. Most significantly, J. Douglas Balcomb and others at the Los Alamos Scientific Laboratory have contributed the LCR (Load Collector Ratio) methods for predicting the heating performance of mass wall and direct gain passive systems. These methods are described in Balcomb's *Passive Solar Design Analysis.*

Inherent in the performance prediction methods are several assumptions. Variables include an allowed temperature control range of 65 °F to 75 °F (heating is needed below 65 °F and excess heat is vented above 75 °F) and the amount of thermal mass incorporated into the building. If the temperature control range is allowed to broaden, the house will require less auxiliary heating; this is something the occupant can alter by adjusting the thermostat. Once a house is built, however, it is very difficult to alter the amount of thermal mass.

The effective thermal mass capacity, or a material's ability to store and release heat on a daily basis, can be measured using Balcomb's methods. Not all configurations of materials are effective. For example, a directly exposed concrete wall or floor thicker than 8 inches will not reduce temperature swings in the living space beyond what would happen with only an 8-inch wall or floor. Material beyond the 8-inch thickness is simply too deep to participate in the daily storage and release of heat.

Balcomb's assumed thermal properties were used for concrete, brick, and pine wood. The values for oak and gypsum were taken from the 1977 *ASHRAE Handbook of Fundamentals.* The values assumed for solar absorptance were: concrete a = 0.8, brick a = 0.8, gypsum a = 0.5, oak and pine a = 0.7. As with any other rules-of thumb, some variations in actual material properties can be expected in an actual constructed system. Further, variations in properties such as absorptance and density can be consciously altered by the knowledgeable designer to achieve a desired overall performance.

Concrete masonry units in the density range of 120 to 140 lbs./cu. ft. are similar to the concrete assumed in the tables and are included under the general heading of "Concrete".

For all of the patterns, it is assumed that the mass material is *solid* throughout its thickness (that is, no voids or other insulating layers occur within the material) and that the surface areas given in the tables are *exposed* directly to the sunlight or room air. For example, floor slabs counted as mass should not be covered with rugs; mass walls should not be finished with wallboard furred out from the mass wall. Anything that interrupts the conductive flow of heat within the mass material or insulates the mass from the living space it is supposed to serve is to be avoided as this significantly reduces the effectiveness of the mass.

As you work with the patterns, several interesting points about using thermal mass effectively will become evident. For example, in the simplest case of directly irradiated mass materials, Pattern 1, some very different architectural materials have an equivalent performance as effective thermal mass:

20 square feet of 2-inch thick gypsum,
3 square feet of 6-inch thick concrete, and
5 square feet of 4-inch thick brick.

All of the above represent the correct amount of thermal mass for one square foot of solar aperture. Notice also that the effectiveness of the mass is directly related to its location. For example, using 4-inch brick as the mass material, the following mass surface areas are required for each square foot of aperture:

5 square feet if located in direct sunlight (Pattern 1), 9 square feet if located in indirect sunlight (Pattern 2), and 17 square feet if remotely located (Pattern 3).

Degree Days per year	Average January Temperature °F	Percent Floor Area Allowed in Glass Average House* (UA = 600)	Well Insulated House** (uA = 300)
4000	40	11	6
5000	30	13	6
6000	25	13	7
7000	20	14	7

*equals approximately R-1 1 walls, R-1 9 ceiling, double-glazed windows
**equals approximately R-25 walls, R-38 ceiling, triple-glazed windows

These examples imply that if thermal mass materials are to be *added* to a nonmassive structure, the patterns should be studied with the intent of locating the mass in the most effective configurations so that the least total quantity (and cost) need be added for the desired size passive solar system. Also, it must be recognized that all architectural materials function to some extent as thermal mass and that even non-massive construction contributes some thermal mass. Otherwise, even non-solar houses with very small aperture areas would overheat on a sunny day. The values for basic construction materials, such as ½”¯inch gypsum board, are included in the mass sizing tables so that these materials can be considered.

TEA's experience with well-insulated, light frame houses suggests that additional thermal mass is not necessary to prevent overheating when the solar aperture is less than a particular percentage of the floor area. This is related to climate it the table above.

As a very rough first approximation of mass requirements for a large aperture passive solar system, the designer can simply subtract from the total aperture at an amount equal to the percentage of the floor area from the above table and use the patterns for added thermal mass in relation to the remaining solar aperture. This shortcut is useful for residential light frame construction and takes into account normal home furnishings and wallboard finishes. If this method is used, gypsum board, for example, would not be evaluated using Patterns 1 or 2, and Pattern 3 would normally not be used at all.

More detailed discussions of thermal storage are contained in the following:

ASHRAE Handbook of Fundamentals. New York, the American Society of Refrigerating, and Air Conditioning Engineers, 1977.

Balcomb, J.D., et al. (Los Alamos Scientific Laboratory). *Passive Solar Design Handbook, Volume Two of Two Volumes: Passive Solar Design Analysis.* U.S. Department of Energy, 1980. (Available from NTIS, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161. $14.00)

Fuller, Winslow and Lewis, Daniel. "Overheating in Light and Heavy Mass Houses." *Proceedings of the Third National Passive Solar Conference.* San Jose, CA, 1979.

Lewis, Daniel; Michal, Charles; and Pietz, Paul (Total Environmental Action, Inc.). *Design of Residential Buildings Utilizing Natural Thermal Storage. U.S.* Department of Energy, 1979. (Available from NTIS, see address above. $14.00)

Total Environmental Action, Inc. *The Brookhaven House.* TEA, 1979. (Available from TEA, Church Hill, Harrisville, NH 03450. $2.00)

Wilson, Alex. *Thermal Storage Wall Design Manual.* New Mexico Solar Energy Association, 1979. (Available from NMSEA, P.O. Box 2004, Santa Fe, NM 87501.$4.00)