Thermal Mass

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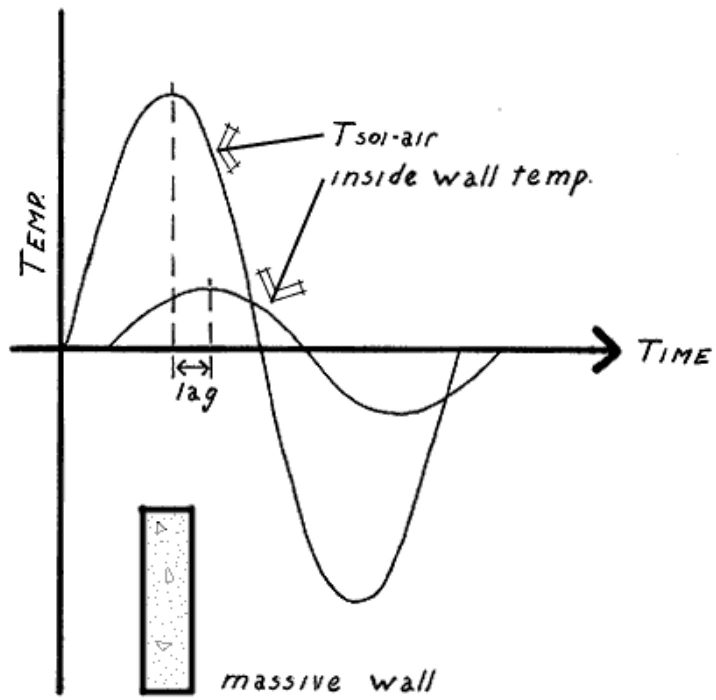
Thermal Mass

- Thermal mass refers to materials have the capacity to store thermal energy for extended periods.

- Thermal mass can be used effectively to absorb daytime heat gains (reducing cooling load) and release the heat during the night (reducing heat load).



Types of Thermal Mass

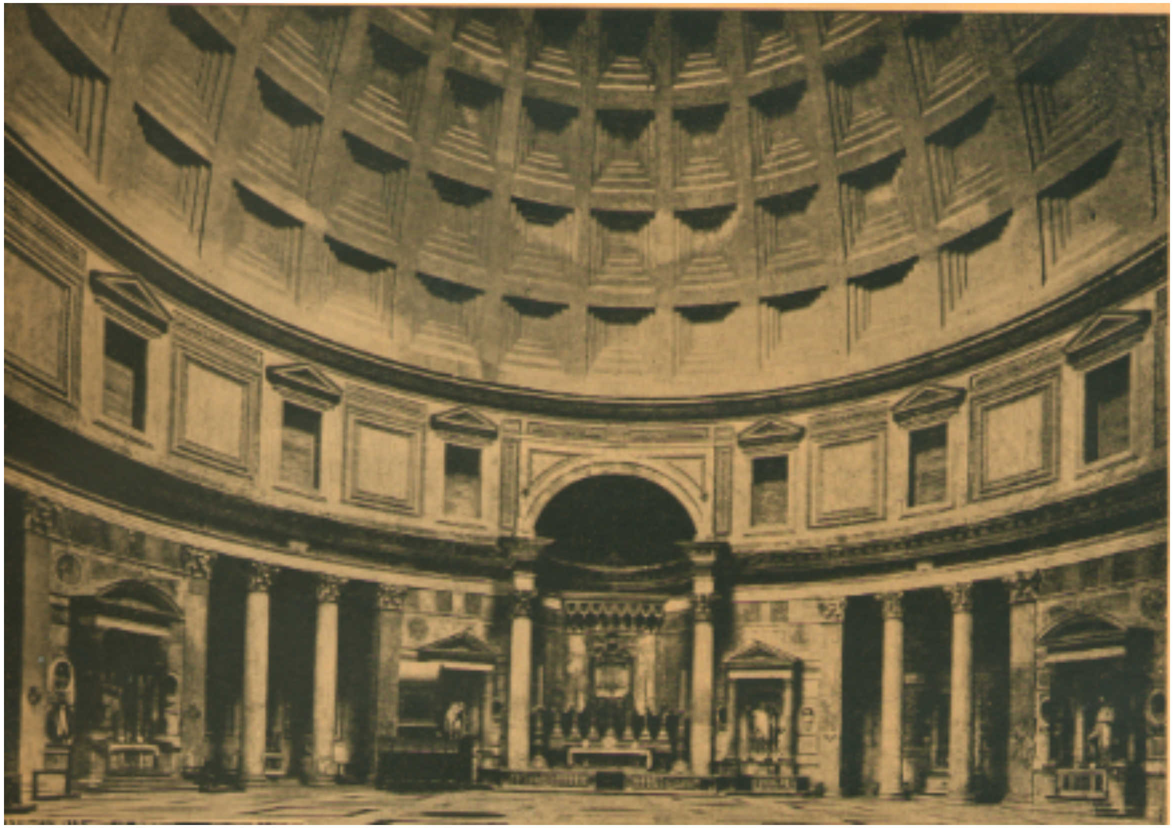
- Traditional types of thermal mass include water, rock, earth, brick, concrete, fibrous cement, caliche, and ceramic tile.
- Phase change materials store energy while maintaining constant temperatures, using chemical bonds to store & release latent heat.

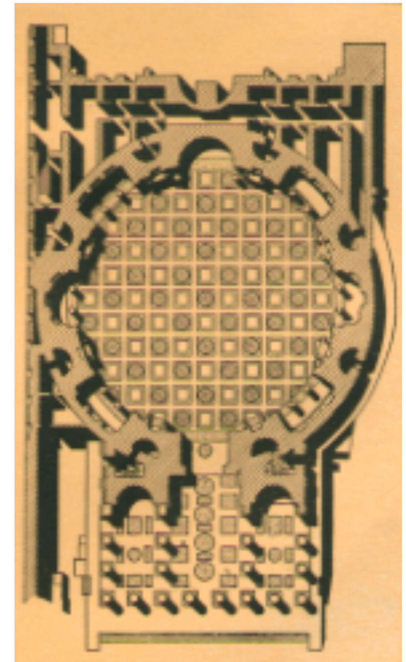
PCM's include solid-liquid Glauber's salt, paraffin wax, and the newer solid-solid linear crystalline alkyl hydrocarbons (K-18: 77°F phase transformation temperature). PCM's can store five to fourteen times more heat per unit volume than traditional materials. (source: US Department of Energy).

Historical Applications

- The use of thermal mass in shelter dates back to the dawn of humans, and until recently has been the prevailing strategy for building climate control in hot regions.

Egyptian mud-brick storage rooms (3200 years old).





The lime-pozzolana (concrete) Roman Pantheon

Today, passive techniques such as thermal mass are ironically considered “alternative” methods to mechanical heating and cooling, yet the appropriate use of thermal mass offers an efficient integration of structure and thermal services.

Thermal Properties of Materials

The basic properties that indicate the thermal behavior of materials are: density (p), specific heat (c_m), and conductivity (k).

The specific heat for most masonry materials is similar (about 0.2-0.25Wh/kgC).

Thus, the total heat storage capacity is a function of the total mass of masonry materials, regardless of its type (concrete, brick, stone, and earth).

Material	Density(kg/m3)
Concrete	600-2200
Stone	1900-2500
Bricks	1500-1900
Earth	1000-1500 (uncompressed)
Earth	1700-2200 (compressed)

Diffusivity

Diffusivity is the measure of how fast heat travels through the material, and is a function of the conductivity divided by the product of the density and specific heat (units: area/time). The time lag between outside and inside peak temperatures is a function of the thickness of the material divided by the square root of the diffusivity.

For solid masonry materials, conductivity can be approximated as a function of density, though precise values will vary according to moisture content : *k=0.072exp(1.35x(density/1000))*.

Using these relations, we find that diffusivity has a non-linear relation to density. For example, the diffusivity of 2200kg/m^3 concrete (k=1.3) is only 1.8 times the diffusivity of 600kg/m^3 (k=0.2) concrete.

Thermal Time Constant

One of the more important mathematical constructs to imagine the behavior of thermal mass is the Thermal Time Constant of an building envelope, defined as the product of the heat capacity (Q) and the resistance (R) to heat transmission. The TTC is representative of the effective thermal capacity of a building.

To calculate the TTC of an area, the heat capacity per unit area (Q_A) is multiplied by the resistance to heat flow of that area (where Q_A=thickness*density*specific heat, R=thickness/conductivity).

In calculating the TTC_A (TTC per area) of a composite wall, the Q_AR value of each layer, including the outside and inside air layers, is calculated in sequence. The Q_AR for each layer is calculated from the external wall to the center of the section in question, thus:

$Q_{Ai}R_i= (c_m*1*p)_i*(R_0+R_1+\ldots+0.5R_i)$

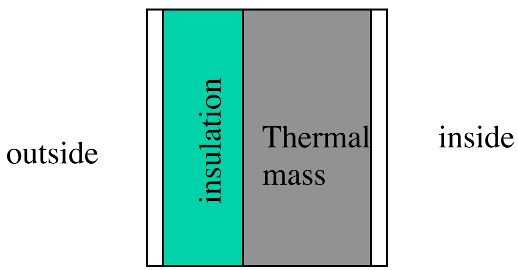
For a composite surface of n layers, $TTC_A=Q_{A1}R_1+Q_{A2}R_2+\ldots Q_{An}R_n$.

The TTC_s for each surface is the product of the TTC_A multiplied by the area. Glazed areas are assumed to have a TTC of 0. The total TTC_{total} of the buliding envelope equals the sum of all TTC_s divided by the total envelope area, including the glazing areas.

→ A high TTC indicates a high thermal inertia of the building and results in a strong suppression of the interior temperature swing.

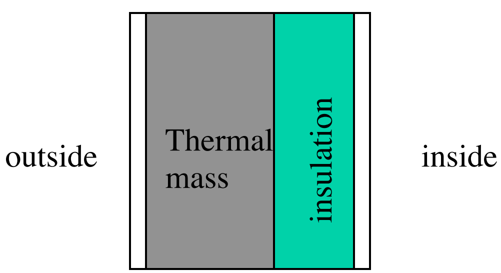
Example TTC Calculations

Wall 1: exterior insulation



TTC = 43.8

Wall 2: interior insulation



TTC = 7.8

TABLE 3-8. CALCULATION OF THE THERMAL TIME CONSTANT OF 2 WALLS (METRIC)

Wall #1

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Polystyrene	0.025	30	0.71	0.41	12	0.12
Concrete	0.10	2200	0.06	0.795	506	40.2
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						43.8

Wall #2

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Concrete	0.10	2200	0.06	0.085	506	4.3
Polystyrene	0.025	30	0.71	0.47	12	0.14
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						7.8

Source: Givoni

Diurnal Heat Capacity

The DHC is a measure of the building’s capacity to absorb solar energy coming into the interior of the space, and to release the heat to the interior during the night hours. The DHC is of particular importance for buildings with direct solar gain.

The DHC of a material is a function of building material’s density, specific heat, conductivity, and thickness. The total DHC of a building is calculated by summing the DHC values of each surface exposed to the interior air.

Note that the DHC for a material increases initially with thickness, then falls off at around 5”. This behavior reflects the fact that after a certain thickness, some of the heat transferred to the surface will be contained in the mass rather than returned to the room during a 24 hour period.

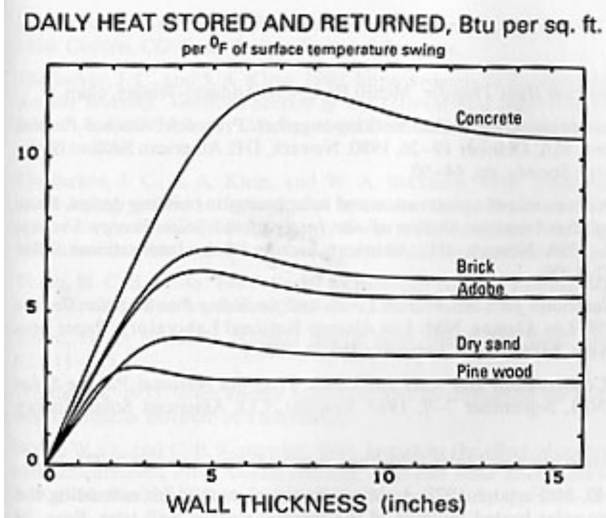


Figure 4.9
Diurnal heat capacity vs. thickness for various storage media. Source: Balcomb

$$s = \sqrt{Pk\rho c/2\pi},$$
$$F_1 = \sqrt{(\cosh 2x - \cos 2x)/(\cosh 2x + \cos 2x)},$$
$$x = L\sqrt{\pi\rho c/Pk},$$

$$DHC_{\text{per area}} = F_1 s$$

P=period (24hr.)

TTC and DHC

Relative values of TTC indicate the thermal capacity of the building when a building is affected mostly by heat flow across the opaque parts of the envelope (i.e., when it is unventilated, and when solar gain is small relative to the total heat transfer through the building envelope).

Relative values of DHC, on the other hand, indicate the thermal capacity for buildings where solar gain is considerable. The DHC also is a measure of how much "coolth" the building can store during the night in a night ventilated building.

Both measures indicate the amount of interior temperature swing that can be expected based on outdoor temperatures (higher values indicate less swing).

Delta T(swing)= $0.61Q_s/DHC_{total}$,

Q_s is the daily total solar energy absorbed in the zone.

TTC and DHC Examples

Building which is externally insulated with internal exposed mass.

Here, both TTC and DHC are high. When the building is ventilated at night and closed during the day, it can absorb the heat in the mass with relatively small indoor temperature rise. Best for hot-dry regions.

Building with mass insulated internally.

Here, both the TTC is and DHC are low. The mass will store energy and release energy mostly to the exterior, and the thermal response is similar to a low mass building.

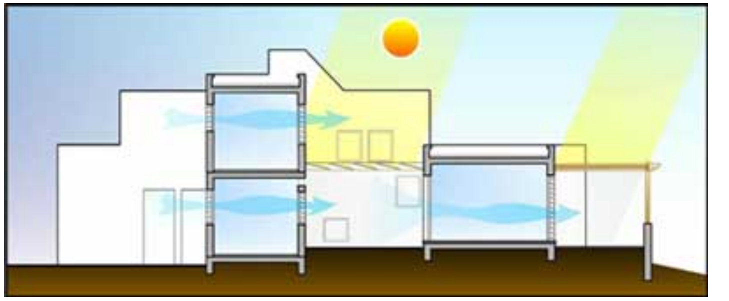
Building with high mass insulated externally and internally.

Here, the building has a high TTC, but a negligible DHC, as the interior insulation separates the mass from the interior. When the building is closed and the solar gain is minimized, the mass will dampen the temperature swing, but if the building is ventilated, the effect of the mass will be negated. With solar gain, the inside temperature will rise quickly, as the insulation prevents absorption of the energy by the mass.

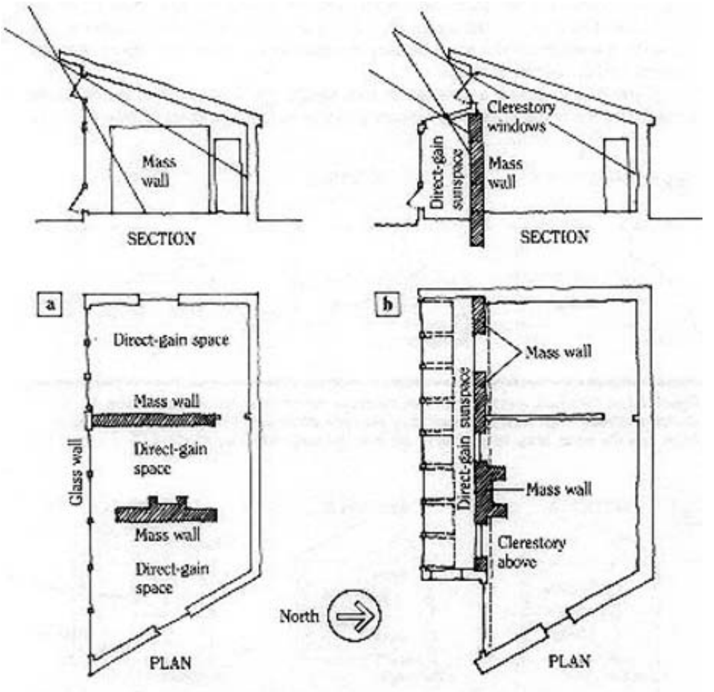
Building with core insulation inside two layers of mass.

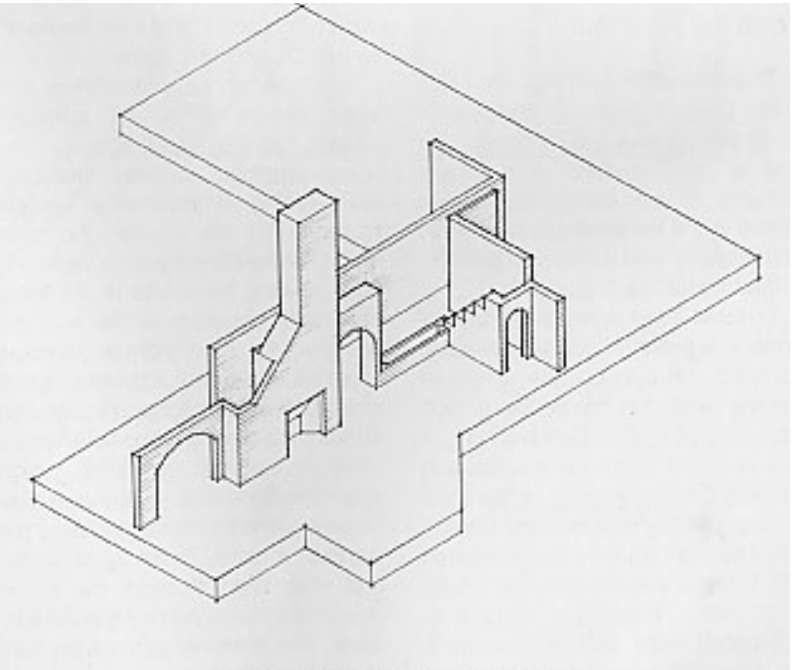
Here the TTC is a function of mostly the interior mass and the amount of insulation, and the DHC is a function on the interior mass. The external mass influences heat loss and gain by affecting the delta T across the insulation.

Strategies



Slow rate of indoor heating in summer (minimize solar gain).
Fast rate of indoor cooling and ventilation in summer evenings.
Higher indoor temperatures during the day in winter.
Slow release of stored heat during winter night.





Brick and masonry thermal spine

Rules of Thumb

- Windows:

Mass surface to solar aperture ratios between 6:1 to 3:1 for passive solar heated and cooled buildings (more south facing glazing in cold areas, less glazing in hot areas).

- Amount of mass (Givoni):

Mass per square meter= $10(T_{max}-T_{min}) + 0.5\ a^*I_{max}$

- Insulation (Givoni):

$R=0.05(T_{max} -25) + 0.002\ (a^*\ I_{max})$ Walls

$R=0.05(T_{max} -25) + 0.002\ (a^*\ I_{max})$ Roof

Other Factors to Consider

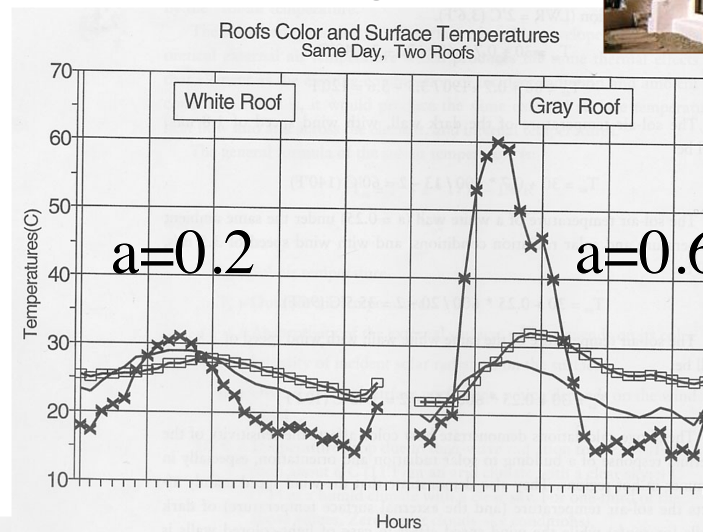
- Hygroscopic & vapor diffusion properties, enthalpic response
- Ventilation, convective heat exchangers, and evaporative cooling methods
- Insulative additives to cast thermal mass
- Fire resistance, earthquake behavior, and building codes
- Acoustics
- Life Cycle Analysis

Figure 5-5. *The Arizona test building with the evaporative cooling solar chimney (left) and a tower (right).*

Absorption and Emission

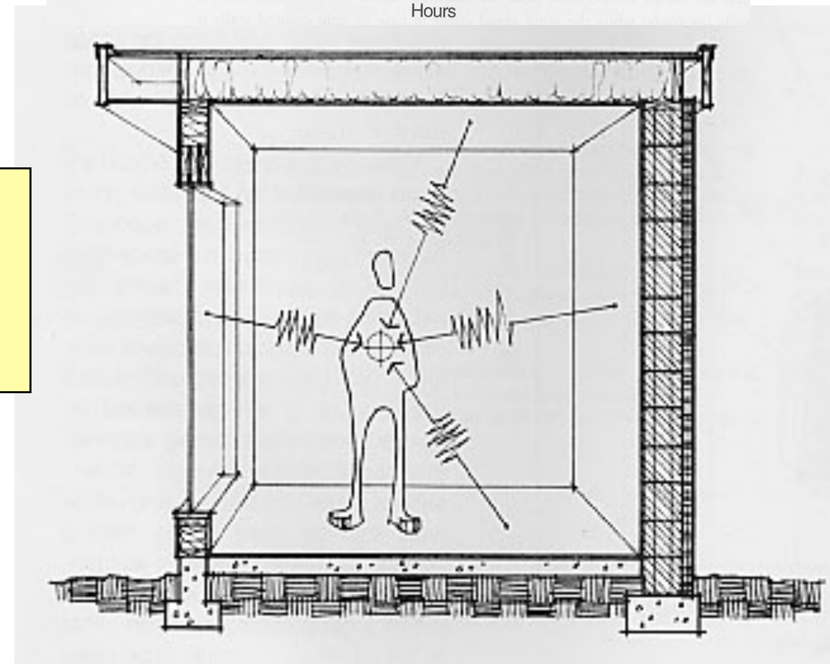
•Absorptivity (a) and emissivity (e) are properties of a material which determine radiant exchange of a surface with its environment. Exact values depend on wavelength.

•Absorptivity is the main factor in determining the temperature response to short-wave (solar) radiation, and is dependent largely by color.



$T_{sol\text{-}air} = T_o + (a*I/h_o)$ - LWR where I is the incident solar radiation, h_o is the external surface coefficient, and LWR is a function of the long-wave radiation to the sky (~6^o for clear sky, 0^o for cloudy sky).

•Emissivity is the main factor which determines the response to long wave (thermal) radiation. Generally e = 0.9 for non-metallic surfaces.

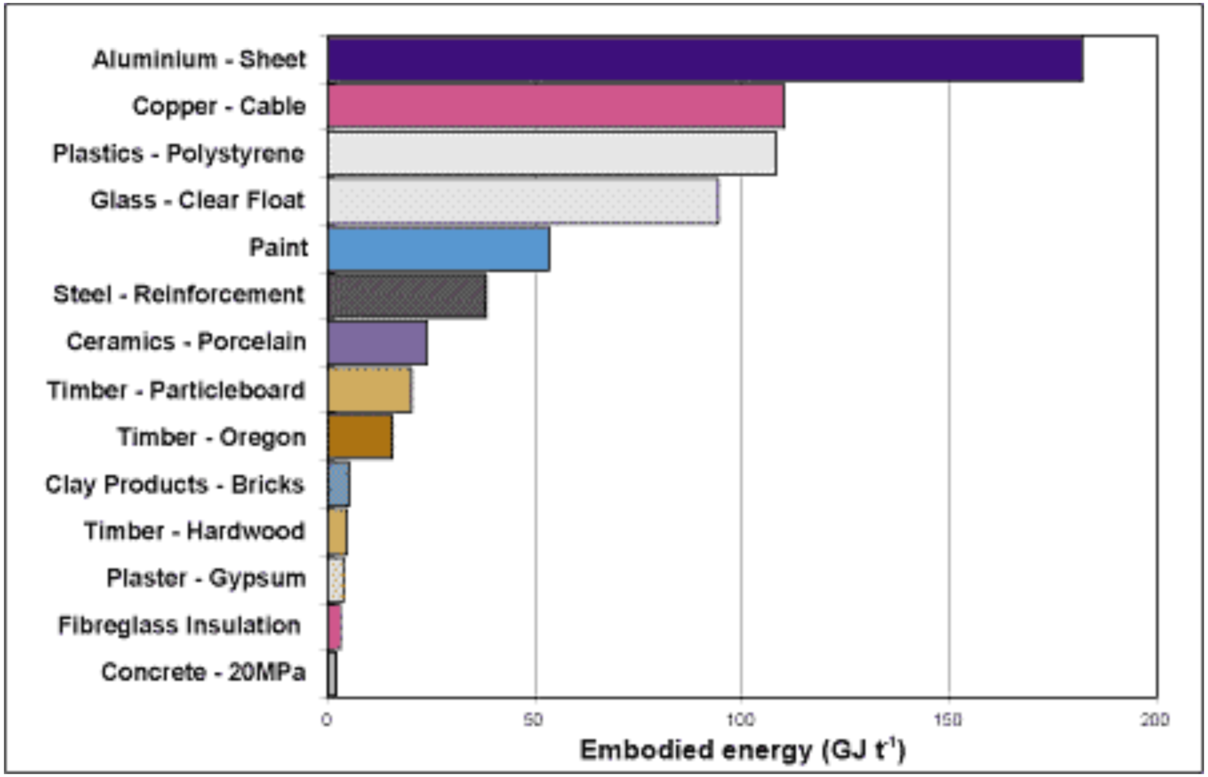


Mean radiant temperature (MRT) is the weighted average of the various radiant surfaces within a space.

•UV: <400nm Visible: 400-760nm Infared: 760-3000nm

•Thermal: 3000-20,000nm Metals e=0.05 Radiation =f(e,A,T^4)

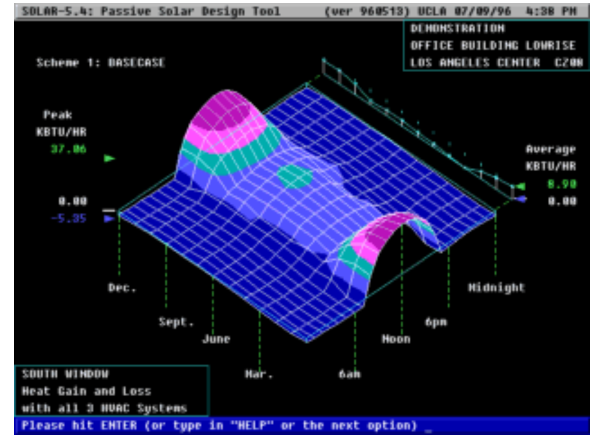
Building Material Embodied Energy



Masonry Embodied Energy

• Concrete block	**29,018 BTU**
• Common brick	**13,570 BTU**
• Adobe brick (14”x10”x4”)	**2,500 BTU**

Computer Programs



•**Solar 5 (free)** Displays 3-D plots of hourly energy performance for the whole building. SOLAR-5 also plots heat flow into/out of thermal mass, and indoor air temperature, daylighting, HVAC system size, cost of electricity and heating fuel. Only four pieces of data initially required (floor area, number of stories, location, and building type), the expert system designs a basic building, filling in hundreds of items of data; user can make subsequent revisions. University of California at Los Angeles.

•**Energy 10 ($50)** Design tool for smaller residential or commercial buildings that are less than 10,000 ft2 floor area, or buildings which can be treated as one or two-zone increments. Performs yearly whole-building energy analysis, including dynamic thermal and daylighting calculations. Passive Solar Industries Council.

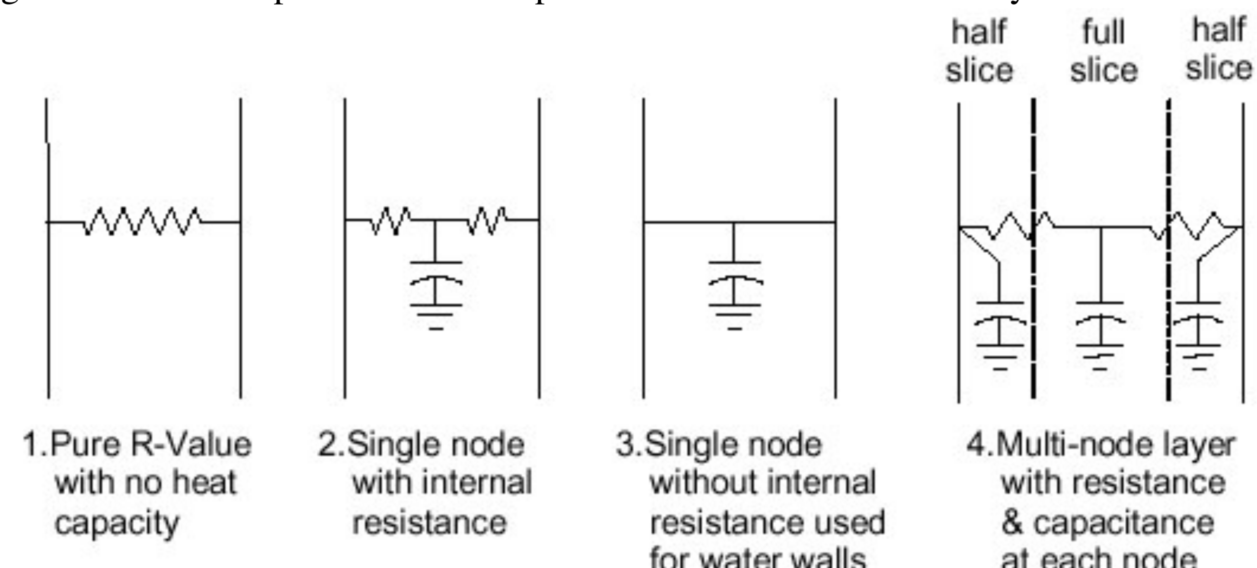
•**BuilderGuide ($80)** Design tool for residences that calculates annual heating and cooling estimates of loads based on simplified, but validated, algorithms; especially suitable for evaluating passive solar houses. Uses solar-load-ratio method (modified degree-day), diurnal heat capacity method, and simplified cooling load method. National Renewable Energy Laboratory

•**Micropas4 ($795)** Energy simulation program which performs hourly calculations to estimate annual energy usage for heating, cooling and water heating in residential buildings. Data is required describing each building thermal zone,opaque surfaces, fenestration, thermal mass. Used extensively for California code requirements. Calculates HVAC size and U-values. Enercomp, Inc.

•**Blast: ($1500)** Performs hourly simulations of buildings to provide accurate estimates of a building's energy needs. The zone models of BLAST (Building Loads Analysis and System Thermodynamics), which are based on the fundamental heat balance method. Building Systems Laboratory, University of Illinois.

Sunrel (National Renewable Energy Laboratory)

•**SUNREL (free on request)** A general-purpose thermal analysis program for residential buildings. The solution approach is a thermal network using a combination of forward finite differencing, Jacobian iteration, and constrained optimization. It was written to aid in the design of small energy efficient buildings, where the loads are dominated by the dynamic interaction of the building envelope, the environment, and the occupants. It is especially appropriate for buildings that incorporate energy efficient design features, such as: moveable insulation, control of interior shading, energy efficient windows, thermochromic switchable glazings, and thermal storage in Trombe walls, water walls, phase change materials and rockbins. Energy efficient buildings tend to be more free floating than buildings which are tightly controlled by large HVAC systems, therefore, proper design is essential for comfort and usability. The goal was to create a program that was simple to use with sophisticated thermal models and yet maintain flexibility to accommc



SUNREL ANALYSIS OF CAPACITY WALLS

Sunrel allows for the description of the wall as composed of one or more layers of material. Each of these layers may consist of either an R-value or a specified material described by its thickness, specific heat, density, and conductivity. In this way, walls of almost arbitrary complexity may be treated. Additionally, if the walls are part of an exterior surface and the user wishes to determine the effects of solar energy on the wall, the azimuth, absorptance, and parameters for shading can also be specified.

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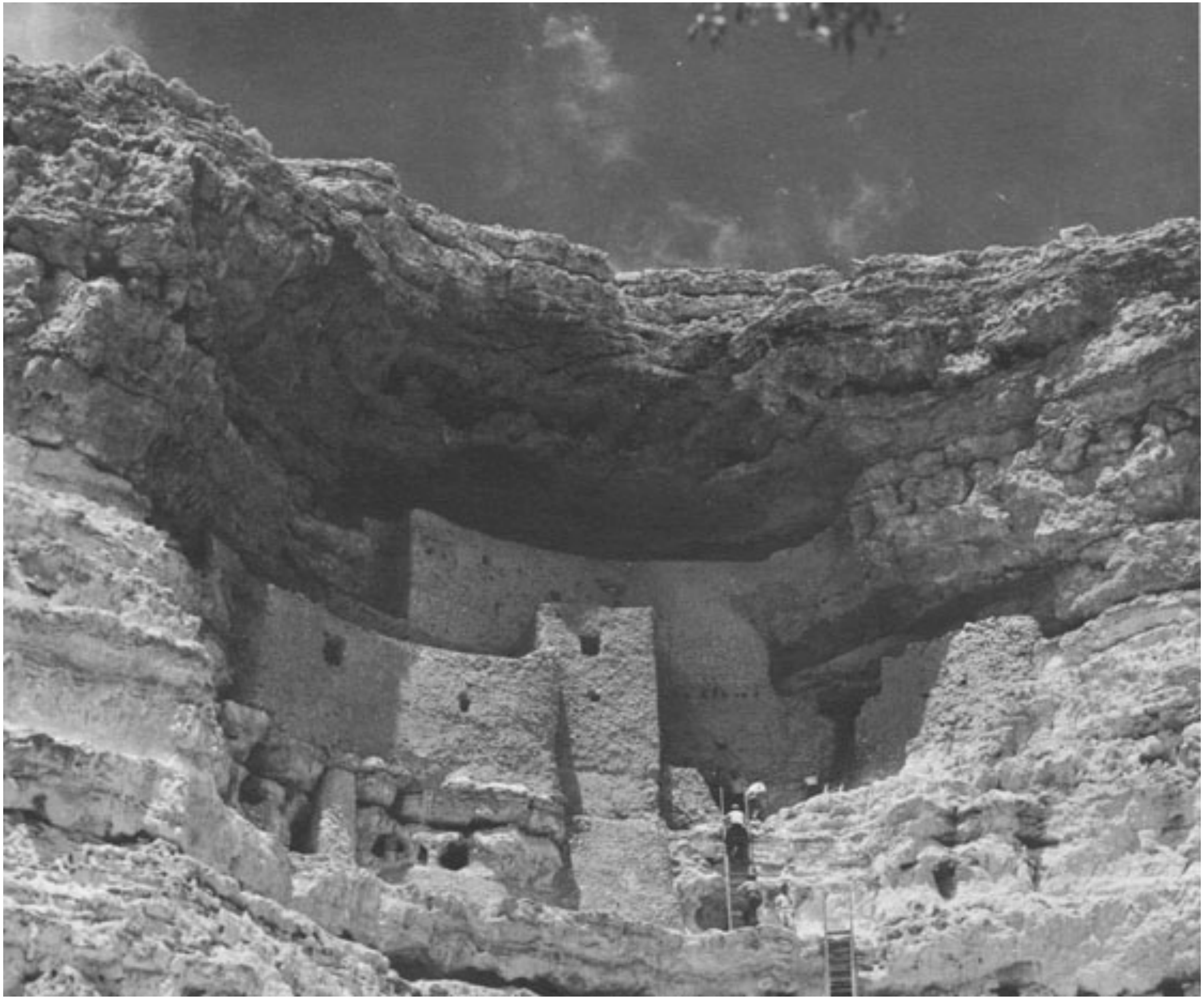

Canyon de Chelly, Arizona