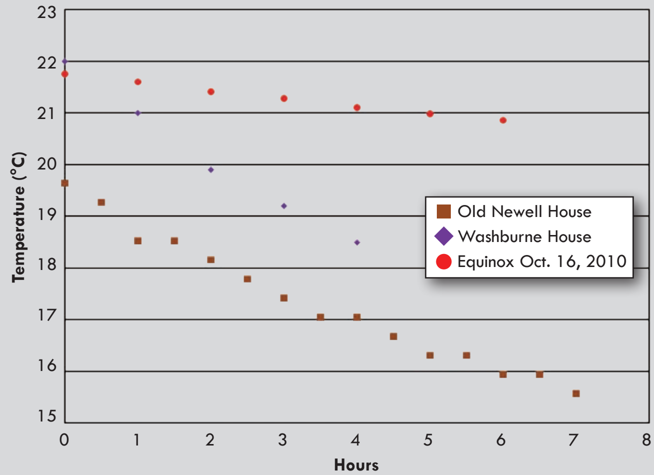

Photo 1: Flaw or feature? Equinox House has an unsealed concrete floor at present while analyses of thermal energy and moisture flows are being studied. **Figure 1:** "Coast" inside ambient air temperature data collected from the old Newell house, the Washburne Trade School passive solar house and Equinox House. Note that the "stairsteps" in the old Newell house data is due to an old 8-bit data acquisition system.

Thermal Mass Design

By Ty Newell, Member ASHRAE; and **Ben Newell,** Associate Member ASHRAE

You may have heard about adding "mass" to a house, but why? Should you have a cement truck drop a load in your living room? Should phase change materials be placed throughout a residence to achieve a "massive" house?

Photo 1 shows the unsealed concrete floor in Equinox House. Frank Lloyd Wright considered concrete floors an important feature of his organic architecture concept, while our bank's appraiser considered it a flaw. We'll take a look at thermal mass in this column, and the considerations examined for the design of Equinox House.

Figure 1 shows results from one of Ty's thermal mass tests, conducted in the 1980s in their family's 1920s-era wood frame house. He turned the furnace off near midnight, when everyone else was sleeping and couldn't complain, on a night that it was –3°C (27°F) outside. Also shown in *Figure 1* are temperature variations for Equinox House and for the Washburne Trade School passive solar house, located in Chicago. The Equinox House data were taken on Oct. 16, 2010, when we did not have any internal energy loads other than 60 W for a fresh air ventilation fan, and when the outside ambient temperature (4.4°C [40°F]) was sufficiently cold to cause a measurable temperature change in the house interior. The Washburne house was built in the early 1980s and was part of a house monitoring research project conducted by Ty for the state of Illinois. The data shown is from Dec. 5, 1986, during a time when the house was "coasting" on stored solar energy for about five hours in the evening without furnace operation or other significant internal energy loads.

The temperature change information does not reveal much from an outward viewing, but some simple analyses give us information on the house's thermal mass characteristics. Assuming the house to act as a "lumped" thermal mass (which, of course, it does not), the temperature change of the house over time with a constant outside ambient temperature and constant internal energy loads is given by:

$$\ln\left(\frac{\theta}{\theta i}\right) = -\left(\frac{UA}{mc}\right)t$$

where

- UA = overall house loss coefficient including infiltration and ventilation flow effect
- mc = house energy mass capacitance = effective house mass times effective house heat capacity
- t = time of test with zero time at the test beginning
- θ = $T - T_a - G/UA$ = house temperature parameter
- θ_I = $T_i - T_a - G/UA$ = initial time house temperature parameter
- G = internal energy loads and sources (W or Btu/h depending on your preference)
- T = inside house ambient temperature
- T_i = inside house ambient temperature at beginning of test (time = 0)

This is the seventh in a series of columns. Find previous columns at www.ashrae.org/ashraejournal.

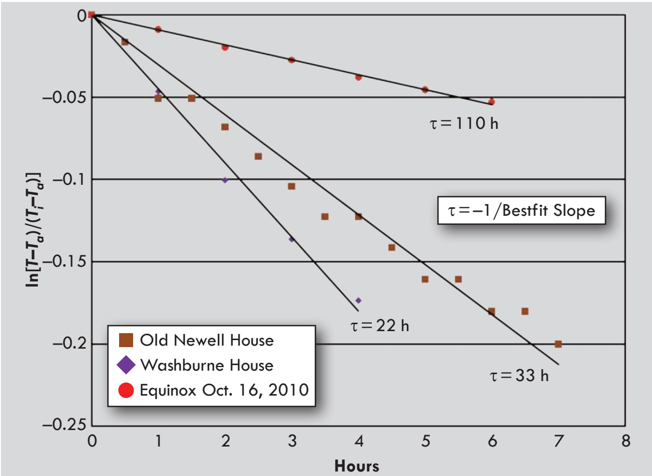

Figure 2: Plots of the logarithmic temperature parameter versus time. The negative reciprocal of the slope is for the thermal time constant, which is shown on the plot in hours for each house.

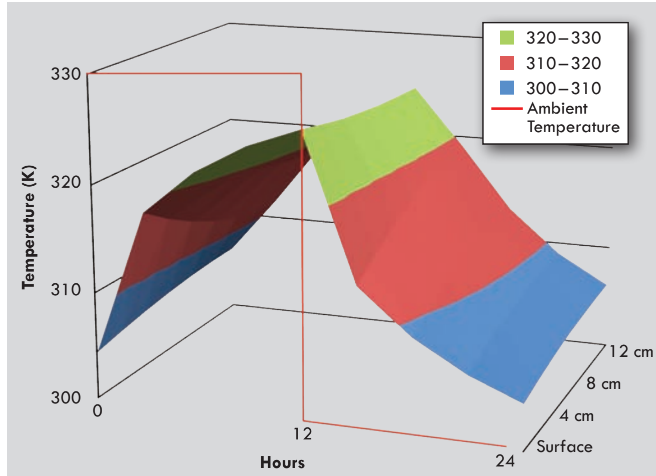

Figure 3: Temperature variations in a 120 mm (4.7 in.) thick, bare concrete slab with insulated bottom and a cyclically varying ambient temperature above the concrete surface (330 K [57°C or 135°F] from 0 to 12 hours and 300 K [27°C or 81°F] from 12 to 24 hours).

T_a = outside average ambient temperature

Conducting a coast test during a time when a building has a small internal energy source term, *G*, is helpful. To coast indicates no thermostat or other controller is actively trying to maintain a setpoint condition, allowing the house to move toward equilibrium with its surrounding influences. The energy source term does not have to be zero as long as it is either known, or at least known to be small relative to other factors. The impact of the internal loading, which can be either positive or negative in value (e.g., an air conditioner versus a furnace), is an adjustment to the apparent outside ambient temperature as seen in the grouping of terms in the temperature parameter. For Equinox House, with a UA value of approximately 100 W/K (190 Btu/h·°F), a 100 W (341 Btu/h) internal load is a change of 1°C (1.8°F) of the effective outside temperature.

The data from *Figure 1* can be plotted using the logarithmic relation between temperature and time as shown in *Figure 2*. Because the logarithmic relation between the temperature parameter and time is ideally linear with zero intercept, the slope of a linear curve fit of the data will give us the value of the parameter (UA/mc) for the house. The negative reciprocal of the slope is the thermal time constant, τ, of the house.

$$\tau = (mc/UA) = \text{thermal time constant of house}$$

The thermal time constant is a measure of the time for the house to drop $\exp^{-1}$ (0.368) of the difference from the initial inside temperature to the outside temperature. *Figure 2* shows the best fit lines through the data sets for each house along with the negative reciprocal of the line slopes in hours. If the outside temperature stayed fixed at –3°C (27°F), our old house would drop to 11.3°C (52.3°F) after 33 hours. Notice that the Washburne house has a time constant of 22 hours for the data shown, and Equinox House has a time constant of 110 hours.

So why does the Washburne house, a purported energy-efficient solar house, have such a low time constant? The Washburne house is very typical of 1980s-era passive solar homes (and probably many of today's) designed with a "shoot from the hip" approach without engineering analyses. It has 70 m^2 (750 ft^2) of windows with 52 m^2 (560 ft^2) on the south side. The house was designed to be very "massive," with concrete slab floor, water storage tanks in the greenhouse area, a massive two-story stone fireplace and an area with trays of some proprietary phase change storage material.

The estimated window *UA* for the Washburne house was 197 W/K (375 Btu/h·°F). With today's window technology, this loss coefficient could be reduced to less than half. The two story house (approximately 130 m^2 or 1,400 ft^2 floor plan with loft/bedroom area) is similar to Equinox House in total floor area of 195 m^2 (2,100 ft^2). The walls and roof were R-24 and R-39, quite respectable for the early 1980s. Infiltration was found to be on the poor side with an estimated infiltration rate of 155 L/s (330 cfm), mostly caused by the internal combustion air supplied to the furnace. The active greenhouse had a humidification impact on the house that was a significant load. Overall, the Washburne house required 35,600 kWh (1,200 therm) of thermal energy just for its annual heating load (compared to Equinox House's estimated total annual requirement of 8,000 kWh-electric for all house energy needs).

A thermally "massive" house has a long time constant. As seen in the relation for the time constant, house massiveness is dependent on the building's loss coefficient as well as the mass. If someone leaves a window open, for example, drastically increasing the house overall loss coefficient, the time constant and massiveness of the house are reduced. Unfortunately, many building designers are under the mistaken idea that adding mass is the only way to increase the thermal massiveness of a structure.

So how does one predict, design or calculate the thermal mass of a house? Following the guidelines we've given for walls, roof, windows, and infiltration in previous columns can result in a house design that is inherently massive. As we discussed in December's article, judicious selection of windows is very important. The time constant of a 0.3 m (12 in.) thick SIP wall with interior drywall is 20 hours, while a super window (U=0.57

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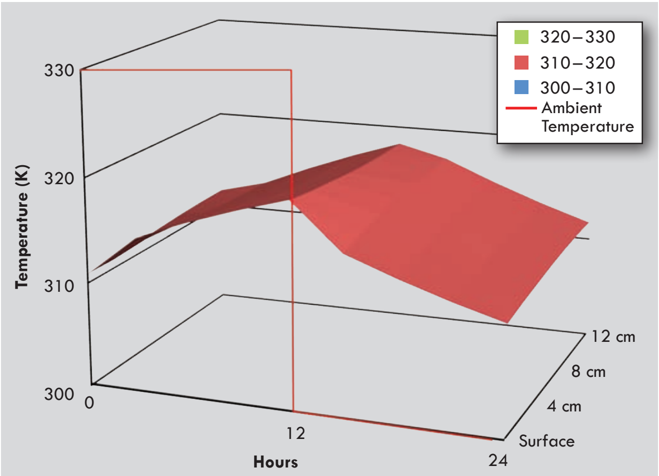

Figure 4: Temperature variations in a 120 mm (4.7 in.) thick, carpet covered concrete slab with insulated bottom and a cyclically varying ambient temperature above the concrete surface (330 K [57°C or 135°F] from 0 to 12 hours and 300 K [27°C or 81°F] from 12 to 24 hours).

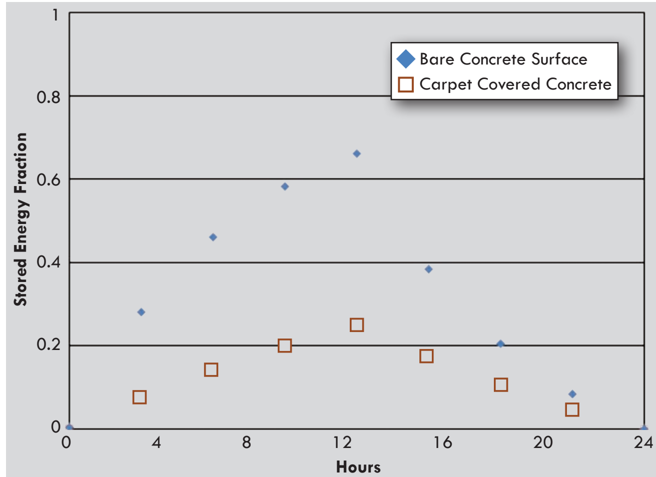

Figure 5: Energy variations in bare and carpet covered concrete slab for the conditions shown in *Figures 3* and *4* expressed as ratio of energy level in concrete mass relative to energy difference between concrete held at ambient temperature extremes.

W/m^2·K=0.1 Btu/h-ft^2·F) would have an inherent time constant of one hour based on the mass of its interior pane.

The very high thermal time constant of Equinox House relies on additional mass to increase the time constant. The concrete slab adds an additional 44 400 kg (97,700 lb$_m$) to the house. With our estimated overall house loss coefficient for Equinox House of 110 W/K (210 Btu/h·°F; see January's column on infiltration), and assuming a concrete heat capacity of 0.9 kJ/kg·K (0.22 Btu/lb$_m$·°F), the predicted time constant for Equinox house is 100 hours. With a drywall mass of 5000 kg (11,000 lbm) spread over 600 m^2 (6,500 ft^2) of interior surface plus the internal wood structure and house furnishings, we find that Equinox House has a time constant similar to the experimental value.

How do we know how much concrete "participates" in the diurnal energy variations of the house? First, on the simplest basis, the square root of the product of concrete's thermal diffusivity times the time length of interest (half day or 12 hours) indicates that thermal energy penetrates 15 to 23 cm (6 to 9 in.) in concrete.

With a bit more sophistication, we can run a simple numerical example to observe the movement of energy into and out of a concrete slab similar to our floor. *Figure 3* shows the temperature profile in a concrete slab subjected to a cyclical, 12-hour step change of ambient temperature from 300 K (81°F) and 330 K (135°F). The bottom of the slab has been given an insulated boundary condition in order to truncate the computational field. The slab is 12 cm (4.7 in.) thick, and the concrete surface is assumed to have a convective coefficient of 5 W/m^2·K (0.92 Btu/h·ft^2·°F) and a surface emittance of 0.9 coupling it to the ambient surroundings. The temperature levels used are for illustration and do not impact the relative transport of energy into and out of the slab or the energy penetration characteristics.

Figure 4 shows the same information as *Figure 3* except that a layer of carpet covers the concrete surface. Assuming the upper surface of the carpet has the same convection coefficient and emittance as before, but now these are in series with the carpet's thermal resistance, results in a combined surface transfer coefficient of 3 W/m^2·K (0.55 Btu/h·ft^2·°F) that includes the surface convection and radiation with the carpet transfer coefficient. A carpet's thermal resistance can be quite significant relative to the concrete slab's internal transfer resistance as seen in the dampened temperature variations shown in *Figure 4*. Note that carpets covering actively heated or cooled floors will also have performance degradation.

Figure 5 shows the fraction of thermal energy in the slab at different times over a cyclical 24 hour period. The energy fraction is the ratio of the energy in the slab referenced to the energy in the change for an isothermal slab changing between the temperature extremes, minus the minimum energy ratio of the slab during the diurnal cycling. The bare concrete energy content changes by 66% of the maximum energy change possible during the cycling, signifying that a majority of the slab is participating in the diurnal energy transfer. Our thermal penetration layer estimate indicates that additional ground below the slab would also participate if we had not assumed an insulated bottom boundary. The carpet covered concrete slab energy fraction variation is more restrictive, varying its energy content by only 25% of the maximum possible slab energy variation. But, how does one explain this to the bank's appraiser?

So, large thermal mass is good for a few reasons, most importantly saving energy and maintaining comfort. A thermally massive structure does not drop much in temperature during thermostat setback periods, which means conditioning systems will run less often and energy storage strategies can be better employed.

Thermal mass also helps stabilize temperatures of a house, which creates a better feeling of comfort. A house that is continually increasing and decreasing in temperature is not comfortable. Nor is a house with surfaces and rooms that are not uniform in temperature. *Figure 6* shows three locations in Equinox House where we collect temperature data. The main living area and the master bedroom receive direct solar energy through the clereesto-

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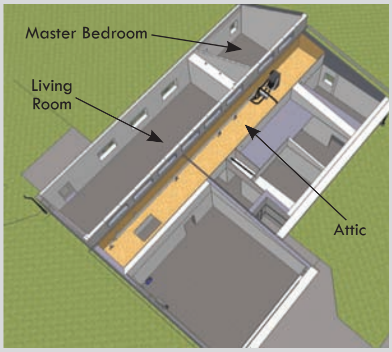
Figure 6: Temperature measurement locations in Equinox. The main living area and master bedroom receive direct solar radiation through the clerestory windows on sunny, winter days. The attic, located above the bathrooms, laundry room and pantry, doesn't have any windows.



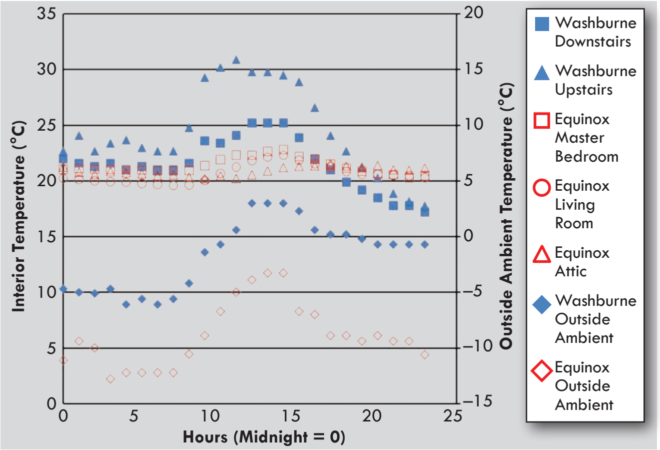


Figure 7: Temperature variations on similar cold sunny days in December for the Washburne passive solar house and Equinox House.

ries, while the second floor attic area does not have windows but is within the thermal envelope. *Figure 7* shows the temperature variations in the Washburne house and Equinox House on similar cold, sunny December days. Our measurements in the Washburne house showed uncomfortable temperatures almost 30% of the time in December. "Uncomfortable" was defined as any time period with ambient air temperatures greater than 26.1°C (79°F).

Thermal mass of a house is an important design consideration, not just for energy, but also to maintain comfort. Physical mass is often thought to be the manner for achieving thermal massiveness. However, insulation and sealing are just as important. With engineering analyses included in the architectural design process, an inherently massive house that results in comfort and excellent energy performance can be achieved.

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