Dear reader of the *"Performance of Adobe"* report by David Robertson, PE,

The CID has asked me to make this almost unknown report available via a PDF file. I should write a few words about why it's important that you read through the 30+ pages.

During the period 1976 - 1987, New Mexico *was* the national leader in research about solar and mass. The spark was the oil embargo of 1973/74. Energy, then as now, was key. Several national and state entities joined with trades folk, contractors and architects to document the effects of solar and mass. Hundreds upon hundreds of thousands of dollars were spent by the two labs, UNM, NBS, HUD, DOE, Eight Northern Pueblos to see how and why it worked. The old saying *"sun and adobe work together"* was put to the test.

The culmination of this work was the *Southwest Thermal Mass Study*, usually tagged *SWTMS*. David Robertson, PE explains its operation in his report. Eight test structures measuring 20' x 20' x 8' were built at Tesuque Pueblo in 1980-81. The site, at 6,330 feet and 5800 degree heating days, was suitable for a cold winter energy study. The belief at the time was that computer modeling alone could not tell the true story of how a structure performed in nature. The buildings included log, adobe, concrete block and frame, plus an instrumentation building.

Adobe has a low R factor, but still works towards dweller comfort. Why? Robertson clears up the mystery, showing how mass saves energy, especially when temperatures vary widely (spring and fall) and how mass moderates extremes, reducing the size and run time of heating and cooling units. Take a look at Figures 2 and 3 (in the back of the report). Also, in Figure 4, we see that the mass effect decreases as the climate becomes colder. At around 5000 degree heating days, the effect is saving you perhaps 7 to 8% in energy use. In Las Cruces, the effect could save you 12%.

Beyond just mass is solar. Incorporating it properly with mass enhances the savings. Robertson says; *"Furthermore, for passive solar applications, the high conductivity (low R-value) of adobe is actually desirable, because heat can be readily absorbed, stored and released in the daily solar cycle--if exterior walls are well-insulated on the outside."*

Table 1 gives building load energy reductions using mass. Note that wall insulation of R-5 does as well as wall insulation of R-20. And yet Robertson suggests R-20. I think that with R-10, one has almost maxed out the benefits. There may continue to be some controversy about this aspect.

By the time the SWTMS report was printed in1986, the "energy crisis" had long been declared over. Printing budgets for energy research results had been cut. In the end, only SWTMS staffers and a few NMERDI offices carried the report. Outside of North Central NM, few contractors, architects or engineers knew of the research. Today, results of SWTMS still influences NM code via the *Residential Applications Manual,* largely watered down in the late 80's and 90's as concerns about energy lapsed. It is now being updated by the Energy and Minerals Dept.

Since the 70's, NM has taken a centuries old, vernacular architectural form and developed it into a refined, energy-producing medium, well noted around the Southwest. Rather than cast this unique honor aside, our codes should continue to reflect appropriate regional themes.

Sincerely,
Joe Tibbets
October, 2009 *p.s.- my apologies for the underlining in the report- my only copy.*

THE PERFORMANCE OF ADOBE AND OTHER THERMAL MASS MATERIALS IN RESIDENTIAL BUILDINGS

An Update on Current Research and Building Codes, With Recommendations

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Adobe as Thermal Mass

Introduction

Adobe is the indigenous, massive building material of the Southwest. It has been used worldwide for millenia, and some estimate that over one-half of the world's population currently lives in some type of earthen structure (Reference 17).

Adobe is a sun-dried mud brick, typically sized 10"x14"x4" in New Mexico. It can be laid, usually with mud mortar, to make a wall 10" thick or 14" thick. As a structural material, it provides several advantages over wood-frame construction, including sound attenuation, fire resistance, and the rounded, aesthetically-pleasing appearance unique to Southwestern homes. Among its disadvantages are somewhat higher cost and slower construction than wood-frame, more difficulty in handling due to its weight, and more difficulty in insulating due to the absense of a cavity in which to place batt (e.g., fiberglass) insulation. A comprehensive book on the engineering and architectural aspects of adobe has been written by McHenry (Reference 17).

In terms of energy-related characteristics, traditional unstabilized adobe is a low-embodied-energy material (Reference 17). That is, less energy is required to manufacture the material (per square foot of wall area), compared to many other wall materials. It can be made by hand if necessary, and solar energy is used to cure the bricks. Frequently it can be made on-site, using raw materials from the site, so transportation energy also is minimal. As it performs in a building, with space heating and cooling equipment, it is also a thermal mass material capable of absorbing heat or coolness for release later in the day.

The goals of this paper are: to explain what thermal mass is and how it operates, with an emphasis on adobe; to review the history and current status of thermal mass research, and national, state, and local codes with respect to thermal mass; and to offer specific recommendations on how best to use thermal mass for energy efficiency and comfort. Much of the material comes directly from the Southwest Thermal Mass Study (SWTMS), an experimental research study on the thermal performance of adobe conducted at Tesuque Pueblo, New Mexico in the early 1980's. An added goal is to provide a summary of that research in "layman's" terms. The focus will be primarily on residential construction, although the theory and most of the recommendations apply to small commercial buildings as well.

The target audience consists of anyone who is interested in energy-efficient construction using massive materials, particularly adobe, and it includes architects, engineers, researchers, government agencies, builders and other members of the construction industry, homeowners, and homebuyers.

What is Thermal Mass?

Thermal mass consists of massive (usually high-density) materials, within a building or as part of a building envelope. Thermal mass moderates heat flow through walls. That is, a daily heat pulse on one side of a wall will be significantly reduced (and delayed) when it reaches the other side. This is also true for lightweight walls, but to a much lesser extent.

Mass has the ability to absorb, store, and release heat. In passive solar applications, mass absorbs excess heat when interior air temperature rises above the mass temperature, stores it, and then releases it when the space temperature drops. This also occurs in conventional (non-solar) buildings in transition seasons (spring and fall) and in the cooling season. Thus, mass operates as a "thermal flywheel," or stabilizer of interior air temperatures.

The Southwest Thermal Mass Study

The Southwest Thermal Mass Study (SWTMS) had its beginnings in the mid-1970's when Bill Haney, a Santa Fe architect, found that the U.S. Department of Housing and Urban Development (HUD) would not permit adobe construction for federally-funded Indian housing projects. HUD's reasoning was that uninsulated adobe did not meet HUD's energy efficiency criteria for new construction. If the adobe was insulated to meet the energy efficiency criteria, it then did not meet HUD's cost criteria. Both criteria were based on insulated wood-frame construction. An added wrinkle was that HUD projects had to use the federal Davis-Bacon wage rates, which required that adobe layers (who traditionally are considered semi-skilled) be paid the same as skilled bricklayers. This also increased the cost of adobe construction.

Haney found that there had been no detailed, extensive research conducted on the in situ performance of thermal mass in residential construction. Much work had been done on the steady-state (constant conditions) performance of building materials, in order to develop steady-state R-values, but analysis of the dynamic heat transfer characteristics of massive materials, under actual conditions and over the long term, had not been performed.

With the then New Mexico Energy Institute (NMEI) at UNM, Haney prepared and submitted a proposal to HUD, the U.S. Department of Energy (DOE), and other federal, state, and local governmental agencies to construct and operate an adobe research facility. Coincidentally, DOE was starting up a thermal mass research program, operated through Oak Ridge National Laboratories (ORNL).

The proposal was accepted, and HUD funded the construction of the facility, DOE funded the research, the Eight Northern Indian Pueblos Council and the Pueblo of Tesuque donated the use of the land and an instrumentation building, and the New Mexico Energy and Minerals Department funded development of the technical reports through the state's Energy Research and Development Program. The project was conducted by staff of NMEI, with assistance from several consultants and oversight by the DOE Thermal Mass Review Panel. A parallel experiment funded by DOE was conducted by the National Bureau of Standards (NBS). The NBS experiment was also overseen by the Thermal Mass Review Panel, which met three times each year for the duration of the project and included representatives of industry, government, and the research community. The adobe industry was represented at panel meetings by Tom Harley of Hans Sumpf Company of Fresno, California.

In 1980 and 1981, the facility was built and instrumented at Tesuque Pueblo, 12 miles north of Santa Fe, at an altitude of 6,330 feet, and in a relatively cold climate with approximately 5,800 heating degree days (base 65^{o}F). Annual average insolation at the site was approximately 1800 Btu/ft^{2}*day on a horizontal surface. The facility consisted of eight simple and well-instrumented test buildings, sized 20'x20'x8' high (Reference 13). Four types of construction were used (adobe, concrete masonry units, milled log, and insulated wood-frame), including five adobe buildings with walls of varying thicknesses (10", 14", and 24") and both "traditional" and stabilized bricks. See Figure 1. The buildings were initially thermally uncomplicated (no windows or doors, heavily insulated ceilings and floors, uninsulated adobe walls, and very low air infiltration rates) so that the behavior of the walls could be isolated and easily measured and understood. Later, windows were added to all but one of the buildings, and one of the adobes was also insulated.

The primary question that the researchers wanted to answer was: If you had two conventional (non-solar) buildings, one lightweight (wood-frame walls) and one massive (adobe walls), otherwise identically constructed and insulated, what would be the difference in space heating and cooling energy consumption over the course of a year? This is what is commonly referred to now as the "thermal mass effect." It was recognized that the measured energy use differences would only be valid for that particular building configuration (e.g., shape, orientation, window area, number of rooms) and for the climate in which the experiment was conducted, in this case Northern New Mexico.

Additional questions posed were: What is the in situ steady-state R-value of adobe? What does thermal mass do and how does it work?

Results of the Southwest Thermal Mass Study

The data from the SWTMS was collected by a Doric datalogger, stored on floppy disks, transferred to magnetic tape, and then plotted, reduced, and analyzed. The results are presented in two reports (References 14 and 20). Building heat flows were summed, and energy balances were performed. Energy balances were generally accurate to within $\pm$10%; that is, the sum of all measured heat flows for a building (walls, floor, ceiling, infiltration, and solar gain) was within 10% of the heating energy use measured for each building. That is good agreement for an experiment using buildings constructed with normal building methods and materials.

Steady-State R-Value

The steady-state conductive (surface-to-surface) R-values of adobe were calculated using long-term averages of wall heat flow and surface-to-surface ΔT. Including the 1/2" of mud plaster on each side of the walls, the R-values (in units of hour*square foot*degree F per Btu) were: 2.0 for the 10", 2.7 for the 14" and 4.4 for the 24". These were for well-cured, in-place adobe walls, with moisture content (by weight) less than 2% for the thinner walls and 3% for the 24-in.(61-cm) walls. No measurable difference in thermal conductivity was found as a function of these levels of moisture content, and the conductivity of the fully stabilized adobe walls was only slightly higher (by a few percent) than the traditional (nonstabilized) adobe walls. Experimental error for the R-value measurements was estimated as $\pm 11\%$.

Note that these values are steady-state R-values only and do not include the dynamic "thermal mass effect," which is discussed below. Also, these values are specific to the particular adobes used, which were from the San Juan Pueblo adobe yard near Espanola, New Mexico, and which had a density of approximately 117 lbm/ft^3 (1870 kg/m^3). The density of adobe can vary from 90 to 120 lbm/ft^3 (1440 to 1920 kg/m^3); the R-value would be higher for lower-density bricks.

Some disagreement exists about the R-value of adobe. Variation in the properties of the raw material thermal properties may explain this. However, even if the R-value of adobe is twice what is given above, adobe is still a poor insulator, and exterior walls should be insulated to be energy efficient. Furthermore, for passive solar applications, the high conductivity (low R-value) of adobe is actually desirable, because heat can be readily absorbed, stored, and released in the daily solar cycle--if exterior walls are well-insulated on the outside.

Reputation of Adobe

If the R-value of adobe is so low, why then does uninsulated adobe have such a good reputation for energy efficiency and comfort? Part of the answer to this question lies in the ability of adobe to moderate weather extremes. However, there may be other, subjective reasons.

Imagine you lived in adobe homes all your life, probably heated with wood, and in the early 70's you were given a new gas-heated wood-frame HUD home. Assume the new home was minimally insulated and not very tightly constructed. Your initial reaction might be that it is a foreign type of construction, not aesthetically pleasing with its straight lines and flat surfaces, and it probably would not withstand the centuries of use your old adobe has. It heats up quickly on summer days and does not maintain an even temperature. In winter, you have to keep the furnace going all night, whereas your old adobe had been absorbing the radiant heat from your wood heating system all evening and would probably make it until morning without another fire. And, to top it all off, you are periodically presented with a large heating fuel bill, whereas the wood you used to heat your adobe house was essentially free, requiring primarily labor.

You conclude that your old adobe is more comfortable, does not require continuous heating, costs less to heat, and requires no cooling. Many of these observations have some technical merit, but they do not fully offset the lack of insulation.

Wall Heat Loss

The question of how thermal mass in a building envelope performs, and what its heat transfer characteristics are, can best be answered by a graphic presentation of wall heat flow. See Figure 2. These plots are based on SWTMS results and other research conducted as part of the DOE Thermal Mass Program. The plots demonstrate the effects of mass and insulation on heat flow through a wall.

The assumptions are that it is midwinter (the wall is continuously losing heat), and the interior air is thermostatically controlled to a constant temperature. The outside surface of the wall is exposed to a sol-air temperature which varies sinusoidally. (Sol-air temperature does not vary sinusoidally in reality, but a sine curve was used to provide a clear conceptual understanding.) Mass is located <u>inside</u> the insulation layer in these cases.

Each of the three plots is a heat-loss-versus-time curve. Heat loss is on the vertical axis, with increasing heat loss toward the top. Since it is midwinter and the walls are losing heat continuously, heat gain is not present on any of the plots. The horizontal axis is time, from 6:00 am to 6:00 am over a twenty-four hour period, increasing to the right. The heavy horizontal line on each plot denotes the average heat loss for the curve.

The first curve (Detail A) shows the hour-by-hour heat flow response of an idealized base-case wall with very low mass and very low R-value. At 6:00 am, as the sun comes up and the outside temperature begins to rise, the wall heat loss starts to decrease. At noon, when the outside temperature is at a maximum, heat loss is at a minimum. Similarly, when the outside temperature drops to its lowest at midnight, that is the time of greatest heat loss. Both return to their original value at 6:00 am the next morning.

The pattern of heat loss in Detail A is similar to the behavior of an uninsulated wood frame wall. (Under actual conditions, outside temperature peaks at around 2:00 pm, and it drops to a minimum just before sunrise.) Such a wall would show some change in the shape and timing of the curve; it would not follow the outside temperature profile exactly.

The second curve (Detail B) shows the heat loss of an idealized wall if mass, but no insulation, were added to the low mass/low insulation wall in Detail A. The curve for the massive wall is the heavy line, and the curve for the low mass/low insulation wall in Detail A is shown for comparison by the lighter line. Since insulation has not been added, and the mass is assumed to have no R-value in this example, the average (and total) heat loss is the same as for the first wall. However, there are two important effects of the mass. First, it produces less variation in the heat flow: the difference between the maximum and minimum is smaller. That is, the mass moderates the extremes. In addition, the mass delays the timing of the maximum and minimum, shifting the whole curve to the right. Thus, whereas the minimum heat loss in a massless wall occurs exactly at the time of the highest outside temperature, it occurs a number of hours later in a wall with mass.

This curve is similar to the behavior of an uninsulated massive wall, such as 10" adobe. A 10" adobe wall produces approximately half of the variation in heat loss as the uninsulated frame wall in Detail A, and the delay is approximately 7-8 hours. Delays for thicker adobe walls are 10 hours for 14" and 18 hours for 24", with coincident reductions in variation of heat flow. These time lags were determined experimentally in the SWTMS. (See the discussion in the later section "Other Thermal Mass Research" and Reference 10 for a more theoretical discussion of the time lag.)

The third curve (Detail C) shows the behavior of an idealized wall with both mass and insulation. Note that the two effects of mass discussed earlier are present: less variation (amplitude) of heat flow and delay (time lag) of heat flow. Here, the variation is further reduced by the presence of the insulation. In addition, the primary effect of insulation is present: the rate of heat loss is always reduced. Thus the average heat loss (and the total heat loss for the 24-hour period) is reduced. This curve is similar to the behavior of a well-insulated 10" adobe wall. Thus, with a combination of interior thermal mass and exterior insulation, the benefits of both can be achieved. These results are not climate-specific.

Building Heat Flow

These two effects of thermal mass, moderation and delay of heat flow, have important implications for space heating and cooling energy consumption, particularly as the mass interacts with other building elements and the space conditioning system.

The most significant is the moderating influence of thermal mass. When heating (or cooling) is required continuously throughout the day, mass has no effect on energy use (the average of cold and very cold is still cold). However, when a building experiences alternating periods of net energy loss and net energy gain during each day, thermal mass will save energy. This is the case in most of New Mexico in spring, summer, and fall, and in buildings with high solar gain in winter.

To see how this works, look at Figure 3. This is a similar curve to those in Figure 2, with two important differences. First, the heat flow for the total building, not just the walls, is shown. Secondly, due to the time of year (or appropriate combinations of insulation and solar gain), the average heat loss for the building is zero. When the curves are above the line, the building is losing heat, and when the curves are below the line, the building is gaining heat. The total gain for the day equals the total loss for the day. Again, these are idealized curves, and these exact conditions rarely if ever occur.

Whereas the lightweight building requires cooling for part of the day and heating for part of the day, the massive building requires neither. There are many days in the spring and fall transition seasons, and in the summer cooling season, when this effect saves energy. It usually does not save both heating <u>and</u> cooling energy, but it saves one or the other.

The delay of heat flow caused by thermal mass can also save energy. Note from Figure 3 that the cooling load for the massive building occurs in the evening and nighttime hours. This timing permits the homeowner to cool the building by ventilating with cooler nighttime outside air. In many, if not all, of cooling season days, this eliminates the need for cooling energy. In a lightweight building, on the other hand, the cooling load occurs in midafternoon, at the hottest part of the day (when refrigerated air conditioners operate at their lowest efficiency), and cooling is required.

Another benefit of thermal mass is apparent from the results: peak load reduction. Figure 3 shows that the building heating or cooling load is more constant, and the peak loads are smaller. This will reduce: utility peak loads (most importantly for electric utilities), and thus utility capacity requirements; the size and cost of heating and cooling equipment in the building; and, to some extent, the energy consumption of heating and cooling equipment in the building as a result of less cycling.

Results Summary

The magnitude of the thermal mass effect will vary with building configuration, climate, and time of year. At the Southwest Thermal Mass Study, the effect on total heating season energy consumption was 3-1/2% for windowless test buildings and

5% for test buildings with windows. When the results were extrapolated to the milder climate of Las Cruces, New Mexico (3,200 HDD), the effect was 12% for test buildings with windows.

It is important to note here that, although the percentage savings may vary from climate to climate, the absolute savings (in terms of energy) is often similar.

Funding was not provided for testing in the cooling season, but it is expected that the effect would be greater, because there would be many more days in the season when buildings experience alternating periods of net heat gain and net heat loss on a daily basis. Utilization of the delay of mass walls through ventilation strategies will further reduce cooling loads.

The DOE Thermal Mass Program

The DOE Thermal Mass Program includes the Southwest Thermal Mass Study and a similar experiment at the National Bureau of Standards (Reference 7). An overview of the program is presented by Christian (Reference 11). The goal of both experimental studies was to develop a detailed and reliable data base on the thermal performance of buildings with various amounts of thermal mass. Once the data was collected, several main-frame building simulation computer models (BLAST, DEROB, TARP, and DOE-2) were used to perform consistency checks on the data. At the same time, computer models were validated in order to perform extensive and detailed modeling of a prototypical house for a variety of U.S. climates.

It was assumed that, if the computer models could accurately predict the performance of building components, the test buildings' overall energy use, and the magnitude and timing of the thermal mass energy savings for different seasons of the year, then the models could predict those savings for full-size buildings in different climates.

Although numerous computer simulations of full-size buildings were performed by a variety of organizations (see later section "Other Thermal Mass Research"), the primary work was done by LBL (Reference 8), using the program BLAST 3.0. The prototype house modeled was a 1,200 ft^2, single-story, three-bedroom house with typical window area and placement, insulation levels, thermostat schedules, internal loads, and furnishings. An important atypical condition was that the floors and foundations were assumed to be massless. As in the experiments at SWTMS and NBS, this isolated the wall mass effect. The principal parameters varied were: climate; wall insulation level and location; and wall thermal mass thickness, density, and thermal conductivity. Weather data from six cities, representing different climates around the U.S., was used.

The results indicated that, for a given wall R-value, annual heating and cooling loads always decreased with increasing mass, regardless of wall type or climate. (In some rare cases in very mild climates, energy use actually increased with an increase in insulation -- see also Reference 7). Generally speaking, loads decreased more when insulation was placed outside the mass, compared to inside it.

Table 1 presents selected results from the simulations. The table shows the annual reductions in sensible heating and cooling loads when wall thermal mass varies from near zero to a level similar to that of 10" adobe (see assumptions in Table 1). The reductions are presented in terms of relative (percent) reduction of total loads, and in terms of absolute reduction of total loads, in MMBtu/year. Results are shown for five cities and for three different levels of insulation: none, R-5, and R-20, all on the outside of the mass.

Note that the percent reductions vary considerably and can be quite high -- in the 30- and 40-percent range -- in mild climates (e.g., the mild heating climate of Phoenix and the mild cooling climate of Denver). The absolute reductions, however, show much less variation. The savings from mass with even higher thickness, conductivity, and density (calculated but not shown here) are greater, but the bulk of the load reductions possible have been realized with this level of mass.

It is important to point out that the percent reductions are unrealistically high, because the floors and foundations are assumed to be massless. If floor mass were added to a level equivalent to a 4-inch concrete slab, the mass effects for the prototype house would be 25% less in the cooling season and 75% less in the heating season, on the average, according to calculations by Christian (Reference 11).

The next step in the Thermal Mass Program, currently underway, is to develop a simplified tool which will predict the energy savings from thermal mass for any building configuration and climate, based on computer results such as these. Such a tool would be used by architects, engineers, builders, and code officials for residential design and construction. The tool could be a microcomputer program, a manual calculation, a special energy calculation sliderule, tables and charts, etc. Some tools have been developed, primarily outside the DOE Thermal Mass Program, and these are discussed in the next section.

Other Thermal Mass Research

Other research in thermal mass has been conducted by numerous industry groups and other DOE research programs. Research by state governments and the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), primarily with reference to energy conservation building codes, will be discussed in the later section on codes.

The industry groups -- such as the National Concrete Masonry Association (NCMA), the Brick Institute, and the Portland Cement Association (PCA) -- have for many years promoted the energy savings benefits of thermal mass and funded research to document and quantify that savings. One of the earliest methods of accounting for thermal mass was the M-factor, developed by consultants to NCMA with the computer program NBSLD in the mid-1970's (Reference 9). The M-factor is a correction to steady-state R-values which can result in less insulation being required in opaque wall sections for massive buildings than for lightweight buildings. Charts of M-factors show the correction as a function of degree-days and weight per square foot of wall area.

PCA developed a "delta-R" methodology using the computer code BLAST which reduced required R-values of wall insulation when thermal mass effects were included.

Arumi of the University of Texas, funded by NCMA and DOE, developed the computer program DEROB to investigate the effects of wall thermal inertia on heating and cooling energy consumption (Reference 3). He used a dimensionless number (gamma) to quantify thermal inertia and developed a manual method to calculate mass effects for various generic wall assemblies.

(A similar number was later presented by Childs in the ORNL report Thermal Mass Assessment (Reference 10). The behavior of building envelope thermal mass can be quantified by combinations of material properties: density, ρ (in pounds-mass per cubic foot), thermal conductivity, k (in Btu per hour*foot*degree F), heat capacity, c (in Btu per pound-mass*degree F.), and wall thickness, L (in feet). The quantity [ρcL] is a measure of the wall's ability to store energy, and the quantity [k/L] is a measure of the wall's ability to conduct energy. The ratio of the two [$(\rho c L^2)/k$] is an indication of the speed at which a temperature profile moves through a wall. The time lag for a single-layer, homogeneous wall is less than or equal to 1/6 of that ratio.)

Much of this early work was regarded as "tainted" by some members of the building industry, particularly the insulation representatives. However, with the increasing research devoted to thermal mass, including the DOE Thermal Mass Program discussed in the previous section, some degree of agreement is being reached both among the extensive computer simulations and among the various members of the building industry. Bion Howard, formerly of NCMA, has compiled the results of many of the computer studies done for different building configurations and climate regions (References 15 and 16).

Based on this compilation, he developed the curves in Figure 4. The curves show the approximate percentage reduction that can be expected in conventional (non-solar) building heating and cooling loads if the building were constructed of masonry walls, as compared to lower mass frame wall construction. These curves are for buildings with wall mass greater than 35 pounds per square foot. (10" adobe would be close to 100 lb_m/ft^2.) Since they represent varying amounts of mass above 35 lb_m/ft^2, various building configurations, and different modeling assumptions, actual savings can vary considerably from the curves shown.

The curves show that both the heating and cooling thermal mass effects vary with the mildness of the climate up to the 30 to 40% range.

Another DOE research program that includes thermal mass is the Affordable Housing Guidelines (AHG) project (Reference 21). AHG is an outgrowth of the now-defunct Building Energy Performance Standards (BEPS) program. In this project, a sliderule methodology was developed at LBL, based on a large number of runs of the computer code DOE-2. The sliderule is used to calculate building heating and cooling energy use, based on desired building insulation levels, window area, infiltration rates, climate location, etc. A builder can then change various parameters (e.g., ceiling insulation level) and determine the change in energy use.

The initial version of the AHG sliderule and documentation (1983 draft) did not include thermal mass as a parameter which affects building energy use. However, material has been developed to include thermal mass adjustments for masonry and log wall construction. This material was sent out for review to an Industry Review Panel in late 1985.

The Guidelines are due to be completed in to late 1986, at which point they will be required for new construction of federal agency buildings. They will also ultimately find their way into the building code standards process of ASHRAE, and hence to state and local building codes and HUD standards.

Passive Solar Research

The research described above is limited to "conventional" construction, in which window area is usually no more than 15% of the floor area and distributed among all orientations. With the concurrent development of passive solar technology in the last decade, there has been a great deal of research on thermal mass in passive solar applications.

The three requirements of a well-designed passive solar system are: 1) a well-insulated, low-infiltration building envelope, 2) solar gain, and 3) thermal mass. Without adequate thermal mass, the best a solar building can do is provide daytime heating: mass is needed to prevent daytime overheating and carry the building through nights and periods of cloudy weather.

Even with sufficient thermal mass, its location, color, thickness, and surface area must be designed to maximize daily heat storage and provide a steady interior environment without excessive temperature swings. This is usually accomplished by the correct ratio of direct gain (daytime heating) and indirect gain (nighttime heating) and maximizing the mass in direct sunlight (radiatively coupled) as compared to the mass heated by room air (convectively coupled). These are entire research areas in themselves.

Perhaps the most comprehensive work to date on passive solar is that of Balcomb et al. at Los Alamos National Laboratory (LANL) (Reference 5). The LANL solar group developed correlations of solar performance with building load and solar aperture for numerous reference designs and climate locations, based on extensive computer analysis (using the computer code PASOLE) and test cell monitoring. Three levels of manual methodologies to determine solar performance were developed, ranging from rules of thumb, to overall annual performance, to monthly performance. The methodologies are simple to use and appropriate for various stages of the design process.

The reference designs include varying levels and characteristics of thermal mass. Sensitivity studies were done to assess the effect of various mass parameters on performance. These parameters include thickness, specific heat, thermal conductivity, absorptance, distribution, and surface area. For example, for a residence in Albuquerque with a small heating load, high direct solar gain, and no night insulation, as the thickness decreases from 4" to 1", the solar savings fraction decreases from close to 100% to close to 0%. In the terminology of the previous sections, this amounts to a "thermal mass effect" approaching 100%. That is, a high mass solar building of this design would use almost no heating energy compared to a lightweight solar building of the same design.

At the present time, these are still two separate areas of research -- passive solar and thermal mass -- but it is likely that these two fields will merge, particularly as conventional housing becomes more and more "sun-tempered." Current computer simulation research at LBL includes quantifying the thermal mass effect as a function of south glass area, from conventional to fully passive solar designs.

Building Codes

The goal of the research presented above is not only to provide up-to-date technical information to industry and the public, but to provide input to building codes and standards. The complex maze of different and overlapping building codes can be very confusing; the Adobe Codes book by Adobe News, Inc. (Reference 1) does a good job of describing current state and local codes.

New construction in the U.S. is required to conform to building codes. They may be a national code, a state code, and/or a local code, depending on location of the site. Usually, the state or local government simply adopts the national code. If the state or local government finds portions of the national code unacceptable, they develop their own and replace the unacceptable sections of the national code. This is the case with the national Uniform Building Code (UBC) structural requirements for adobe. The UBC required minimum 16" wall thickness -- New Mexico found this unacceptable and rewrote the section to allow a 10" minimum thickness.

If the building is HUD housing (e.g., HUD public housing, including Indian housing, or housing financed through FHA), then the HUD Minimum Property Standards (MPS) must be met. Prior to 1985, HUD wrote its own MPS, but since mid-1985 the MPS (Reference 12) are based on national codes, or on the state or local codes if they are found acceptable by HUD. If the building is a federal building, owned by the federal government and used by a federal agency, it must conform to a different set of federal standards.

The common denominator to most of these codes -- the code upon which most codes are based -- is the Uniform Building Code (UBC). The energy portion of the UBC is the Model Energy Code, which is based on ASHRAE Standard 90, the ASHRAE standard relating to energy conservation (Reference 2). It is through the Standard 90 revisions and addenda (Reference 4) that research such as that on thermal mass is ultimately incorporated into building codes and HUD Minimum Property Standards. This process is shown in flow-chart format in Table 2.

The ASHRAE Standard 90 was initially developed in 1975 (called Standard 90-75) and specified minimum requirements for energy conservation in new construction. Three methods of compliance were allowed: 1) component (e.g., minimum wall R-values), 2) acceptable practice (e.g., typical wall sections), and 3) systems (e.g., computer modeling of entire building). Many states were reluctant to adopt portions of 90-75, because, for example, passive solar could not comply unless a systems approach, very expensive for individual homes, was used. In addition, there was no credit for wall thermal mass.

The State of New Mexico funded its own research in 1976 to develop an alternate method of compliance which would permit credits for thermal mass and passive solar without going to a systems approach (References 18 and 19). Recognizing that steady-state R-values quantify peak wall and window losses or gains, research conducted through the New Mexico Energy Institute at the University of New Mexico calculated effective U-values ("U" is the inverse of "R"), which quantify average heat flows. By the time 90-75 was implemented in late 1977, builders could simply replace steady-state values with effective U-values which, varied with wall type, climate region, color, and orientation. For example, a 10" uninsulated adobe wall, which has a steady-state U-value of 0.24 Btu/hr-ft^2-^{o}F (this includes interior and exterior finish and surface film coefficients), has an effective U-value of 0.05 in the warmest climate and with dark color and south orientation (fully exposed to the sun) -- a reduction of 80%. The same wall in the coldest climate still shows a significant reduction to 0.13. Similar calculations were performed for windows. For example, window areas which face south have a negative effective U-value, which indicates that they are net heat gainers.

Some years later, in 1982, California developed its own energy code, which includes thermal mass credits (Reference 6). For the component package compliance method, mass is traded for R-value; that is, buildings with thermal mass in exterior walls require less R-value than those without thermal mass. In all climate zones and in all packages, walls with greater than 40 pounds per square foot of wall area require far lower steady-state R-values to meet the total building energy budget than buildings with lightweight walls. Typical R-value reductions are from R-19 to R-2.5 and R-11 to R-2.5. Note, however, that California has relatively mild climates -- the coldest climate has only about 5,600 heating degree days. Such large reductions in insulation levels would not be recommended in New Mexico.

It is important to note that both of these energy codes state performance in terms of <u>wall</u> performance, whereas the SWTMS and other thermal mass research results discussed earlier generally state performance in terms of whole building performance. This explains why the thermal mass effects in the codes seem to be much greater. Even after taking this into account, there is still significant disagreement among the research results. This is to be expected: the results are not likely to be the same, due to varying computer models, assumptions, climates, and building configurations.

According to Bion Howard of NCMA, as of 1985, credits for thermal mass are part of the energy code for the following ten states: Arizona, California, Colorado, Florida, Nevada, New

Mexico, North Carolina, Oregon, Utah, and Washington. This includes many of the states where adobe is used. Results are now being compared and refined, and simple, accurate predictive methodologies are being developed. It will likely be several more years before thermal mass credits are used on a nationwide basis.

Recommendations on Use of Thermal Mass

This section presents specific recommendations on how best to utilize adobe or other thermal mass materials in an energy-efficient manner. Some of the recommendations are specific to New Mexico and the Southwestern United States, but the theory, and the recommendations in general, are applicable anywhere in the U.S. The recommendations are based on the Southwest Thermal Mass Study results, current thermal mass research, and current knowledge about passive solar. Many of the recommendations are summarized in Figures 5A and 5B.

Concepts

Take advantage of the unique properties of thermal mass discussed earlier. The ability of mass to store heating or cooling energy, as in passive solar applications, produces the greatest "mass effect" and saves the most energy. Passive solar techniques are recommended and will perform well in massive structures in all but the most mild heating climates. Utilize the moderation of heat flow to reduce energy use and provide a comfortable and steady radiative environment. Use the delay to reduce peak heating and cooling loads and shift loads to off-peak hours when you can use natural heating or cooling sources. Reducing peak loads also reduces the capacity and hence the cost of heating and cooling equipment.

Density

The denser (and usually more conductive) a mass material is, the better, particularly for passive solar applications. This is the exact opposite of wanting a high R-value (low density) for adobe. Mass and insulation have separate functions but can be designed to work together harmoniously. The object is to get as much heat into and out of the mass on a daily basis.

Thickness

A thickness of 10" of adobe seems to be optimum for most applications. The main reason for this is that it provides the optimum delay -- whether for heat flow through conventional exterior walls or through passive solar Trombe walls. A 10" wall provides about an 8-hour delay -- good for both heating and cooling. (Note, however, that for well-insulated adobe walls, the daily variation in heat flow is quite small, so that only a small peak is shifted.)

For interior solar storage (e.g., direct gain), solar research at Los Alamos indicates that only the first 2" to 4" of most mass materials is usable for heat absorption, storage, and release on a daily basis. Although 4" adobe interior veneer could be used, 10" will provide thermal storage for periods longer than a day, and it will provide building structural requirements as well.

Surface Area

Surface area is another important parameter of thermal mass. For both conventional and solar applications, maximize the amount of mass that is in direct contact with the room air and that is in direct "visual" (radiant) contact with the occupants. For direct gain solar situations, place as much mass area as possible in direct sunlight; radiative coupling is far more effective than convective coupling and will reduce overheating. In terms of direct gain thermal performance, there is no "ideal" amount of thermal mass or thermal mass surface area: the more, the better.

Insulation

Insulate thermal mass walls, as you would any other exterior walls. Insulation is recommended in all climate zones of New Mexico. Suggested levels for much of New Mexico are: roof, R-30 to R-40; walls, R-20 (in addition to the R-value of the mass); stem walls (for on-grade floors), R-10. Use more insulation in very cold zones or when using electricity for heating. In hot zones in New Mexico, you could use less insulation because evaporative cooling is so energy-efficient, but not if refrigerated air conditioning is used.

An important finding of the SWTMS and the NBS study (Reference 7), was that floor losses for slab-on-grade floors are significant. It is not usually necessary, or even desirable, to insulate <u>under</u> on-grade floors, but it is important to insulate the stem walls. Be sure to insulate any other potential "thermal shorts" in the building envelope, such as parapets. (See Figure 5.)

Always insulate the exterior of thermal mass; again, thermal contact with the interior space is the key. As a general rule, insulate on the north, east, and west, and glaze the south. The north can take a little more insulation than east and west. Any unglazed south wall area should also be insulated.

Insulate walls with rigid insulation. Three inches of polyurethane or polyisocyanurate will provide R-21, and the cost per R is only marginally greater than polystyrene. Two other methods are used. Foam-in-place polyurethane is more expensive than the rigid, but it seals the building well, and it may be more aesthetically pleasing than the flat surfaces of the rigid insulation. A third option is a frame/batt curtain wall attached to the exterior of the adobe. This also is more expensive than the rigid.

Air Infiltration

Because adobe is a continuous, sealed material, air infiltration is usually (not always) less than in other types of construction. Current construction practice includes exterior stucco and interior plaster, which adequately protect against infiltration through any cracks or gaps which may exist or develop in the adobe wall. Furthermore, there is no indirect infiltration, as can occur in frame walls, where air can penetrate the exterior finish and into the framing/insulation cavity (thereby reducing the effectiveness of the insulation), but not necessarily into the heated space. In general, massive structures are less susceptible to any air infiltration that is present, because the heat is stored in the mass, not in the air.

In any building, massive or not, air infiltration is commonly a major source of heat loss, and careful attention should be paid to caulking and weatherstripping. (In very tight buildings, indoor air quality can be affected and the use of an air-to-air heat exchanger may be required, but this is not usually a problem unless extreme measures are taken.)

Ventilation

In the heating season, ventilation should be used sparingly to remove odors, excessive moisture, and unacceptable or toxic fumes. Homes that are very tightly constructed should use ventilation more. Ventilate during the day, when outside air temperatures are warmer.

In the cooling season when the cooling system is on, leave windows open for evaporative cooling. If you live in a humid area that requires refrigerated air conditioning, keep windows closed.

When the cooling system is not on, thermal mass can be used to its full advantage. When outside air temperature drops to a comfortable level, open windows and doors for natural ventilation. Since 10" adobe has an 8-hour delay, this will often be when the peak heat pulse will be coming through the walls (although in a well-insulated adobe wall, the peak will be not much greater than the average). Ventilate all night and in the early morning until outside air temperature rises to an uncomfortable level. Then close all windows and doors; the lower mass temperatures due to nighttime rejection of heat will keep the space comfortable. Such a strategy can delay the use of the cooling system well into the cooling season, or prevent its use entirely, depending on climate location.

Thermostat Setback

An important strategy for saving energy in buildings is thermostat setback (or "set-up" in the cooling season) during periods when the building is not in use, or when lower temperatures can be tolerated, such as at night. Although this strategy is less effective in massive structures because they take longer to cool down and heat up, it still is effective, and it is recommended that thermostat setback be used. Remember that the building will take longer to respond, so the thermostat should be setback, and reset to its normal position, earlier than in lightweight buildings.

Comfort

Human comfort is a complex phenomenon which involves numerous factors, including air temperature, air velocity, relative humidity level, the radiant environment (temperature and location), clothing and activity level, and acclimation. The key factors are air temperature and the radiant environment temperatures. If the surfaces that the human body "sees" and radiates to are at a temperature below the comfort region, say 55°F, air temperature will need to be greater than normal comfort temperatures, perhaps 80 or 85°F. (Note that a thermostat also responds somewhat to the radiant environment, so a thermostat setting of 75°F might produce an air temperature of 80 or 85°F). This is the case in an uninsulated adobe in midwinter. Similarly, if the radiant environment is warm, lower air temperatures can be tolerated to provide the same comfort level. This is often the case in a passive solar house.

Massive walls reduce variation in the radiant environment and contribute to a more steady overall thermal environment. If walls are at temperatures within the comfort range, this increases comfort, particularly during transition seasons (spring and fall), during dramatic air temperature changes (high solar gain or door open), and in climates which have high daily temperature swings such as New Mexico. Any changes in air temperature that do occur will be slower than in lightweight buildings.

Other Massive Materials

The recommendations and discussions above apply to all other types of earthern construction, as well as to other high-density massive materials such as concrete, bricks, or blocks. In general, the denser and more conductive the material is, the better it performs, particularly as a passive solar heat storage medium. Materials with different thermal properties will likely have different time delay properties, so adjust thicknesses to get the desired delay.

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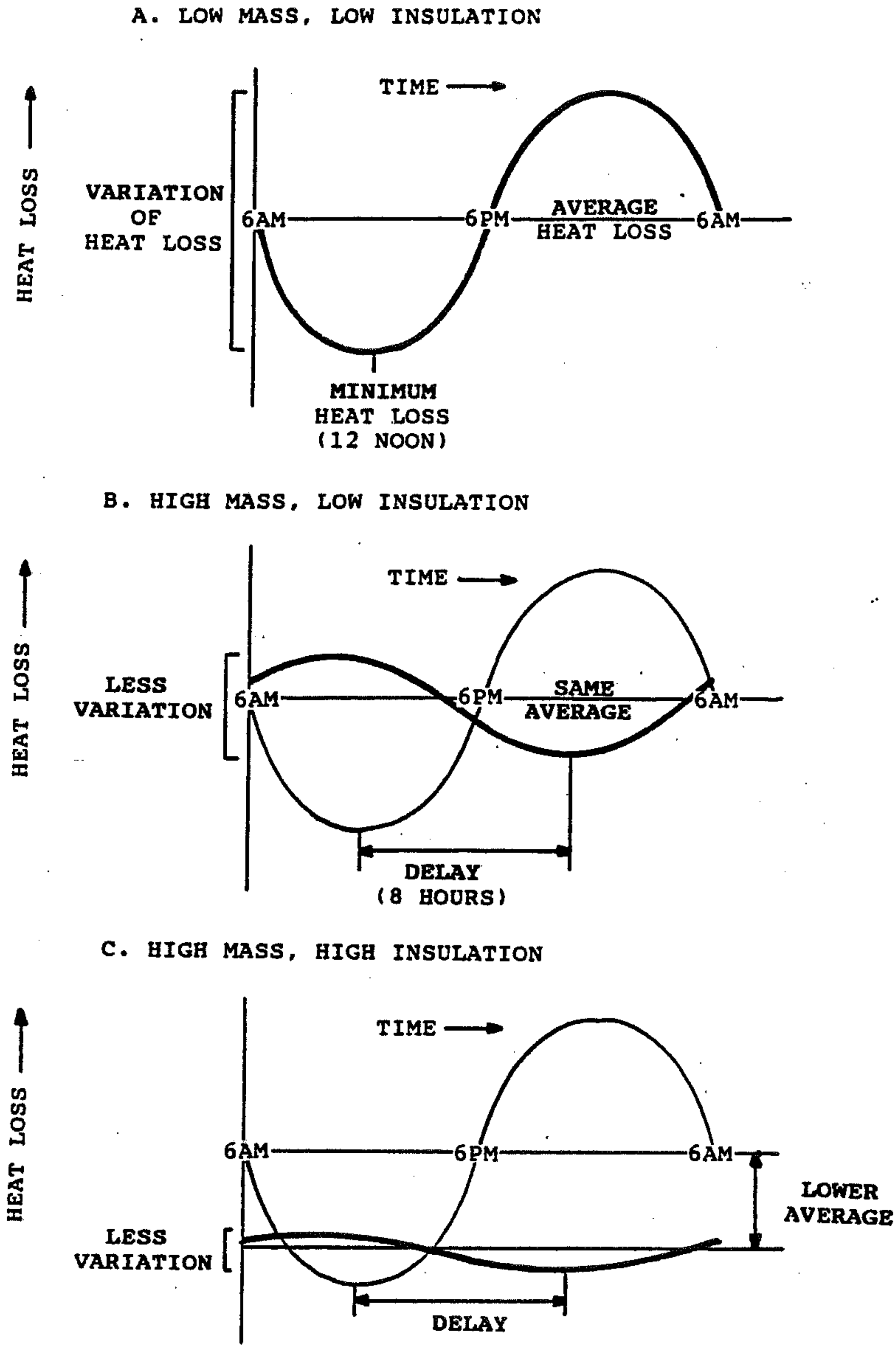


FIGURE 2. THE EFFECTS OF MASS AND INSULATION ON WALL HEAT LOSS. Note that mass reduces variation of heat loss and delays the timing of heat loss, and that insulation reduces the average heat loss.

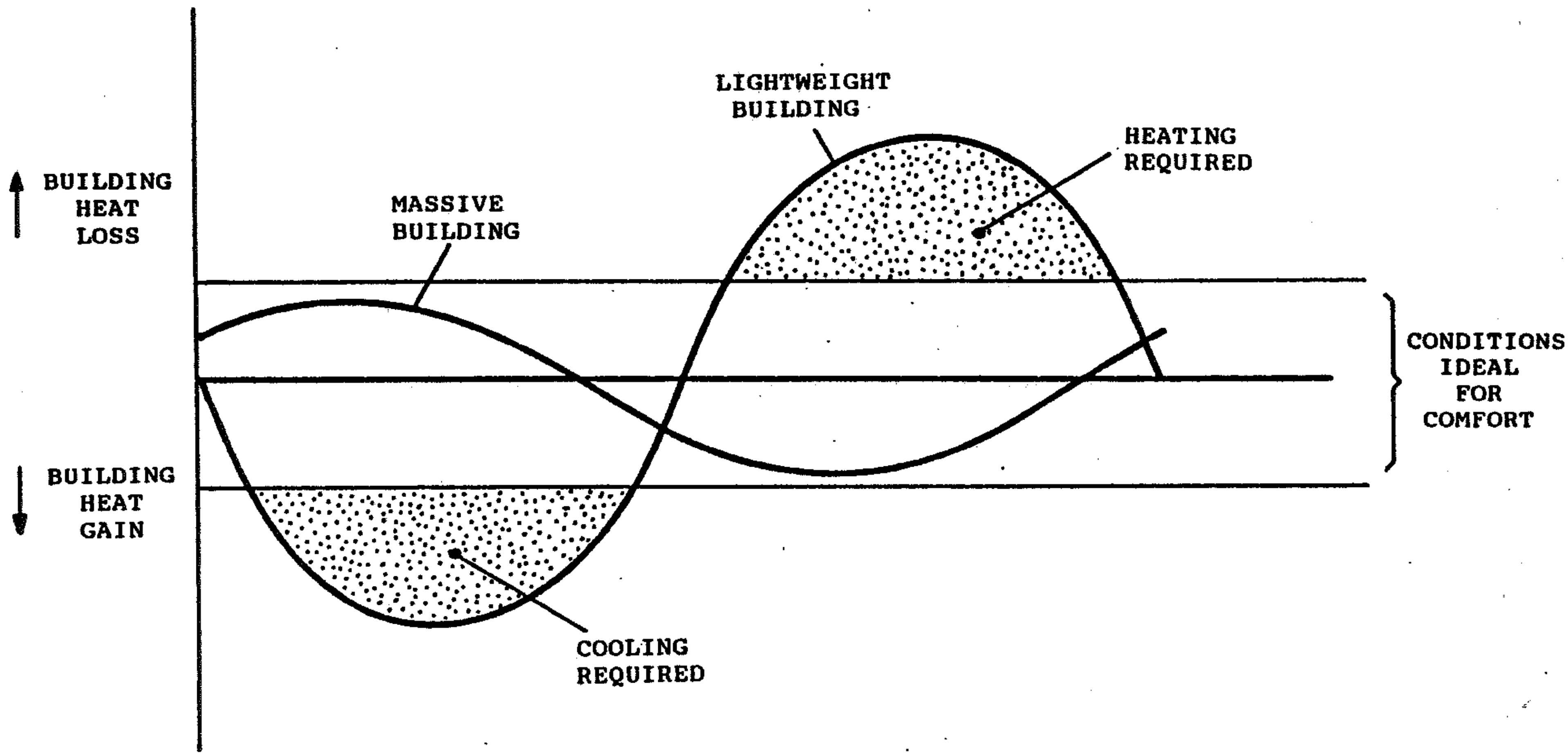


FIGURE 3. DAILY BUILDING HEATING AND COOLING LOADS. Under certain conditions, a massive building might require no space conditioning, whereas a lightweight building with similar insulation levels might require both heating and cooling over the course of a day.

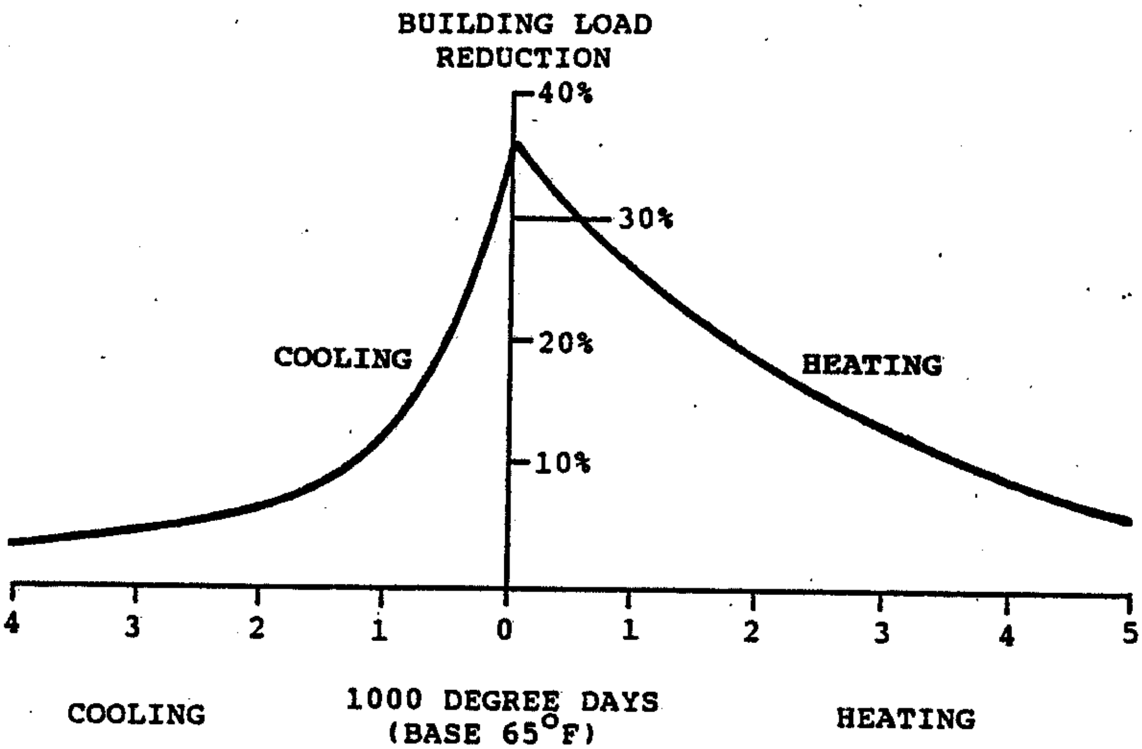


FIGURE 4. BUILDING ENERGY LOAD REDUCTIONS FOR MASONRY WALL VS. WOOD-FRAME WALL. These curves are for walls with 35 pounds per square foot or more. Note that the mass effect is strongly dependent on the mildness of the climate. (Source: The Construction Specifier, June 1985.)

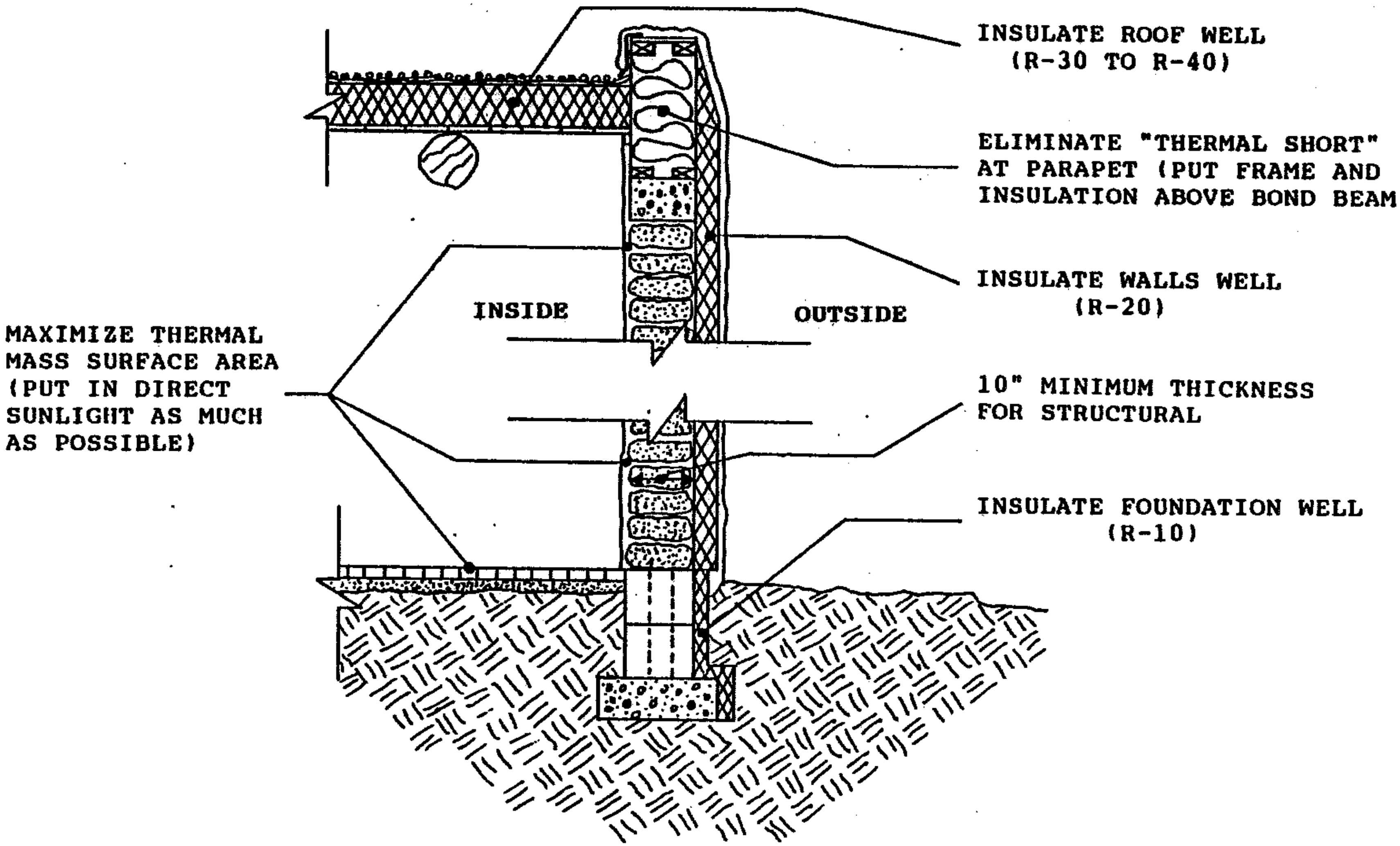


FIGURE 5A. RECOMMENDATIONS FOR USE OF THERMAL MASS IN EAST, WEST, AND NORTH WALLS.

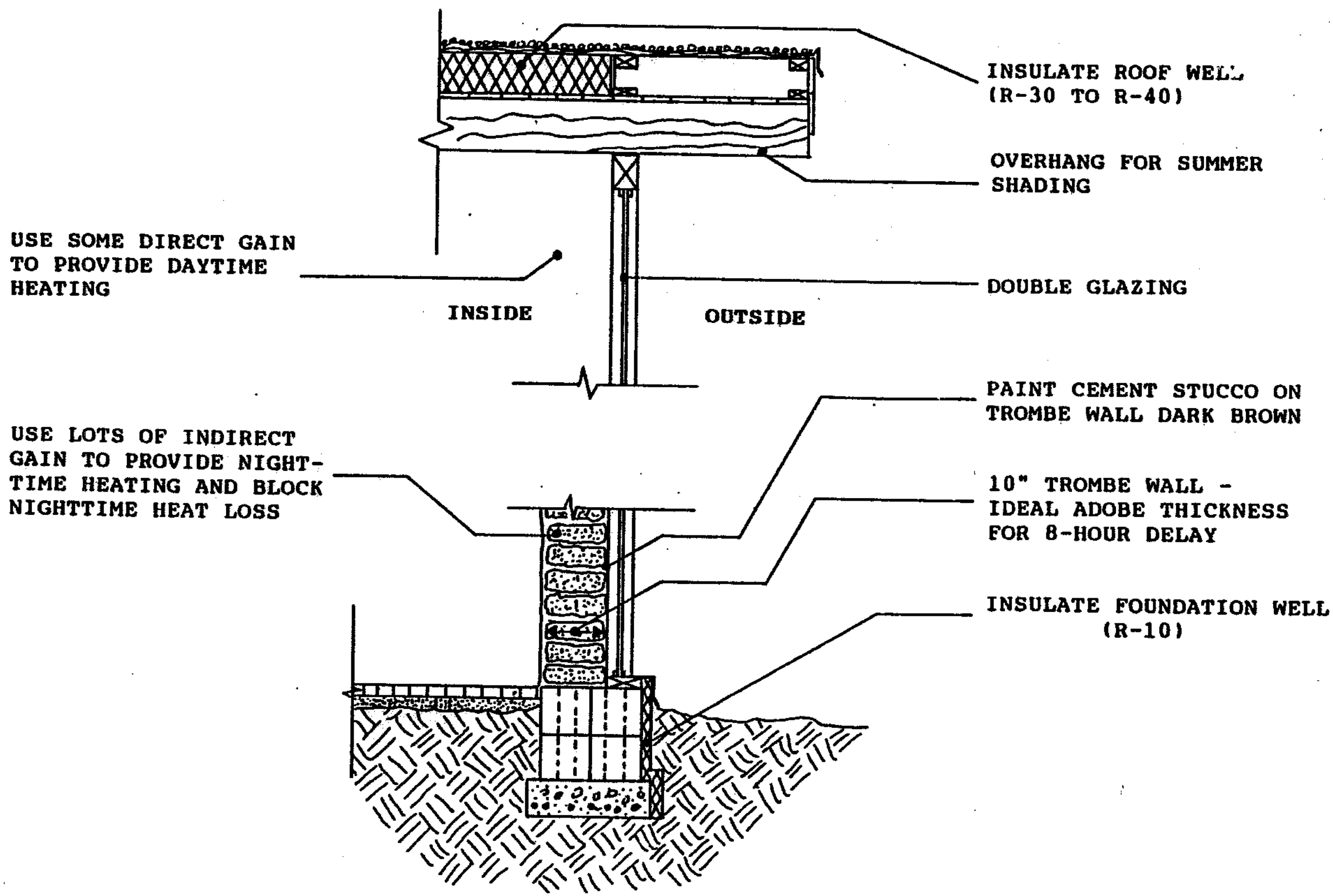


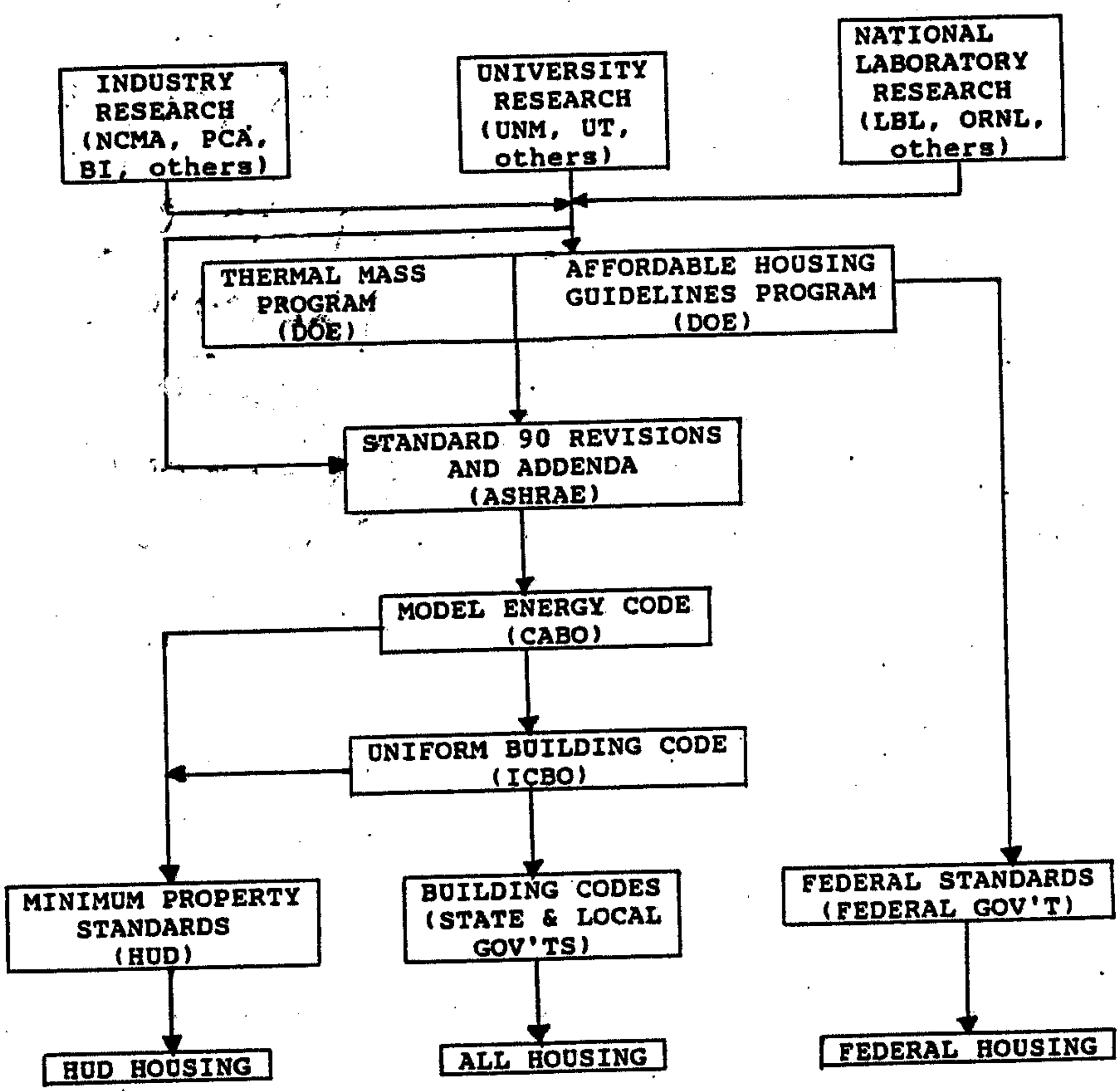
FIGURE 5B. RECOMMENDATIONS FOR USE OF THERMAL MASS IN SOUTH WALLS.

TABLE 1. SELECTED ANNUAL SENSIBLE HEATING AND COOLING LOAD REDUCTIONS FROM BLAST SIMULATIONS. Reductions assume a massless floor and foundation. If concrete slab floors were used in the simulations, these numbers would be considerably smaller (see text).

LOCATION	BUILDING LOAD REDUCTION in percent (absolute in million Btu)	
	Heating	Cooling
ATLANTA, no insulation	10.7 (4.5)	29.7 (8.1)
ATLANTA, R-5 outside	12.1 (3.0)	24.5 (4.8)
ATLANTA, R-20 outside	10.6 (2.0)	19.9 (3.4)
DENVER, no insulation	11.8 (9.6)	52.9 (10.5)
DENVER, R-5 outside	13.6 (6.4)	40.9 (5.8)
DENVER, R-20 outside	12.0 (4.3)	32.0 (4.0)
MINNEAPOLIS, no insulation	2.8 (3.6)	35.2 (5.7)
MINNEAPOLIS, R-5 outside	3.2 (2.6)	30.2 (3.5)
MINNEAPOLIS, R-20 outside	3.0 (2.0)	25.0 (2.6)
PHOENIX, no insulation	39.5 (7.4)	16.7 (11.3)
PHOENIX, R-5 outside	38.2 (3.6)	11.5 (5.5)
PHOENIX, R-20 outside	31.6 (2.1)	8.5 (3.6)
WASHINGTON, no insulation	7.0 (4.7)	36.4 (7.9)
WASHINGTON, R-5 outside	8.1 (3.3)	31.2 (4.8)
WASHINGTON, R-20 outside	7.3 (2.3)	25.7 (3.4)

Assumptions for mass properties: thickness, 7.2"; conductivity, 0.50 Btu/hr*ft*^{o}F; density, 90 lb_m/ft^3; specific heat, 0.30 Btu/lb_m; R-value, 1.2 hr*ft^{2}*^{o}F/Btu. (For comparison, adobe would be: thickness, 10"; conductivity, 0.46 Btu/hr*ft*^{o}F; density, 117 lb_m/ft^3; specific heat, 0.24 Btu/lb_m; R-value, 1.8 hr*ft^{2}*^{o}F/Btu.)

TABLE 2. INCORPORATION OF THERMAL MASS RESEARCH INTO RESIDENTIAL BUILDING CODES AND STANDARDS.



NCMA-National Concrete Masonry Association
PCA-Portland Cement Association
BI-Brick Institute
UNM-University of New Mexico
UT-University of Texas
LBL-Lawrence Berkeley Laboratory
ORNL-Oak Ridge National Laboratory
DOE-U.S. Department of Energy
ASHRAE-American Society of Heating Refrigerating and Air-Conditioning Engineers
CABO-Conference of American Building Officials
ICBO-International Conference of Building Officials
HUD-U.S. Department of Housing and Urban Development