# PERFORMANCE



## structural and thermal

To evaluate how traditional and alternative wall systems and buildings perform structurally and thermally, testing and modeling were performed on material samples and buildings. By measuring their physical characteristics, we can reach useful conclusions regarding the applicability of these systems to meeting today's housing needs.

Of particular concern are earthen materials, such as adobe or rammed earth, which have historically been vulnerable to earthquakes when used in seismic zones. In recent years, research into the structural properties of earth has demonstrated methods of construction that permit the safe use of earthen walls even in earthquake zones. This requires adequate foundations, continuous bond beams at the roof level, and sufficient thickness-to-height ratios for the walls. Because straw bale is a light-weight variant of frame and plaster construction, it does not face as great a threat from lateral forces. However, it raises other concerns, in particular, the need to protect the straw from moisture and rot.

The structural analysis which follows was prepared with the advice of the structural engineer Steven Hess, with materials strength testing performed by Pattison Evanoff Engineering, both of Tucson, Arizona.

The thermal perfomance study investigates the effectiveness of interior conditioning strategies of vernacular houses as compared to a contemporary manufactured housing. Heat loss and gain and the effects of thermal mass walls in contrast with insulated walls are simulated using a computer modeling program, *CalPas 3*, developed by the Berkeley Solar Group.

Energy modeling and thermal performance analyses were performed by Christina Neumann, B.Arch., LEED (TM) A.P. under the direction of Dr. Nader Chalfoun. Dr. Chalfoun teaches architecture and directs the House Energy Doctor program at the University of Arizona in Tucson.

# building systems **STRUCTURAL ANALYSIS**

Traditional houses built with adobe, rammed earth or straw bale walls have withstood centuries of rain, wind, snow and even earthquakes when properly constructed. When built well, they can outlast and out perform conventional wood-frame houses.

Recent research and experience by practicing architects, engineers and builders in the U.S. Southwest have identified the most important factors in the structural stability of traditional wall materials. These factors have been codified as amendments to conventional building codes for earthen and straw bale wall systems.

The structural engineer Steven Hess, a member of the code committee which developed the Tucson/Pima County alternative materials codes, has summarized the critical engineering issues involved with traditional wall materials.

Most U.S. building codes do not specifically provide for earthen building materials. The exceptions to this rule are found in the southwestern states of California, Arizona, and New Mexico, all states with a tradition of adobe construction as a legacy of their Spanish Colonial past. Even in these states, as interest in adobe and rammed earth resurfaced in recent decades, design professionals interested in traditional materials received a cool reception from code officials.

The main stumbling block was the use of tensile design of unreinforced earth. Code officials treated adobe and rammed earth with great suspicion. Very conservative assumptions were made regarding the design properties of earth. Design strengths were assumed to be 30 psi in compression and 4 psi in shear and tension. In reality the compressive strength of adobe is typically much higher, as evidenced by testing performed for this study. Historic adobes from an 1880s era house on Court Avenue in Tucson, Arizona, averaged 177 psi in compression. Modern adobe bricks averaged from 300 for asphalt stabilized bricks, to 450 psi for cement stabilized bricks. Actual strengths can be 10 to 15 times the assumed strength. Compressed earth blocks can achieve even higher strengths and densities.

In southern Arizona, architects and engineers involved with earthen materials came together in the mid-1990s to develop an updated code provision for adoption as an amendment to the International Residential Code (IRC). The result was the joint Pima County/City of Tucson Earthen Materials Appendix Chapter to the IRC, which subsequently has served as a model code for other communities. One of the main concessions of this model code is the "zero-tension" allowance in the design of the earthen walls.

Earthen buildings are vulnerable to lateral forces. Due to its weight, the primary threat to adobe or rammed earth structures is from earthquakes, although wind loads can be a problem for free-standing garden walls. The problem is that earth walls are monolithic and cannot readily be reinforced with tension-resisting elements. An alternate method of analyzing and resisting lateral loads is necessary.

The zero-tension approach works well for non-cantilevered building walls when it is realized that, due to an earthen wall's thickness and mass, fixity at the base of the wall is generated. Using a fixed base with a pinned restraint at the roof attachment elevation, reasonable allowable wall heights are found to be allowed within the code specified design parameters for lateral load combinations.

There are two methods for attaining a pinned restraint of a wall above the base which normally occurs at the roof. Method one is a horizontal diaphragm as traditionally found in most other buildings. Method two is the use of a horizontal bond beam spanning between cross wall supports which are normally constructed of concrete with reinforcing. Method two can be adapted to special cases where no horizontal diaphragm is available for the support of the wall, such as at gable end walls.

A prescriptive Residential Code for Earthen Materials has been written for Pima County and the City of Tucson, Arizona, which utilizes the horizontal bond beam design approach for earthen wall construction. It contains bond beam size tables based on various wind loads and Sds seismic response factors (a value based on the zip code location of the project ). A copy of the current IRC version of this code can be found at :
*http://www.cityoftucson.org/dsd/Codes_Ordinances/Building_Codes/2003_IRC_Amend_v1.pdf*

Engineering principles recognize that cantilevers can still be stable even if the resultant falls outside the kern. Design utilizing zero tension at the cantilever with a focus on the Factor of Safety for Overturning for the stability of the wall will produce moderate cantilevered wall heights. For cantilevered parapets, the code allows a minimum parapet height of two times the parapet wall thickness from the last wall support without calculation. Some designers avoid the cantilevered parapet by using a veneered adobe parapet backed by a braced wood stud wall.

Cantilevered adobe or rammed earth fence walls are designed for wind loads (and seismic as required) using the basic stability of the wall for overturning. It is important to have the masonry or concrete stem as thick as the wall above or if thinner, reduce the design wall width at the base of the wall. A masonry or concrete stem is required to be 6 inches above grade in order to eliminate moisture wicking from the soil below grade into the earthen materials wall. If the earthen materials wall comes in contact, or goes below grade, the moisture in the soil will be absorbed into the wall, wicked up a short distance into the wall, and then evaporate to the atmosphere when it gets to the surface of the wall. As the moisture evaporates, salts carried in solution re-crystallize at or beneath the surface of the earthen wall. These salt crystals expand as they form and cause the outer wall surface to spall off in layers, eventually causing a "cove" at the base of the wall. This condition is referred to as "basal coving".

Roof joist, trusses, and beams supported by earthen walls should bear on top of the wall and as near the center of the wall as practical. Bearing loads in general should not be supported off ledgers (which will produce wall moments from the ledger eccentricity) due to the zero tension provisions of the code. The code will allow up to a 75 lbs/foot of ledger load without calculations which is intended to cover non-bearing ledger conditions or very short spans of hallways or porches. Heavy point loads should be checked for a maximum allowable bearing load of 45 psi.

The general historical earthen wall building configuration is a series of rectangular rooms placed together to form the overall building with generally small window and door openings. House plans for other materials, such as studs and stucco or reinforced masonry, frequently do not convert well to earthen material wall floor plans due to tall walls, large openings, and infrequent shear walls. With this in mind, people wishing to utilize this type of construction may be best advised to go with the most experienced and reputable designers and builders for earthen wall construction.

## STRAW BALE WALLS

Straw bale construction was codified in an amendment chapter to the International Residential Code adopted by code officials in Pima County, Arizona. The Pima County Straw Bale IRC amendment can be found on-line at: *http:/www.dcat.net/resources/Tucson_Pima_Co_SB_Code.pdf* This local amendment has served as model straw bale code, and has been adopted in other localities where straw bale has been used.

The straw bale code is a prescriptive code for load bearing walls. It notes the characteristics for the bales relative to size, plant material, moisture content, and density. The code goes over the basic construction of a straw bale wall relative to the stacking and pinning of the walls and all other aspects of building with straw bales. The actual allowable wall heights and lengths are set by proportions and the only engineering allowable stress given is a 360 psf allowable vertical load (2.5 psi) on top of the walls.

Most engineered straw bale is post and beam type, in which the straw bales serve as infill and the structure derives no structural stability from them. Most engineers regard straw bale walls as highly compressible and not ideal to sustain long-term loadings without deforming and thereby risking damage to the structure.

The most important factor for straw bale is not compressive strength, but the moisture content of the straw. Excessive moisture will cause the straw to rot, or mold to form, causing failure of the wall system. In straw bale construction, it is essential to keep the bales dry. For this reason, parapet type roofs are not recommended. A metal roof with a deep continuous overhanging eave and gutters and downspouts is preferred to guarantee that the water is kept away from the wall. It must be anticipated that load-bearing straw bale walls will compress under full loading over a period of from 4 to 6 weeks during construction. Protective plaster cannot be applied to the exterior until all the potential settlement has taken place.

Because straw bales weigh only 7 pounds per cubic foot (in contrast with 125 pcf for earth), dead-loads from the walls are low. The allowable roof live and dead load delivered to the top of straw bale walls is limited to 360 pounds per square foot (equaling 2.5 pounds per square inch).

Moisture content of straw bales at the time of their installation shall not exceed 20 percent of the total weight of the bale. Five bales are to be selected at random from the lot or shipment of bales to be used in construction. Testing may be performed in the field using an electric resistance moisture meter calibrated to read by percentage, with probes long enough to test the center of each bale. A testing lab may also confirm the moisture content by weighing the bales before and after fully drying them in an oven.

While straw bales vary widely in the type of straw, degree of compaction, density and moisture content, they are nonetheless a uniformly sized, mechanically bundled low-cost unit that can be readily used for super-insulating building blocks. Extra care must be taken in the erection and finishing of this system to ensure its longevity.

TABLE 4.1: COMPRESSIVE STRENGTH OF HISTORIC ADOBE (ca. 1880)

| *Sample #* | *Area (sq. in.)* | *Max Load (lbs.)* | *Strength (psi)* |
|---|---|---|---|
| 1 | 7.26 | 500 | 131 |
| 2 | 9.90 | 650 | 171 |
| 3 | 7.70 | 800 | 210 |
| 4 | 8.36 | 750 | 197 |

Average: 177 psi

*Testing performed by Pattison-Evanoff Engineering, Tucson, AZ*

*Cement stabilized adobe brick for testing. Photo: B. Vint*

Quality control of traditional building materials can be achieved through the testing of samples by a certified testing laboratory. Representative samples should be taken at random from each production run, at a minimum of five samples from each lot. The Earthen Wall Structures amendment to the International Residential Code, as adopted in Pima County, Arizona, is referenced in the annotated bibliography. Compliance with standards must be documented. Testing for this study was performed by Pattison Evanoff Engineering of Tucson, Arizona.

Adobe samples from an historic building, circa 1880, located on North Court Avenue in Tucson were tested to evaluate the properties of adobe over the long-term. After 125 years, the samples average 177 psi in compressive strength (Table 4.1). These are traditional adobes made on site from unamended mud (without the addition of chemical stabilizers). Unamended adobes vary in weight from 110 to 125 pounds per cubic foot, depending upon the soil's clay/sand/silt distribution and resulting block density. Compressed earth blocks have characteristics similar to rammed earth.

Modern adobes, manufactured in mechanized adobe yards, are typically stabilized by the addition of asphalt emulsion or Portland cement. Greater strengths are attained by these adobes, as demonstrated at Table 4.2. The stabilized adobes sampled weigh from 115 to 120 pounds per cubic foot: weight of adobes should be verified with the local brick manufacturer.

Monolithic earthen assemblies must be field-tested during construction for quality control. Following are the specifications and testing procedures for rammed earth developed by Quentin Branch of Rammed Earth Solar Homes Inc., Tucson, Arizona.

1. Soil shall contain not more than 0.2% soluble salts by volume.

2. Soil shall be stabilized with a minimum of 5 percent Portland cement by volume. Sulfate-resistant cement shall be used in regions with high gypsum soil content.

3. The following procedures shall be used to demonstrate compliance with the Earthen Wall Structures, IRC 2000 Section R614:

    A. Soil will be tested from the on-site stockpile as it is being used.

    B. Three specimens will be molded from each 40 tons of earth materials prepared for placement in the walls. One will be moist-cured for 7 days and air dried for 7 days, and will exceed 300 psi when broken. The second sample will be moist-cured for 14 days and air-dried for 14 days, and will exceed 500 psi when broken. The third specimen will be retained for confirmation of 500 psi, if necessary.

## TABLE 4.2: COMPRESSIVE STRENGTH OF MODERN ADOBE (2004)

A. Cement Stabilized (made by Tucson Adobe West)

| *Sample #* | *Area (sq. in.)* | *Max Load (lbs.)* | *Strength (psi)* |
|---|---|---|---|
| 1 | 26.23 | 12,066 | 460 |
| 2 | 26.57 | 11,956 | 450 |
| 3 | 25.51 | 13,265 | 520 |
| 4 | 12.55 | 5,898 | 470 |
| 5 | 12.73 | 4,837 | 380 |

Average: 456 psi

*B. Asphalt Stabilized (made by Old Pueblo Adobe, Tucson)*

| *Sample #* | *Area (sq. in.)* | *Max Load (lbs.)* | *Strength (psi)* |
|---|---|---|---|
| 1 | 26.32 | 7,369 | 280 |
| 2 | 26.24 | 8,134 | 310 |
| 3 | 29.78 | 8,934 | 300 |

Average: 297 psi

*Testing performed by Pattison-Evanoff Engineering, Tucson, AZ*

C. Soil will be tested in accordance with ASTM D558 (Moisture Density of Soil Cement Mixtures) or ASTM D698.

D. A sand-cone density or nuclear back-scatter test will be performed in the wall. The finished wall must exceed 95 percent relative compaction.

E. Copies of the engineering testing laboratory reports shall be attached to the inspection card at the construction site for the building inspector's review.

4. Rammed earth weighs between 123 and 127 pound per cubic foot (average 125 pcf).

A shared characteristic of earthen building materials is that when wet both rammed earth and adobe lose strength. The degree to which moisture affects compressive strength is demonstrated at Table 4.3. Earthen walls may be protected against the deleterious effects of water by cement stabilization or by coating with a compatible plaster.

TABLE 4.3: COMPRESSIVE STRENGTH OF RAMMED EARTH – DRY & WET
*(made by Rammed Earth Solar Homes, Inc. of Tucson)*

| *Sample #* | *Area (sq. in.)* | *Max Load (lbs.)* | *Strength (psi)* |
|---|---|---|---|
| 1 (Dry) | 12.42 | 3,974 | 320 |
| 2 (Wet*) | 12.56 | 1,382 | 110 |

Average: 215 psi

** Soaked for 4 hours*

*Testing performed by Pattison-Evanoff Engineering, Tucson, AZ*


*Rammed Earth test cylinders. One loaded to failure dry. One loaded to failure wet. Photo: B. Vint*

# THERMAL PERFORMANCE ANALYSIS

Indigenous inhabitants of the US/Mexican deserts relied on their instincts to inform themselves about their regional climate to obtain *thermal comfort,* or that state of contentment a body desires within its thermal environment. From Acoma Pueblo to the Gray Ranch, the vernacular examples profiled in *Ch. 2, Design,* feature regional building adaptations that represent a thousand years of research and evolution. These peoples did not have a constant stream of harnessed energy to power mechanical conditioning devices, such as air conditioners or gas furnaces. Instead, they developed building techniques that demonstrate resourceful use of natural forces and materials for passive heating and cooling, such as *solar orientation, thermal storage mass walls, earth cooling, evaporative cooling, vegetated and built shade devices, and natural ventilation.*

Energy-efficient construction and adaptable operational techniques which evolved from the local climate to gain a greater level of thermal comfort are called *passive conditioning* strategies. Since these strategies emphasize thermal comfort with minimal or no energy consumption, they hold important lessons to apply to contemporary affordable housing design. The following section is an investigation of the effectiveness of US Southwest regional passive strategies. It focuses on predicting the thermal efficiency of some pre-selected urban and rural vernacular examples as a function of the site features, building form, and building envelope. *Thermal performance will be measured by the efficiency of the building enclosure to provide thermal comfort rather than the more typically chosen analysis of mechanical heating and cooling loads.* Both urban and rural vernacular houses have been analyzed through field testing and computer energy simulation as separate cases, due to climatic differences between their locations. The urban case is the Fish Stevens Duffield House of Tucson, Arizona, and the rural case is the Upshaw House on the Gray Ranch near Animas, New Mexico. The emphasis here is on strategies that vernacular builders employed for passive conditioning. The performance of these traditional houses will be compared to that of a contemporary manufactured house. The affordability of a house depends on the operational costs for utilities and maintenance over the lifetime of the housing unit, or *lifecycle cost* as much as the initial purchase cost, *or first cost.*

*CalPas 3* is the software used for the energy simulation. Supplemental information on this software can be found in the *Appendix* (see p. 199). Although it is a common practice to use computer simulation to predict heating and cooling loads based on pre-set summer and winter interior temperatures, simulation of traditional buildings is different. Analysis of interior conditions without use of any mechanical system for conditioning requires simulation that will shift the focus to predicting interior "floating" temperatures as related to human thermal comfort. This way, researchers can determine the effect of the building envelope and its role in passively creating a comfortable indoor environment, particularly during summer and winter which are times of seasonal and diurnal climatic extremes. These are the most difficult times for low-income families on a fixed budget who may find themselves with excessively high heating and cooling bills.

*High desert monsoon clouds. Photo: B.Vint*

## DESERT CLIMATE FEATURES

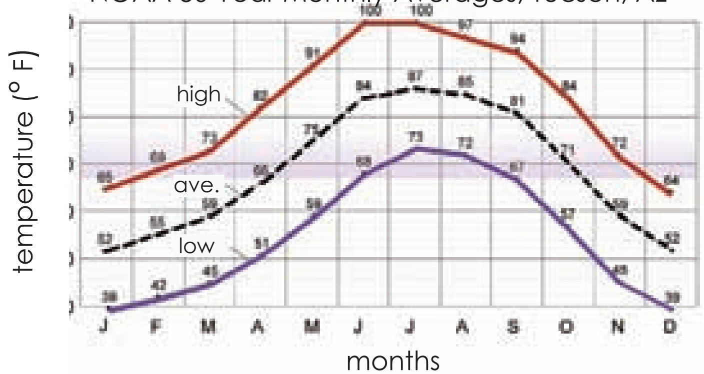
The climate of the U.S./ Mexico border is most characterized by extremes, in both temperature and precipitation cycles. The predominant climatic zone of this region is the semi-arid desert most typified by the following two features:

■ *Rainfall* averages 10-12" per year typically occurring 40-50 percent in the summer monsoon season and 50-60 percent throughout winter after long periods of drought. The landscape is dappled with mountainous regions which create points for condensation thus producing rain. Moisture from the intense summer storms comes northwest from the Gulf of Mexico in Mid-July to September. The winter rains (November to March) originate in the Pacific and produce snows above 6,000 feet. These snows are an extremely important form of natural water storage releasing much needed water during the dry seasons. 80 to 95 percent of the annual stream flow produced is from the winter rains.

■ *Blackbody Raditation:* cloud formation for shade can create large temperature swings from day to night. During all seasons, swings of 32°F or more are common. As the heat of the day builds up, the sparse ground cover, which is typically light in color, creates a high amount of reflectance. Thus, there is little capacity for heat retention so a large portion of the daily heat gain radiates back into the coolness of cloudless the night sky.

## TEMPERATURE

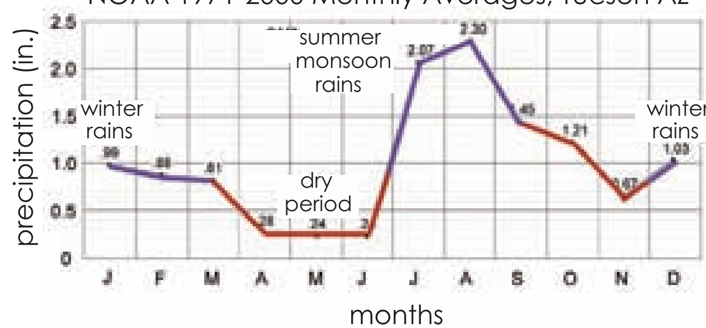
NOAA 30 Year Monthly Averages, Tucson, AZ




*Graph of monthly average maximum and minimum temperatures demonstrates great range of temperatures over the course of the year. Winters tend to be a bit more mild than summers in terms of temperature extremes from human comfort.*

## PRECIPITATION

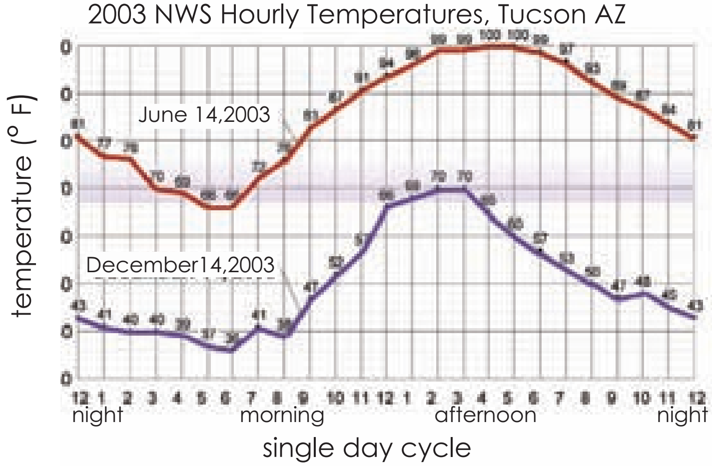
NOAA 1971-2000 Monthly Averages, Tucson AZ




*Graph of monthly precipitation averages shows the two peak times of rainfall in both the late summer and early winter. The driest period is from March to Mid-July.*

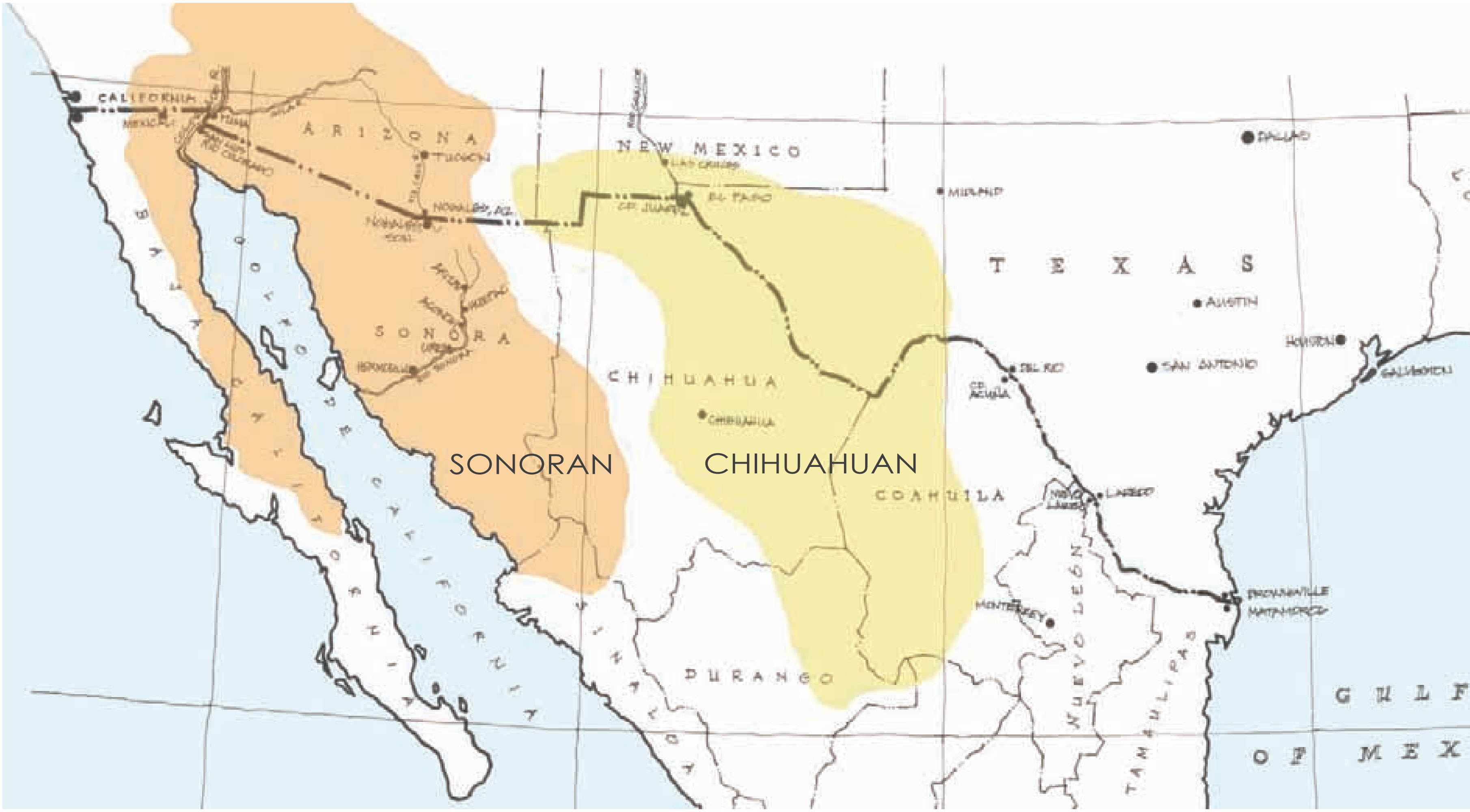
## DIURNAL SWING

2003 NWS Hourly Temperatures, Tucson AZ




*Graph demonstrates the large temperature swing from day to night, typically around 32°F in both summer and winter. This temperature fluctuation is called diurnal swing and is due to the lack of humidity in the air and clearness of the night sky.*

# DESERTS OF THE US/ MEXICO BORDER REGION

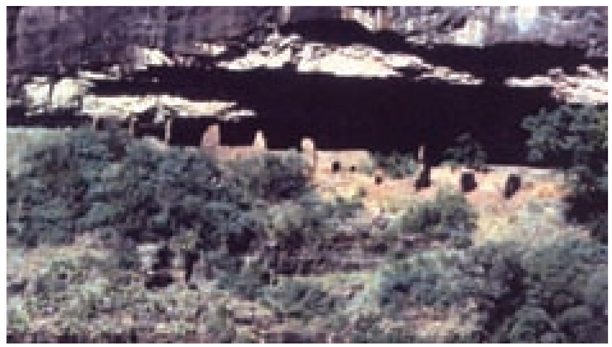



*Sonoran Desert:*
*120,000 sq. miles*

*Chihuahuan Desert:*
*200,000 sq. miles*

*"The steady-state approach to the thermal environment assumes that any degree of thermal stress is undesirable. A constant temperature is maintained in order to save people from the effort and the distraction of adjusting to different conditions. And yet, in spite of the extra effort required to adjust to thermal stimuli, people definitely seem to enjoy a range of temperatures. Indeed, they frequently seek out extreme thermal environment for recreation or vacations... Americans flock to beaches in the summer to bake in the sun and travel great distances in the winter to ski on frosty mountain slopes. People relish the very hotness or coldness of these places (Moore, 32)."*

Bioclimatic design is the development of habitat which takes into consideration environmental variables like dry bulb temperature, relative humidity, air movement and radiation to human perception and response (Peyush Agarwal, University of Arizona,1998 ). The correct balance of these variables create a state of thermal comfort. If you're a lizard, it may mean sitting in the warm afternoon sun to heat your cool reptilian body. Yet in the same conditions, a human may be wanting to keep cool by sitting close to a water body (aka. the pool).

*The desert tortoise dwells in earthen burrows where it can be protected from extreme ground surface temperatures that range from freezing to 160 °F. The natives of Sierra Ancha (east Arizona) built stone and earthen burrows within the cliffs.*
*Photos: (l.)USGS-* Curtis Bjurlin, photographer *(r.) B.Vint*


*Shelter producing shade is essential for desert survival as it prevents excess water loss by transpiration and overheating. The spines of the hedgehog cactus provide the same function as the woman's umbrella, subduing the direct sunlight.*
*Photos: (l.)C.Neumann (r.)B.Vint*

Approximately 2,500 species inhabit the Sonoran Desert, alone. The border region also encompasses the Chiuauan Desert. This wealth and diversity of plant and animal life in the border region proves that natural strategies to protect from the extremes of the climate have been effective for thousands of years. Many desert creatures are less active by day and increase their activity at night and early morning when their bodies will work more efficiently. The siesta, or period of rest from early afternoon until evening, is a cultural practice in many warm regions. By being active during cooler times, excess energy is not needed to condition enclosures. In addition, traditional clothing is often loose and light in color to limit dehydration via perspiration and minimize solar absorption.

## NATIVE SHELTER

To temper severe exterior conditions, a heavy barrier is one of the most effective strategies. The relatively high thermal capacity of thick earth walls help moderate the interior temperature by retarding heat flow and retaining occupant humidity and act as a heat sink. Pack rat holes, desert tortoise burrows and adobe homes all function in this manner. According to Alexis Karolides of the Rocky Mountain Institute, the Mexican settlers of San Luis Valley, CO, gauged the thickness of their adobe home's walls by the depth of local ground squirrel holes.

## BUILDING ENCLOSURE

▪ *thermal mass and wall thickness*

Thermal tempering technique which uses high mass materials with greater thermal storage capacity (traditionally adobe or stone) to absorb and hold thermal energy therein creating a thermal barrier. This technique works most effectively in a diurnal (24 hour) cycle when there is a great temperature differential (32°F) from night to day due to the aridity. In summer months, the massive walls create a cooler more thermally comfortable interior, maintaining a space temperature lower than skin temperature during times of day when solar heat gain is most intolerable.

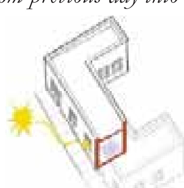
▪ *the diurnal cycle (in cooling)*

Noon- *Mass walls are absorbing heat from day. Interior temperatures of home are still very cool.*

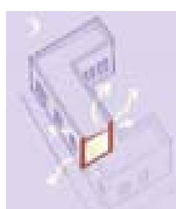
6 pm- *Mass walls closer to heat storage capacity. Interior temperatures of home have risen but still are thermally tolerable, as compared to outside conditions.*

Midnight- *Exterior surface temperatures are dropping as heat is being released into night sky. House should be opened for natural ventilation to cool down interior discharging heat from massive walls.*

6 am- *Walls and interior space have released stored heat from previous day into cool night sky.*



day



night

**see Ch.2, Design:*
*Casa Grande, Court Ave., Casa Cordova*

## BUILDING FORM

▪ *surface area and shared walls*

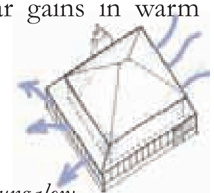
A technique to increase thermal efficiency of enclosure is by decreasing the surface area of the thermal barrier in relation to its volume. This is a traditional technique in extreme climates, both warm and cold, and often several living units are attached by shared walls. The *S.V.R.* or Surface to Volume Ratio is one way to measure this efficiency.

s.v.r. = s.f. (exterior)/ c.f. (gross)

**see Ch.2, Design:*
*Acoma Pueblo, Court Ave.,*
*Fish Stevens Duffield House, Empire Ranch*

▪ *windows: size, location and shading devices*

Openings in the building enclosure allow the modulation of solar gain and natural ventilation. Size is an important variable. Oversized windows may allow unwanted heat gain in summer while undersized windows will impede the cooling effects of natural ventilation and passive solar gain for warmth in winter. Orientation of windows is important as well since both cross (across space) and stack (from low to high points in space) ventilation become more effective when windows are aligned with prevailing winds. Shading devices, such as overhangs, light curtains, and shutters work, in passive cooling to modulate light and ventilation but prevent intense direct solar gains in warm months.

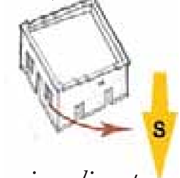


** see Ch.2, Design:*
*Court Ave., Gray Ranch*
*Fish Stevens Duffield House, Bungalow*

## SITE FACTORS

▪ *solar orientation*

Positioning of the building to optimize solar gain during winter and minimize solar gains during summer. In the US/Mexico border region, a south orientation for the length of the house is best for passive conditioning in all seasons. In winter, thermal mass on the interior of the house helps to absorb heat and keep interior conditions comfortably warm when it is cold outside *(see "thermal mass and wall thickness.)"*




**see Ch.2, Design:*
*Acoma Pueblo, Gray Ranch*

▪ *vegetative barriers and site microclimate natural evaporative cooling and ventilation*

Arrangement of the building components to expose a significant amount of the living spaces to a thermal buffer zone. In traditional building, the courtyard normally functions to create a vegetated mircroclimate which provides cooling via shade and humidity. The shade provided by the vegetation allows for a greater number of larger openings which help to vent the interior of the house and the thermal mass at night. The courtyard also provides a secure place to sleep at night when the house is releasing the heat from the day and the interior spaces may be uncomfortably warm for occupants.

** see Ch.2, Design:*
*Casa Cordova, C.O. Brown*
*Fish House (Fish Stevens Duffield House)*

## thermal performance analysis

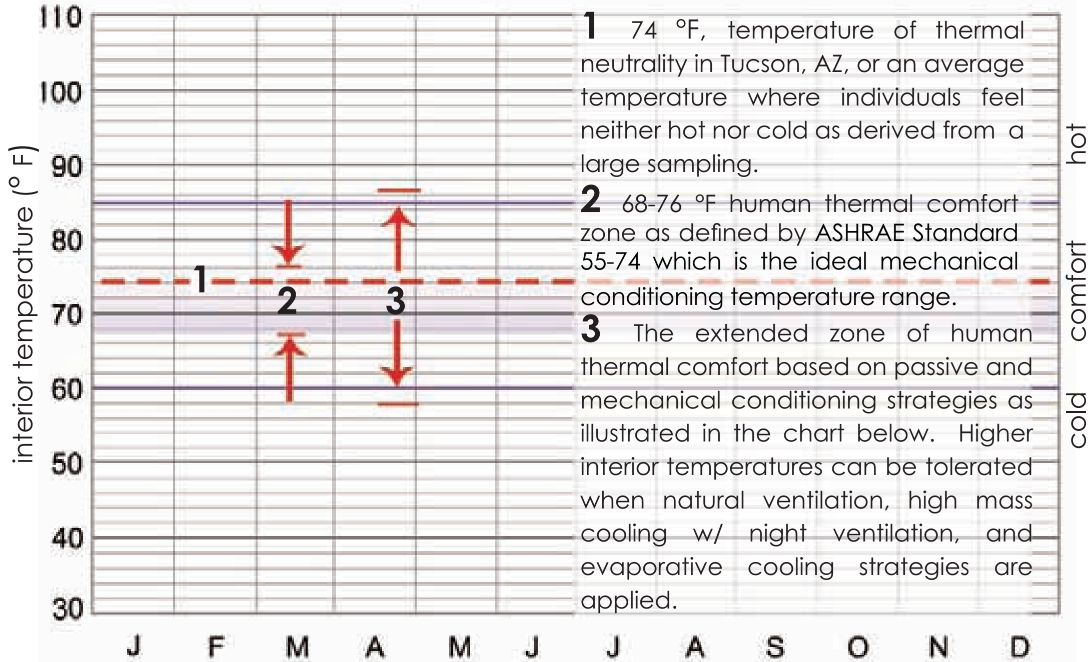
Most results of this study are displayed in the form of graphs, such as the example at right, which chart each modeled building's monthly interior temperature over the course of a year. The emphasis is upon analyzing bioclimatic data, mainly high, low, and mean interior temperatures, as opposed to the more conventional approach with predicted energy loads. These loads are created by mechanical systems which keep the building interior at constant temperatures within the typical human comfort zone. As defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55-74, the human comfort zone range is from 68-76 °F pending these conditions are met:

- *Mean Radiant Temperature (MRT) equals Dry Bulb Temperature (DBT)*
- *Still Air Condition equals 0.2 m/s (40 ft/min.)*
- *Relative Humidity is 30%- 60%*
- *Occupant is sedentary, normal dress*

This human comfort zone is represented by the purple band in the graphs, as in the example to the upper right. The psychrometric chart to the lower right is another bioclimatic analysis tool which combines the predicted mean interior temperatures (dry bulb temperature) with other data such as wet bulb temperature and relative humidity to define human thermal comfort conditions and strategies to extend this zone. These strategies include passive solar heating, natural ventilation, evaporative cooling, high mass cooling in addition to mechanical heating and cooling. Overall, the study's approach to measure predicted mean interior temperatures allows analysis of the building's thermal performance by passive means as it traditionally functioned to condition the interior spaces.

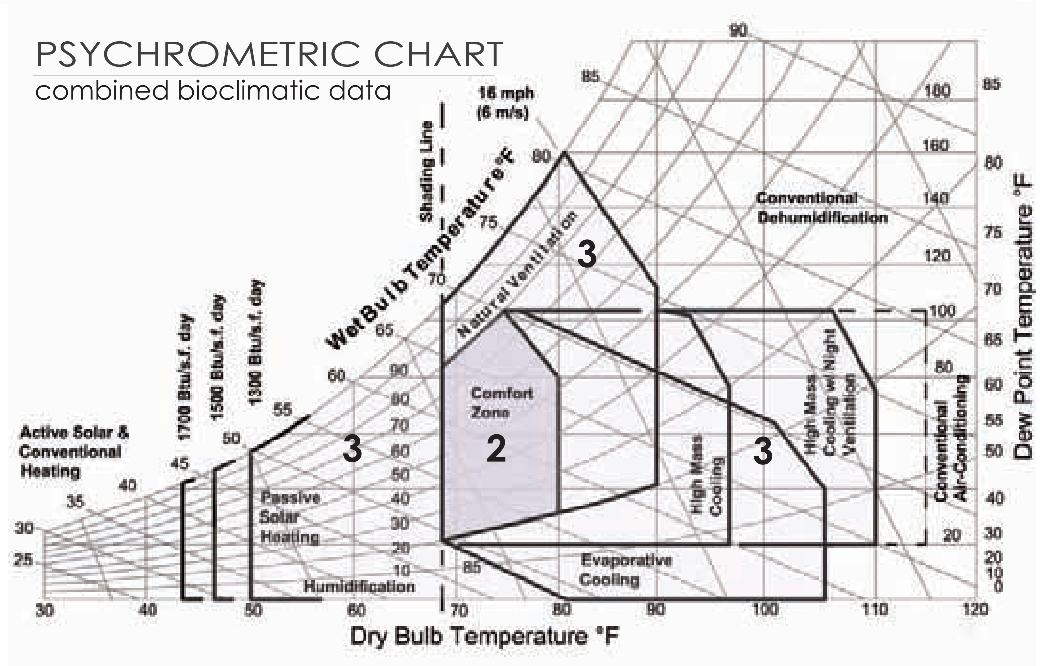
## EXAMPLE GRAPH

mean monthly temperatures




## PSYCHROMETRIC CHART

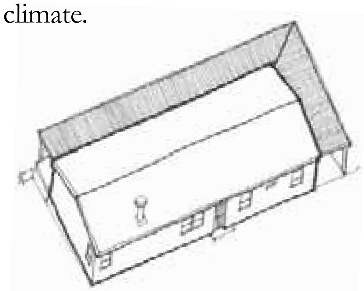
combined bioclimatic data



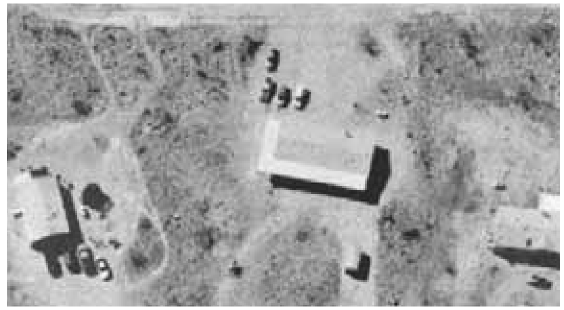
## BASE CASE ANALYSIS
### manufactured house

The base case is a manufactured house to be compared with the traditional urban and rural housing examples. This house, located in Tucson, AZ, is a 2x4 wood frame 1659 s.f. manufactured house with light grey vinyl exterior siding and asphalt shingle roofing.

Wood framed buildings, such as this base case, are classified as *low mass construction* since they are primarily composed of low density and low conductivity materials, such as vinyl paneling, wood studs, fiberglass insulation, and gypsum panel board. Adobe and concrete block buildings are of *high mass construction* and have a thermal storage capacity anywhere from eight to forty-five times that of wood. Adobe block has 680 times the thermal storage of fiberglass (Moore, 12). Low mass systems maintain interior conditions by creating a thermal barrier instead of absorbing heat like a high mass system. Therefore, it makes no difference if an insulated or uninsulated house is used for comparison purposes to the traditional high mass buildings in this study, since both conditions represent low mass construction (see similar results to graph at right). The study seeks to measure efficiency of passive conditioning techniques, particularly mass effect and natural ventilation in an arid climate.



**For scaled house plans and supplemental information, such as area and volume, see Appendix.*

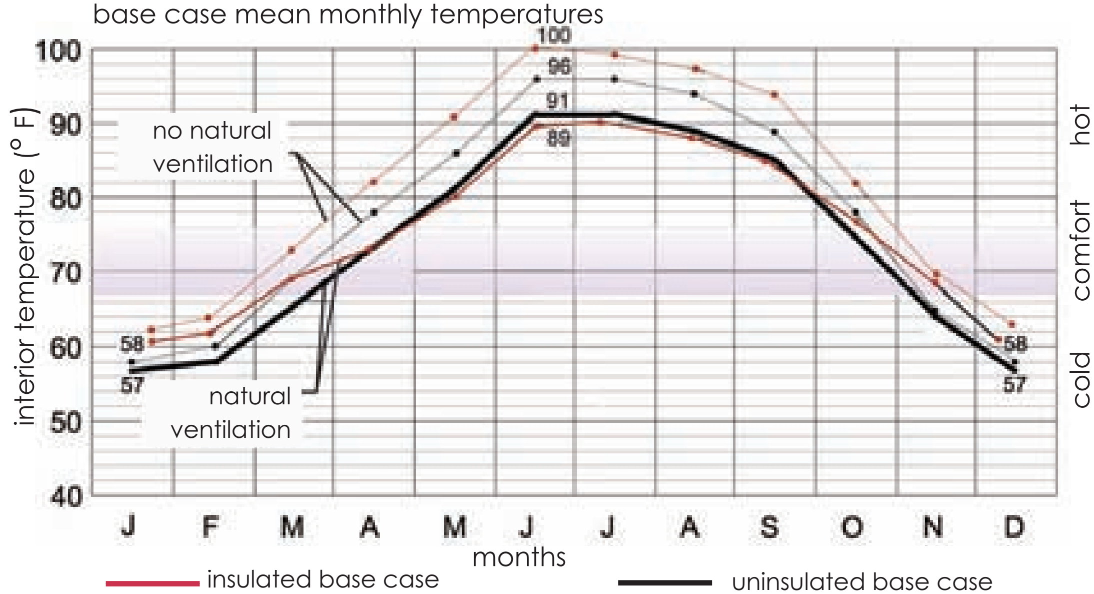


*Aerial Site Photo: Pima County Maps Dept.*

*Base case South Elevation Photo: C.Neumann*


*Base Case Plan.*

## MANUFACTURED HOUSE
base case mean monthly temperatures



**R ROOF-** NOT INSULATED

| | BTWN RAFTER (90%) | @ RAFTER (10%) |
|---|---|---|
| INSIDE SURFACE | 0.62 | 0.62 |
| 5/8" GYPSUM BOARD | 0.56 | 0.56 |
| 1/2" PLYWOOD | 0.63 | 0.63 |
| NOMINAL 2x6 RAFTER | --- | 5.22 |
| 6" FIBERGLASS BATT INSUL. | --- | --- |
| PLYWOOD SHEATHING | 0.61 | 0.61 |
| PERM.FELT MEMBRANE | 0.06 | 0.06 |
| ASPHALT SHINGLE ROOFING | 0.44 | 0.44 |
| OUTSIDE SURFACE | 0.17 | 0.17 |
| | TOTAL R: 3.09 | 8.29 |

AVE R = 3.61 **U= 0.28**

**R WALL-** NOT INSULATED

| | BTWN STUDS (92%) | @ STUDS (8%) |
|---|---|---|
| INSIDE SURFACE | 0.62 | 0.62 |
| 5/8" GYPSUM BOARD | 0.56 | 0.56 |
| 1/2" PLYWOOD | 0.63 | 0.63 |
| NOMINAL 2x4 STUD | --- | 4.35 |
| 6" FIBERGLASS BATT INSUL | --- | --- |
| PLYWOOD SHEATHING | 0.61 | 0.61 |
| VINYL PANELING | 0.61 | 0.61 |
| OUTSIDE SURFACE | 0.17 | 0.17 |
| | TOTAL R: 3.20 | 7.55 |

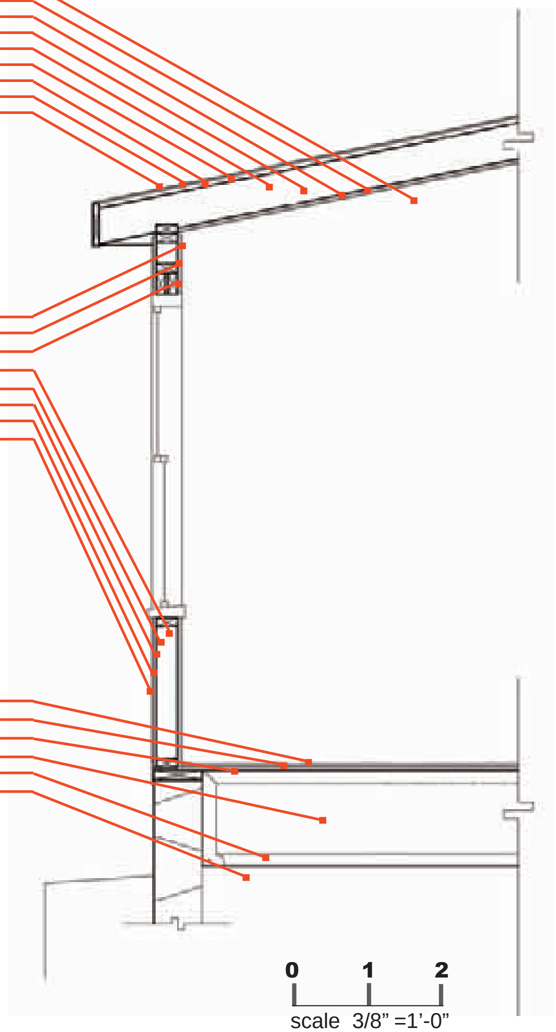
AVE R = 3.55 **U= 0.28**

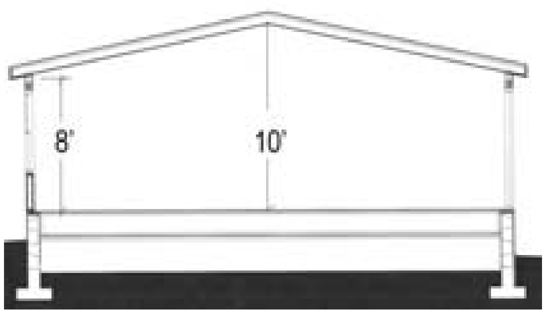
* NOTE: U-VALUE FOR SINGLE PANE VINYL WINDOW= 0.5 ACCOUNTED FOR IN CALPAS 3 AS SEPARATE ELEMENT FROM ROOF, WALL, OR FLOOR.

**R FLOOR-** NOT INSULATED

| | BTWN TJI (96%) | @ RAFTER (4%) |
|---|---|---|
| INSIDE SURFACE | 0.62 | 0.62 |
| CARPETING W/ RUBBER PAD | 1.23 | 1.23 |
| 1/2" PLYWOOD | 0.63 | 0.63 |
| 16" DEEP TJI | ---- | 16.0 |
| 6" FIBERGLASS BATT INSUL | ---- | ---- |
| OUTSIDE SURFACE | 0.17 | 0.17 |
| | TOTAL R: 2.65 | 18.36 |

AVE R = 3.29 **U= 0.30**




*base case building section*

MANUFACTURED HOUSE TYPICAL WALL SECTIONS

## ANALYSIS #**1**

### urban adobe house

The Fish Stevens Duffield House in Tucson, Arizona is the urban study case to be compared with the standard manufactured home base case. Urban climates are typically characterized by the following features:

▪ *Elevation:* Traditionally, urban centers naturally developed around water sources both for agriculture and trade. In the case of many border cities such as Tucson (2400 ft above sea level), these water sources are at lower elevations as compared to rural regions. As a rule of thumb, temperatures will rise in summer by 1°F for each 330 ft elevation drop, or *adiabatic lapse rate* (Moore, 57).

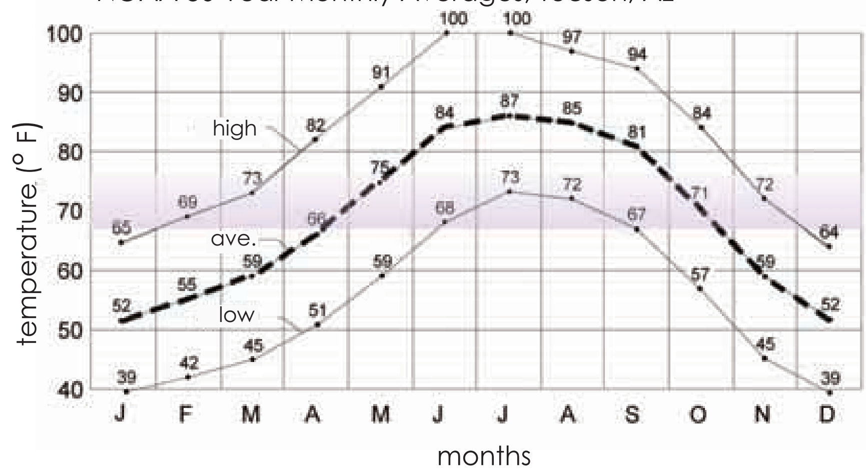
▪ *Heat island effect:* Due to the prevalence of concrete and asphalt paved area which retain heat, and the lack of ground cover and vegetation, little humidity is retained and temperatures are higher.

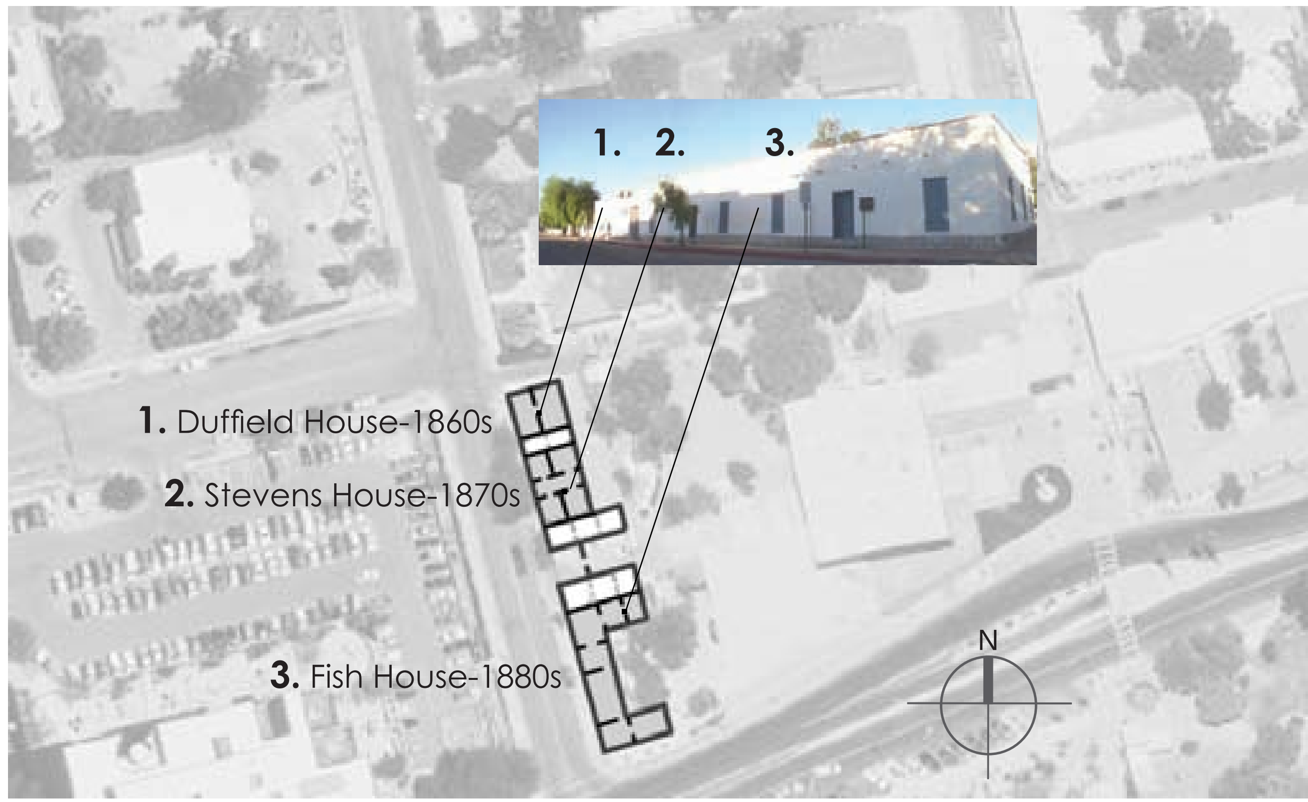
▪ *Terrain friction and windbreaks:* Urban obstructions, which include buildings and street trees reduce wind speeds which can be a hindrance to cooling in summer but help elevate temperatures in winter to aid in heating. Greater building density dramatically changes wind patterns at ground level.

▪ *Building density and configuration:* Produces distinctly different microclimates in traditional urban centers. Entire blocks of housing dating to historic Territorial era construction (1850s-1920s) exhibit shared mass walls. This situation can make passive cooling via natural ventilation more challenging but can lower energy costs since surface area of individual units is reduced. In addition, window opening and placement may be decided with respect to the urban context for or security.

## TEMPERATURE

NOAA 30 Year Monthly Averages, Tucson, AZ



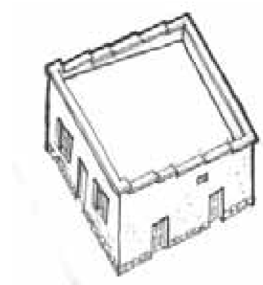

*Aerial view of Fish Stevens Duffiled House in the center of Downtown Tucson. Pima County Maps Dept.*

These individual unit plans are all part of the Fish Stevens Duffield House in the historic El Presidio Neighborhood of Tucson, Arizona. Each of these individual units correspond with the urban vernacular archetypes presented in *Ch 2, Design*. The wall and sub-roof is composed of high mass adobe as demonstrated in the building section on the next page which is a typical condition for all three houses. The 675 s.f. Duffield House, dating to the 1860s, is a two-room adobe structure and basically determined the orientation, height, and width of the subsequent attached houses.The placement of this house on a north-south axis, with its primary entrance opening to Main Avenue, was based upon the urban street layout.

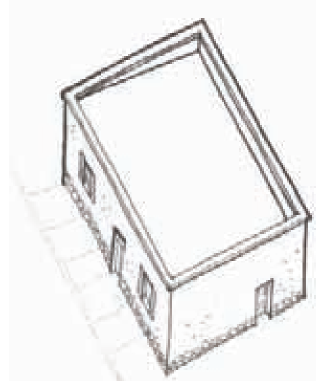
The 1020 s.f. Stevens House, with its central hallway, exemplifies the zaguán plan (*see Ch.2, Zaguán House*) and was connected as an addition to the Duffield House in the 1870s.

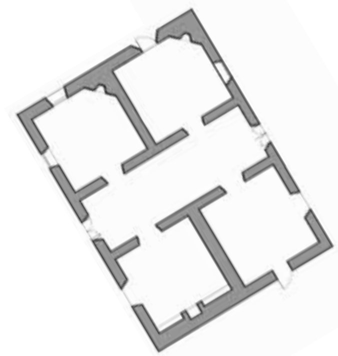
Finally, the 2136 s.f. Fish House was added to the complex in the 1880s and is typical of a courtyard house which accommodates a courtyard on the east side. All are composed of 20”-24” thick exterior adobe walls, 16” interior adobe walls and have an earth and saguaro rib ceiling below a built-up roof system which was added in the 20th Century. Windows are wood-framed, single-pane double-hung with louvered shutters on the exterior and light curtains. The concrete floors are also a 20th Century addition. The section on the next page shows in detail the material composition.

**For scaled house plans and supplemental information, such as conditioned area and volume, see Appendix.*

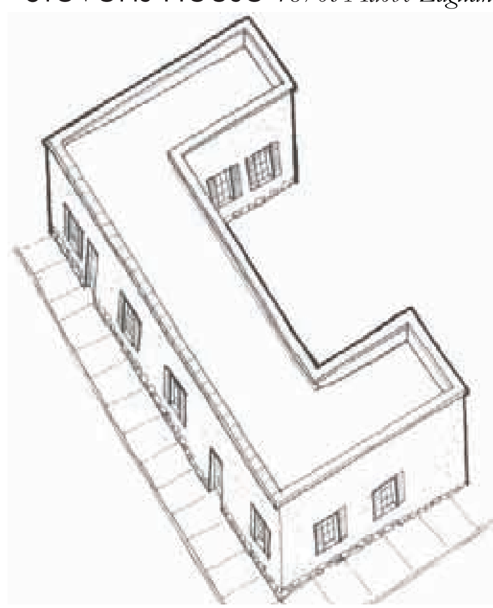


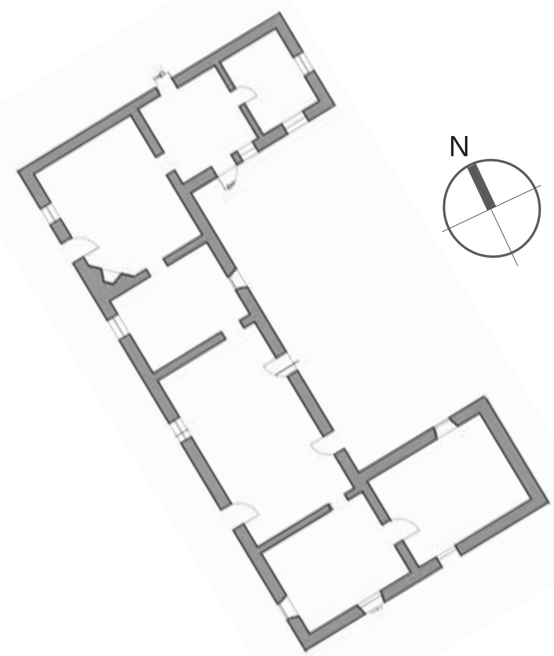
Duffield House *1860s Adobe Row House*





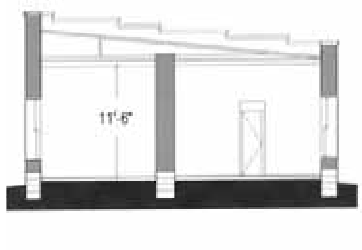
Stevens House *1870s Adobe Zaguán*



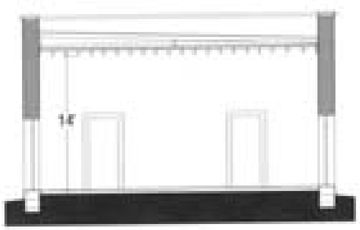



Fish House *1880s Adobe Courtyard*

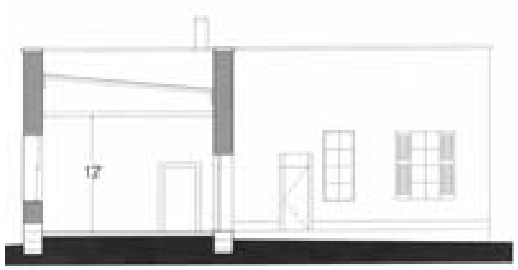
# CONDUCTIVITY AND HEAT RESISTANCE




*Duffield house section*




*Stevens House Section*




*Fish House Section*

**U ROOF-** BUILT-UP ROOFING ABOVE ORIGINAL EARTH ROOFING

| | BTWN RAFTER (90%) | @ RAFTER (10%) |
|---|---|---|
| OUTSIDE SURFACE | 0.17 | 0.17 |
| SILVER PAINTED BUILT-UP ROOF | 0.33 | 0.33 |
| 3/4" PLYWOOD SHEATHING | 0.93 | 0.93 |
| ROUGH SAWN 2x6 RAFTER | -- | 6.11 |
| 6" EARTH ON SAGUARO RIB | 1.74 | 1.74 |
| 6" TIMBER BEAM | -- | 6.11 |
| INSIDE SURFACE | 0.62 | 0.62 |
| TOTAL R: | 3.79 | 16.01 |

AVE R = 5.0 $\boxed{U= 0.2}$

**U WALL-** UNINSULATED PLASTERED ADOBE

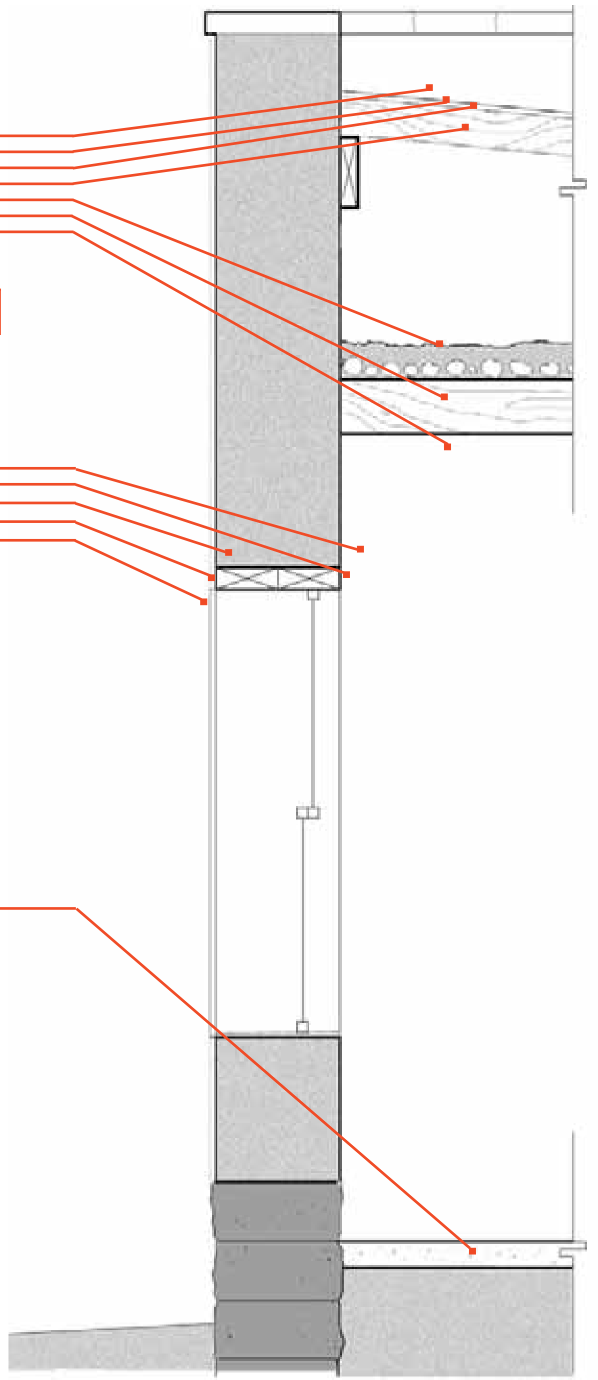
| | |
|---|---|
| INSIDE SURFACE | 0.62 |
| 1" LIME PLASTER SURFACE | 0.61 |
| 22" UNSTABILIZED ADOBE | ----- |
| 1" LIME PLASTER SURFACE | 0.61 |
| OUTSIDE SURFACE | 0.17 |
| TOTAL R: | 2.01 |

$\boxed{U= 0.51}$

ADOBE SPECIFIED HAS A VOLUMETRIC HEAT CAPACITY OF 25 BTU/CF-F AND CONDUCTIVITY OF 0.30 0 BUTH-FT/S.f.-F.
U-VALUE FOR SINGLE PANE VINYL WINDOW= 0.5
ACCOUNTED FOR IN CALPAS 3 AS SEPARATE ELEMENT FROM ROOF, WALL, OR FLOOR.

**U FLOOR-**

4" CONCRETE SLAB FACTORED AS MASS ELEMENT IN CALPAS 3 UNDER THE "SLAB" COMMAND. THE DENSITY OF THE STANDARD CONCRETE SPECIFIED IS 140 LBS/ CF. VOLUMETRIC HEAT CAPACITY IS 28 BTU/CF-F AND CONDUCTIVITY IS 0.980 BTUH-FT/ S.f.-F. NO CARPETING IS APPLIED TO THIS SURFACE.




# URBAN ADOBE TYPICAL WALL SECTIONS

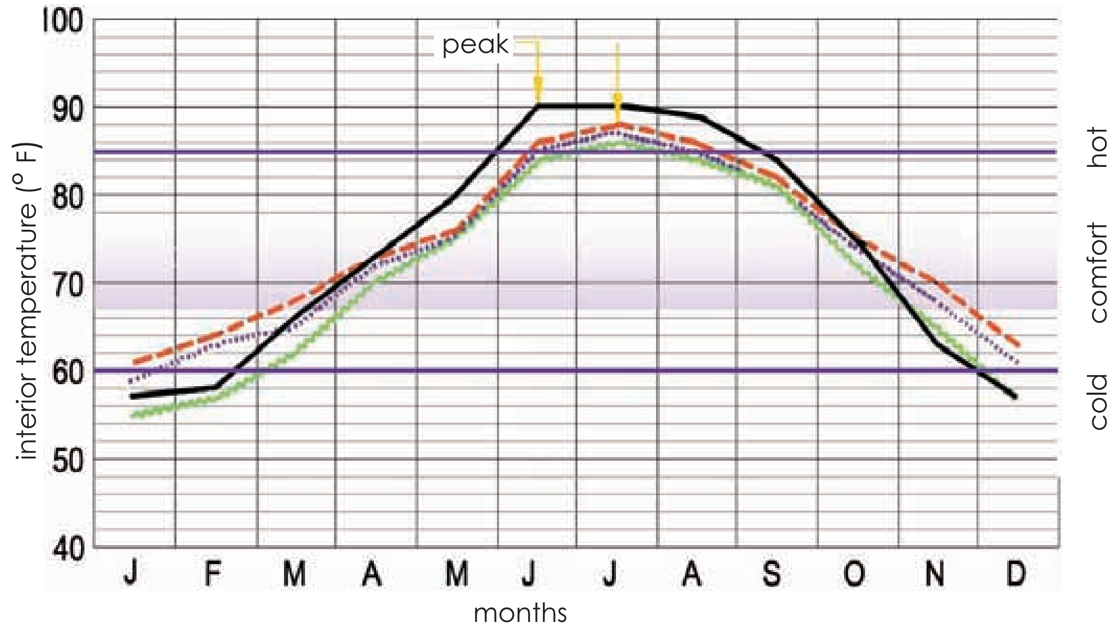
## EFFECT OF BUILDING FORM

■ *investigation summary:* Analyze thermal performance as a function of monthly mean interior temperature for manufactured housing base case and three urban adobe cases.

■ *investigation results:* Although variables such as square footage and orientation vary between the base case and urban cases, the results indicate the relative effectiveness of combined thermal mass, natural ventilation and shutters. All three urban cases are predicted to perform better than the base case in both passive heating and cooling. Interestingly, all adobe cases will reach a peak interior temperature a month after the base case demonstrating their ability to delay heat gain. The Duffield House performs best in passive heating by 2-6°F while the Fish House is best in cooling by 2-4°F. The compact form of the Duffield and Stevens Houses is effective in passive heating unlike the thin form of the Fish House, which accommodates an east courtyard, and allows for more wall/window surface area. In the buildings historical state (no thermally engineered windows, doors and roof) this building form is an asset in passive cooling but a liability in passive heating with the building's current north-south orientation.

### MEAN MONTHLY TEMPERATURE COMPARISON

Fish Stevens Duffield Houses vs. Manufactured House

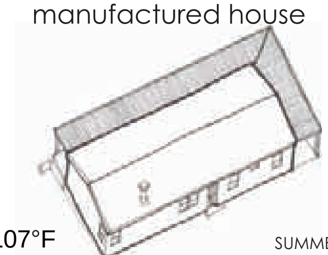



1659 s.f. s.v.r.* = 17%
base case
manufactured house

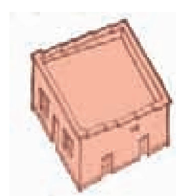
675 s.f. s.v.r.= 17%
Duffield House

1020 s.f. s.v.r.= 28%
Stevens house

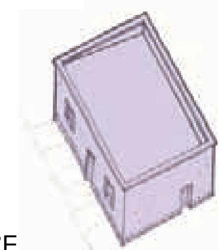
2136 s.f. s.v.r.= 31%
Fish house



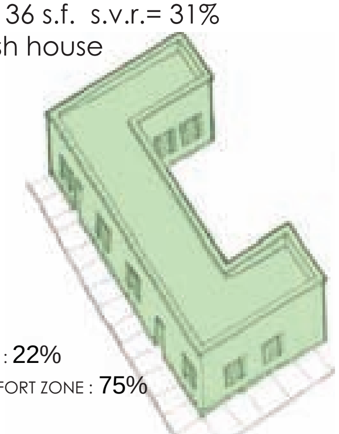
SUMMER HI: 107°F
WINTER LOW: 42°F
% YEAR - COMFORT ZONE : 15%
% YEAR - EXTENDED COMFORT ZONE : 54%



SUMMER HI: 91°F
WINTER LOW: 59°F
% YEAR - COMFORT ZONE : 32%
% YEAR - EXTENDED COMFORT ZONE : 83%



SUMMER HI: 92°F
WINTER LOW: 53°F
% YEAR - COMFORT ZONE : 23%
% YEAR - EXTENDED COMFORT ZONE : 81%

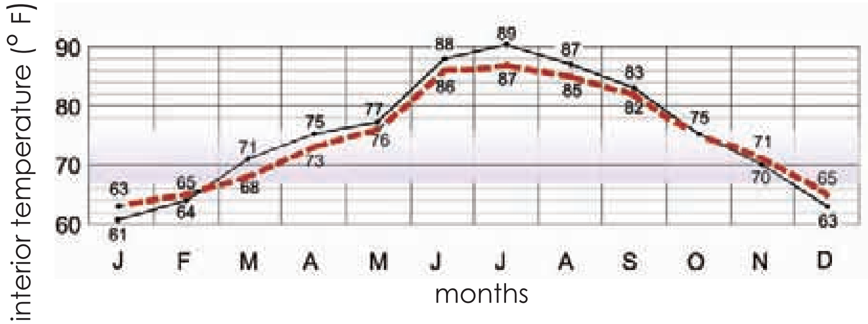


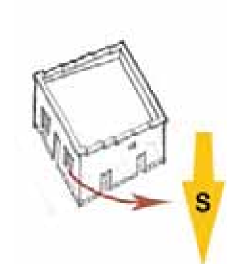
SUMMER HI: 89°F
WINTER LOW: 55°F
% YEAR - COMFORT ZONE : 22%
% YEAR - EXTENDED COMFORT ZONE : 75%

* *s.v.r. = Surface to Volume Ratio, see p. 129*

## ORIENTATION

Duffield House- west face reoriented to south




— current orientation,14° E of S  ----- adjusted orientation, 90° E of S

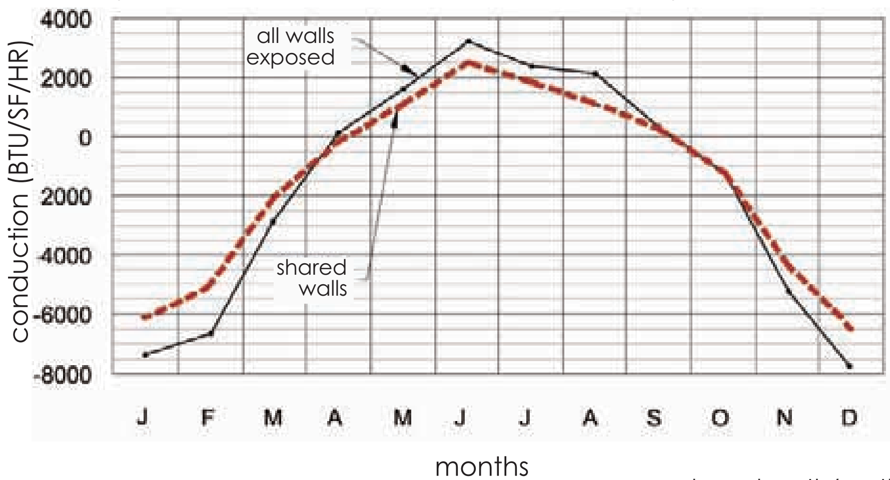
## EFFECT OF SOLAR ORIENTATION

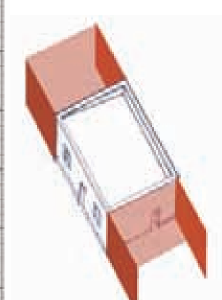
■ *investigation summary:* Analyze thermal performance as a function of monthly mean interior temperature when west faces of urban cases area reoriented to the south.

■ *investigation results:* In the case of the Duffield House, reorientation is predicted to improve passive cooling by reducing peak temperatures in summer by 2°F. Passive heating improves as well with temperatures rising 2°F in winter. For the Stevens House, temperatures drop in summer by 4°F and rise in winter by 1°F. While the Fish House showed the greatest improvement in passive cooling, dropping 3°F in summer, no change is predicted in winter. The Fish House may benefit by having a greater amount of south facing glazed area in proportion to the amount of mass wall and a seasonal shading strategy to prevent direct gains in summer.

## SHARED WALLS AND ENERGY CONDUCTION

Stevens House- effect of shared North and South Walls



— freestanding adobe  ----- shared north/south walls 27% surface area reduction

## EFFECT OF SHARED WALLS

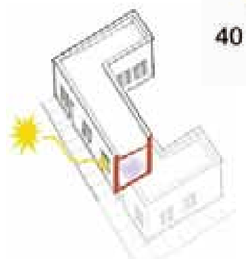
■ *investigation summary:* Analyze the impact of shared walls on the thermal efficiency as measured by energy conduction (heat gains and losses in *Btu/ft².°F*) of an urban adobe, the Stevens House. This house is the only urban adobe in the study that features shared walls on both the north and south faces.

■ *investigation results:* The graph demonstrates that by sharing walls (in this case 27 percent of wall area shared with adjacent buildings), conduction losses in winter and gains in summer are significantly reduced. This means that as exterior conditions become extreme in both summer and winter, the interior is less affected. If a SEER 12 heat pump for both mechanical heating and cooling were conditioning the Stevens House, the graph represents 12 percent annual energy and financial savings.

## EFFECT OF THERMAL MASS

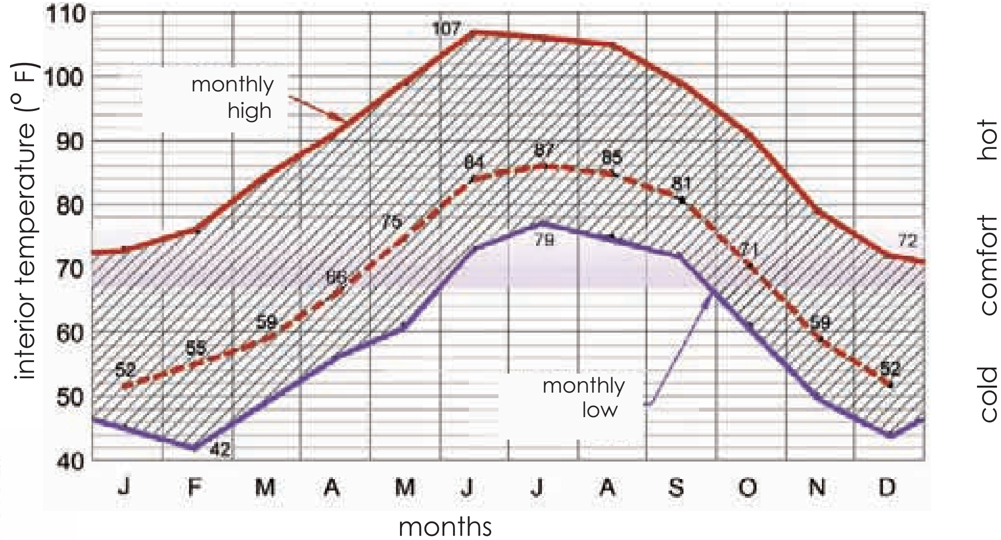
■ *investigation summary:* Analyze extent of heat tempering effect in both high and low mass structures as a function of the difference between monthly high and low interior temperatures. This difference is represented by the diagonally hatched areas in the following graphs.

■ *investigation results:* The Fish House is the *high mass* urban adobe used for comparison to the *low mass* manufactured house base case. Graphs for the low mass case are at right and the high mass cases are on the next page. The graphs dramatically show that the difference between predicted average monthly high and low temperatures is much larger for the manufactured base case both with and without natural ventilation. In the Fish House case, monthly high and low temperatures fluctuate consistently about 5°F as opposed to the typical 20-40°F fluctuation with the base case directly proving the heat tempering effect of high mass house. In the high mass adobe case, lows are in the mid-50s°F and highs in the low-90s°F in great contrast to the low mass base case where temperatures range from the low-40s°F to highs in the mid-110s or so. Additional proof of the high mass adobe house's greater thermal heat capacity is evidenced in the similarity of results whether ventilated or unventilated unlike the low mass case. While the high mass case reaches an interior high of 92°F when unventilated, the low mass case will reach an interior high of 117°F . An enclosure overheating to this extent would be dangerous to occupy. With the high mass house, the heat is being stored in the walls and not in the occupants (to their extreme discomfort).



## MONTHLY HIGH AND LOW TEMPERATURES

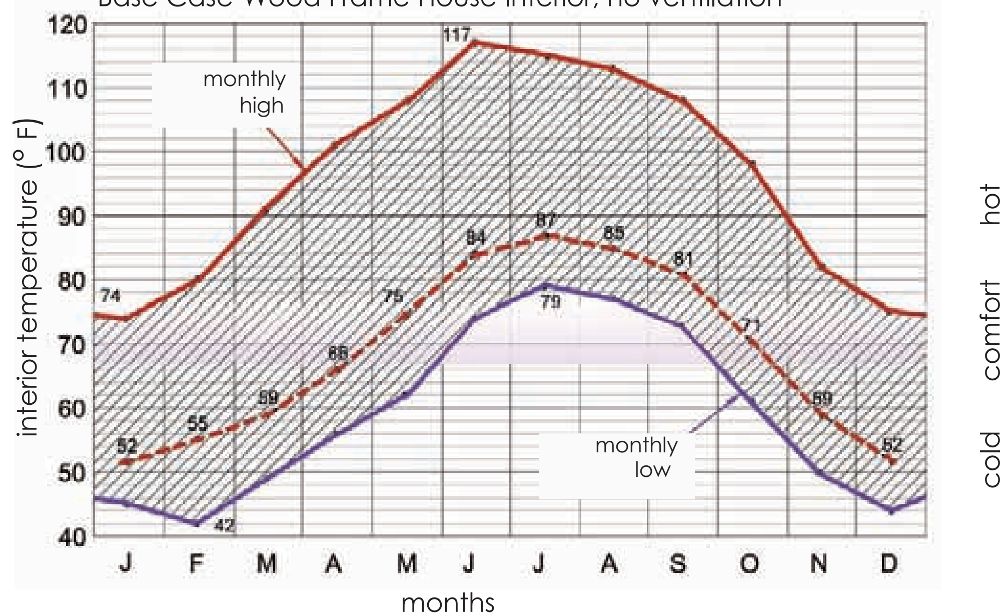
Base Case-Wood Frame House Interior, natural ventilation




NOAA average monthly dry bulb temperature, Tucson AZ

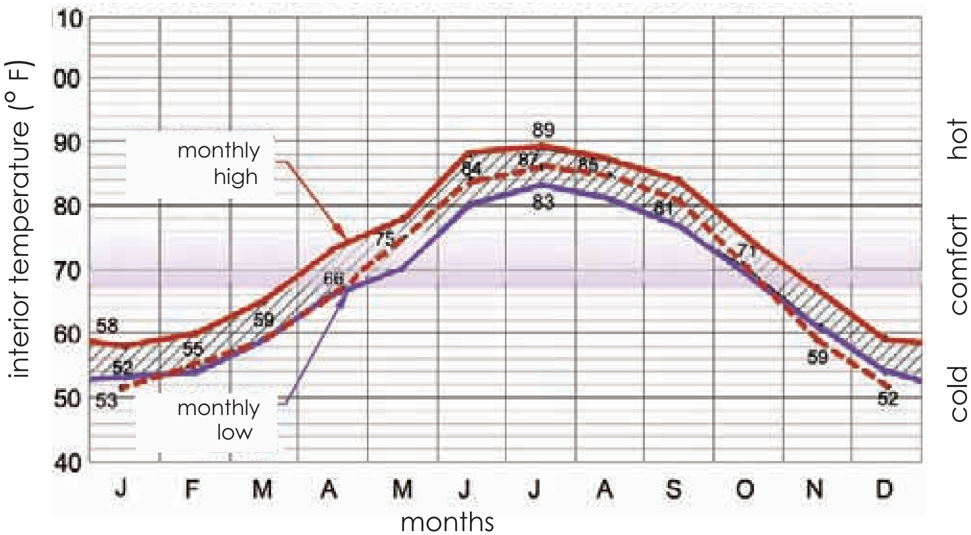
## MONTHLY HIGH AND LOW TEMPERATURES

Base Case-Wood Frame House Interior, no ventilation



## MONTHLY HIGH AND LOW TEMPERATURES

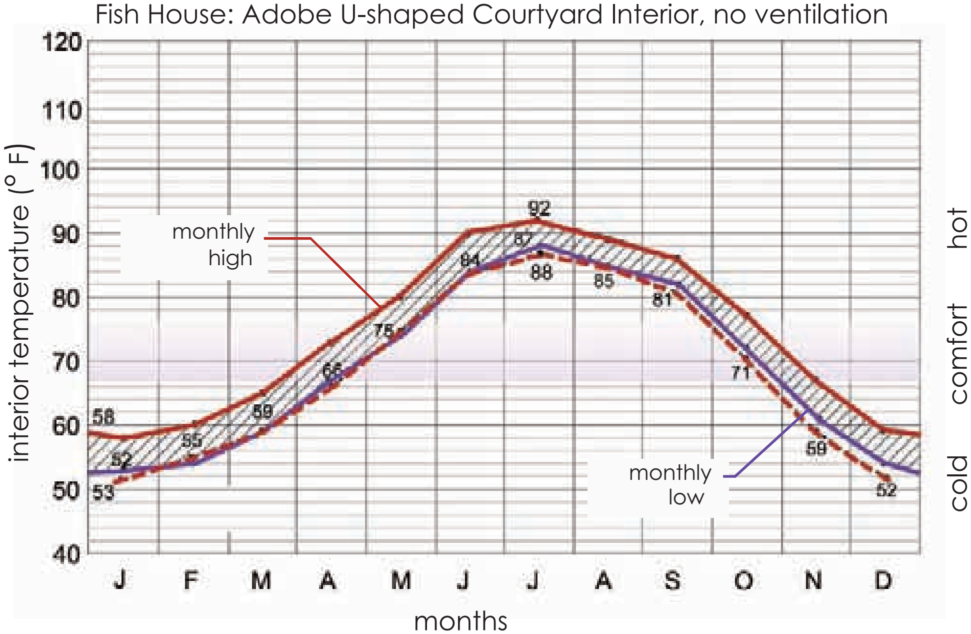
Fish House: Adobe U-shaped Courtyard Interior, natural ventilation




NOAA average monthly dry bulb temperature, Tucson AZ

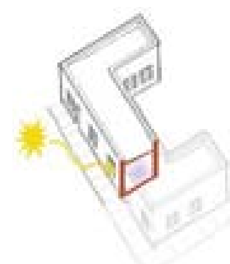
## MONTHLY HIGH AND LOW TEMPERATURES

Fish House: Adobe U-shaped Courtyard Interior, no ventilation

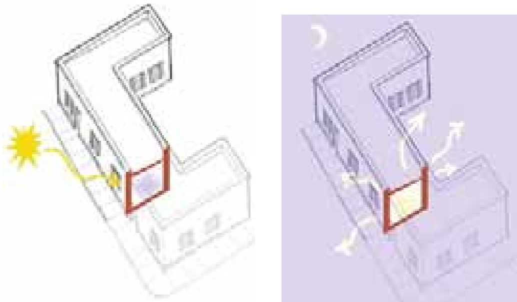



Adobe's ability to regulate mean interior temperature has a direct impact on thermal comfort. The body often feels thermal discomfort in the midst of temperature change but then has the ability to adapt and acclimate, even in temperatures as low as 60°F and as high as 87°F in arid conditions. While the adobe enclosure may be out of perfect thermal comfort range for a good portion of time (68-76°F), the lack of internal temperature fluctuation helps the body to function with less stress. Thermal mass walls also draw excess heat from the skin surface during warm periods and radiate stored heat to the skin surface in cool periods and which more gently conditions the body. When the range of thermal comfort can be increased, less mechanical intervention is needed thus saving in energy costs.

In all, the base case is being more readily affected by the extremes of the diurnal cycle as illustrated additionally by the graphs on the next page.



## EFFECT OF DIURNAL SWING



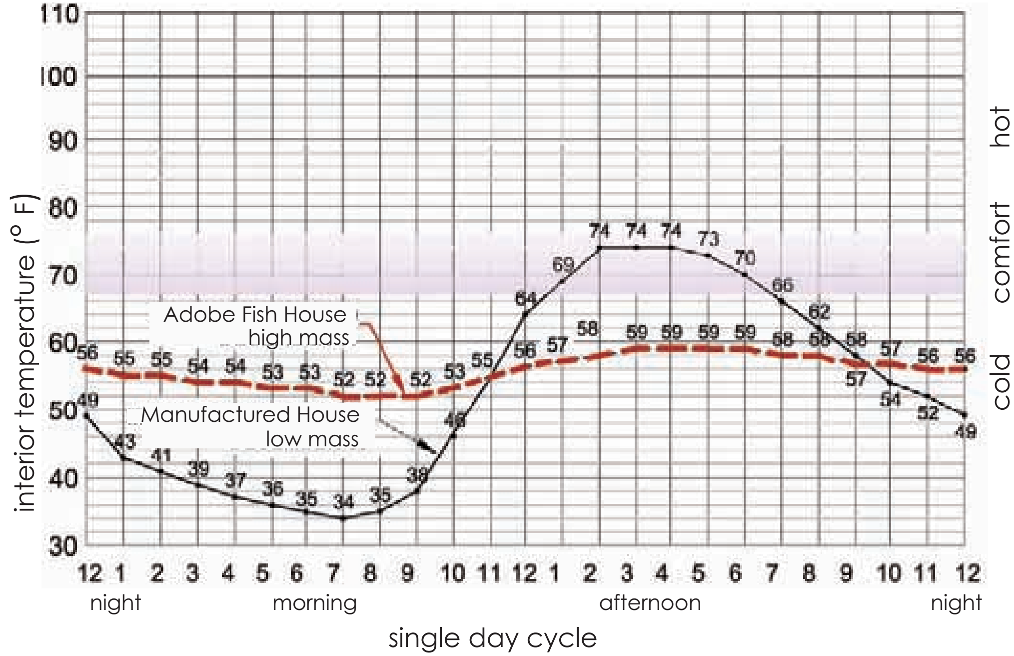
■ *investigation summary:* As a continuation of the previous investigation, analyze extent of tempering effect of thermal mass in comparison to the 2x4 wood frame base case. In this investigation, the fluctuation of interior temperature is analyzed over one diurnal cycle in summer and winter.

■ *investigation results:* The thermal tempering effect of the high thermal mass adobe Fish house is again evident here when demonstrated on a diurnal basis. The mean interior temperature of the low mass base case fluctuates an average of 40°F in winter and 37°F in summer while the adobe fluctuates 7°F in winter and 8°F in summer. The results for the adobe Fish House indicate that the tempering effect of the thermal mass may be more effective in passive cooling than in passive heating if the interior adobe walls are not receiving sufficient solar gains in winter.

Evidenced by these graphs as well is the 2-6 hour delay in peak interior temperatures created by the high mass adobe house as opposed to the low mass manufactured house which is more directly responding to outdoor temperature fluctuations.

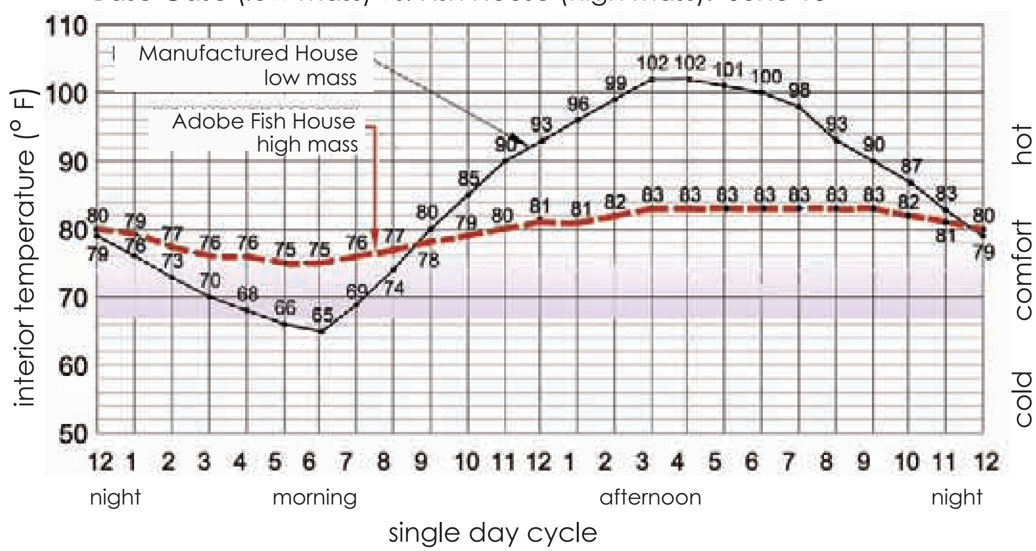
## HOURLY MEAN INTERIOR TEMPERATURES

Base Case Interior (low mass) vs. Fish House (high mass): December 11



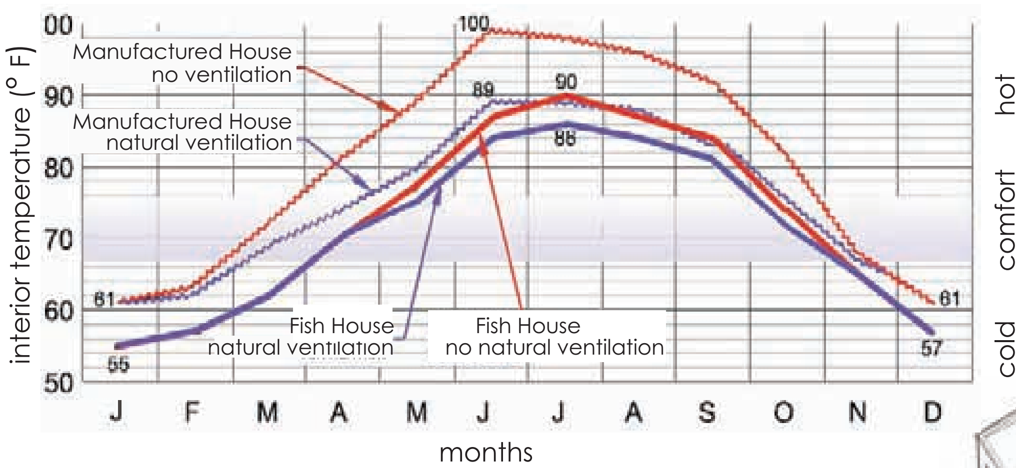

## HOURLY MEAN INTERIOR TEMPERATURES

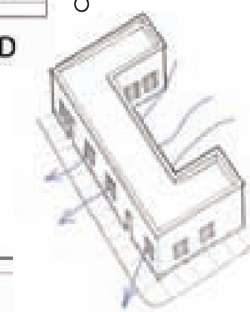
Base Case (low mass) vs. Fish House (high mass): June 15



## NATURAL VENTILATION

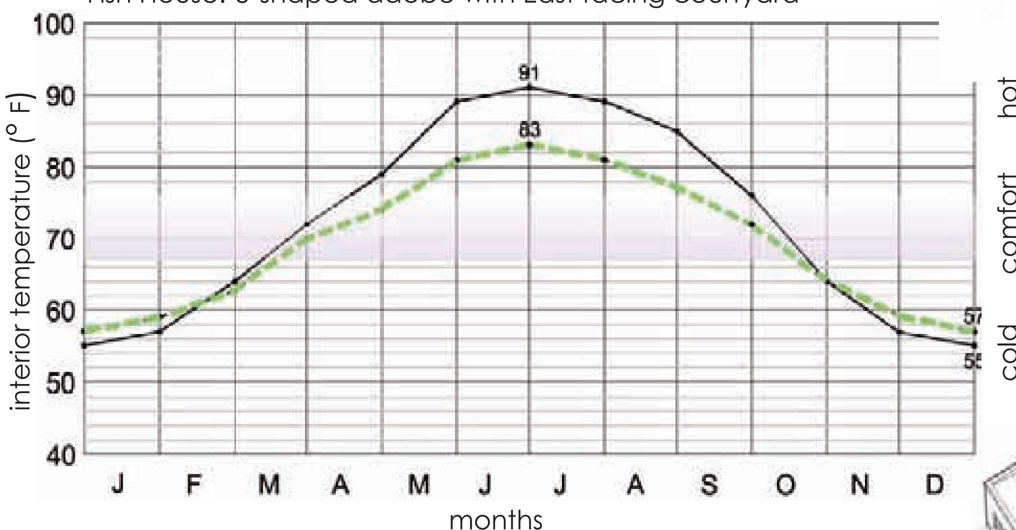
Base Case (low mass) vs. Fish House (high mass): (10% inlet & outlet)



## URBAN COURTYARD

Fish House: U-shaped adobe with East facing courtyard

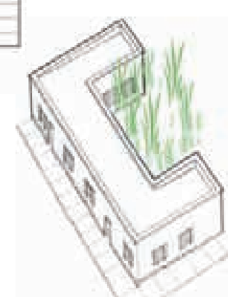



no shade/vegetation in courtyard, existing window area

shaded/ ventilated courtyard

area of four windows opening into east courtyard increased 4x and modeled to be heavily shaded in warm months.

SG Factors: Nov.-Feb-1.0, Mar.-Apr. 0.4, May-Sept. -.1, Oct, 0.4



## EFFECT OF NATURAL VENTILATION

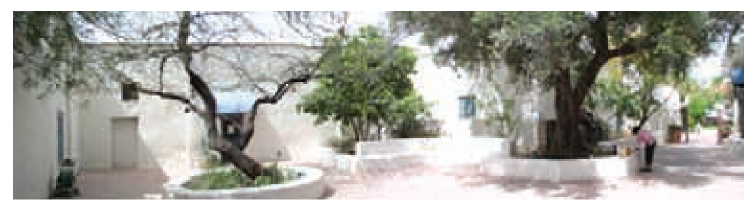
▪ *investigation summary:* Analyze the effectiveness of natural ventilation (10 percent inlet, 10 percent outlet area vs. no natural ventilation) as a function of mean interior temperature for both the adobe Fish House and the manufactured house base case.

▪ *investigation results:* The results indicate that natural ventilation is a necessary and effective technique in passive conditioning, particularly in passive cooling. The peak mean interior temperature of the Fish House would be intolerable at 90°F but natural ventilation drops it to a peak of 86°F, at the very upper limit of thermal tolerance in this climate. Interestingly, the manufactured house rises to 102°F interior without natural ventilation which is 12°F above the predicted peak for the Fish House, further proving adobe's heat tempering capability.

### the urban courtyard

▪ *investigation summary:* Analyze the effect of the vegetated courtyard of the U-shaped adobe, the Fish House, as a function of mean monthly interior temperature.

▪ *investigation results:* The mean interior temperature of the U-shaped adobe is predicted to stay 6-8°F cooler in summer when a vegetated courtyard is combined with significant area of opening facing the shaded courtyard. The courtyard is predicted to be an asset in passive heating as well due to added east glazed area combined with deciduous vegetation which thins to allow more solar gain in winter.



*The Fish House Courtyard. Photo: C.Neumann*

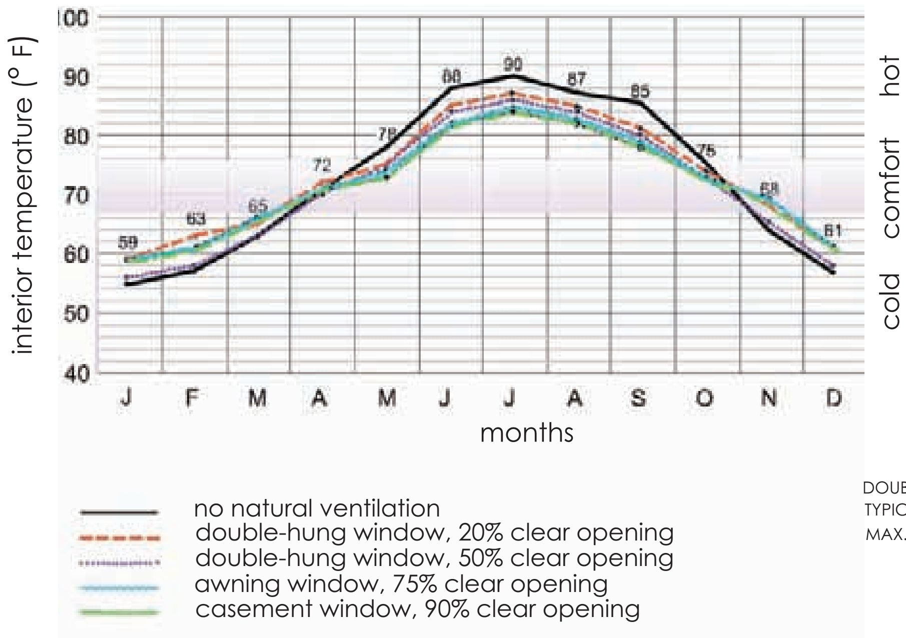
## WINDOW TYPE, SIZE, DEPTH

■ *investigation summary:* Analyze the effect of natural ventilation via inlet/outlet area as a function of mean maximum temperature of the urban adobe, the Stevens House.

■ *investigation results:* Improved performance in both passive heating and cooling is most significant with the awning and casement windows which both lowered maximum temperatures by 5°F and increased minimum temperatures by 4°F. This investigation proves that natural ventilation is absolutely necessary to utilizing the thermal mass of adobe for passive conditioning. Opening area must be in proper proportion to the amount of mass and modeling programs, such as CalPas can help to determine the correct balance as every building is unique in terms of form, site, and extent of passive conditioning. The significant depth of the mass, in this case 22", provides additional shading for the glazing as compared to the base case. The glazing of the manufactured house is inset 1-1/2" while the glazing for the adobe is inset 18". The thicker adobe wall provides much more depth for essential shade to the glazing in summer.

## INLET AND OUTLET AREAS

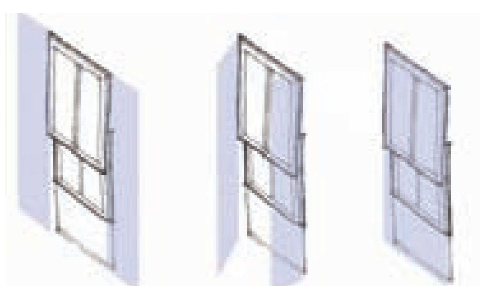
Stevens House: natural ventilation and mean max temperature




DOUBLE HUNG WINDOW
TYPICAL OPENING AREA: 10%
MAX. OPENING AREA: 45%

## OPERABLE SHUTTERS

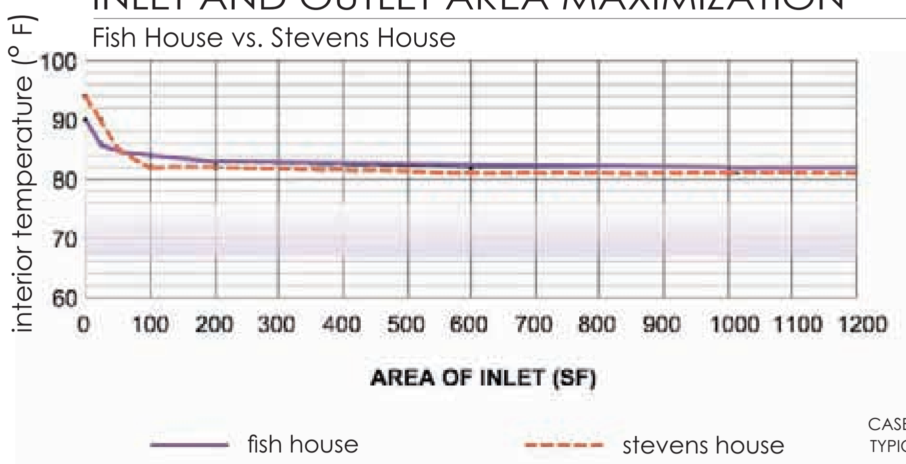
The louvered shutters on the Fish Stevens Duffield House are essential in passive cooling. Tests with the Fish House predict a 1-2°F interior mean temperature drop with the use of shutters from March until September.

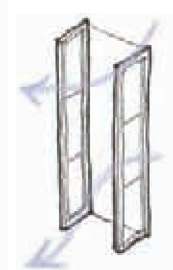


WINTER: SHUTTERS OPEN 80% OF TIME
SPRING/FALL: OPEN 50% OF TIME
SUMMER: SHUTTERS OPEN 20% OF TIME

## INLET AND OUTLET AREA MAXIMIZATION

Fish House vs. Stevens House



CASEMENT WINDOW
TYPICAL OPENING AREA: 10%
MAX. OPENING AREA: 90%

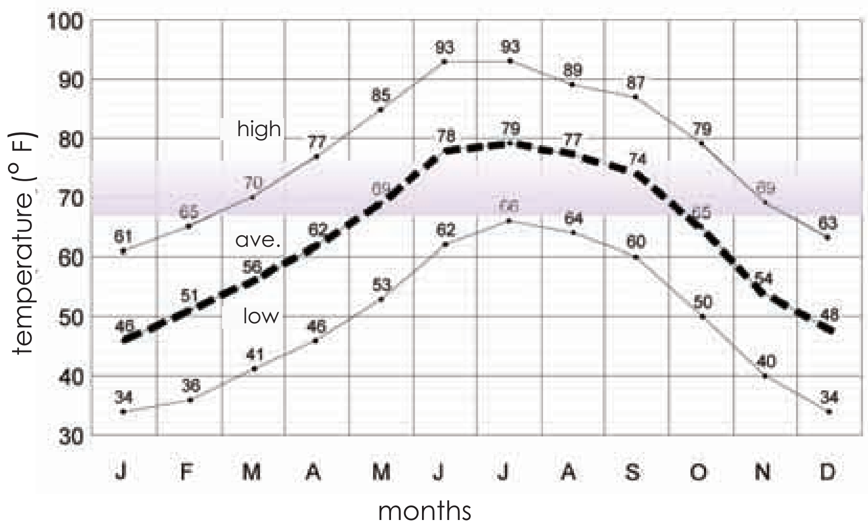
## rural adobe house

The Upshaw House on the Gray Ranch in Animas, NM, is the rural example to be compared with the base case manufactured home. The Upshaw House is located at an elevation of 5,000 ft. in the desert grasslands of southern New Mexico. The complex consists of a freestanding adobe home with several small storage buildings, all clustered by shrubs and trees. The closest residence to this complex is five miles away in the Coronado National Forest. The average temperature of this area is approximately 5°F below the urban climate of Tucson and heating is more of a concern than cooling. Rural climates typically have these features:

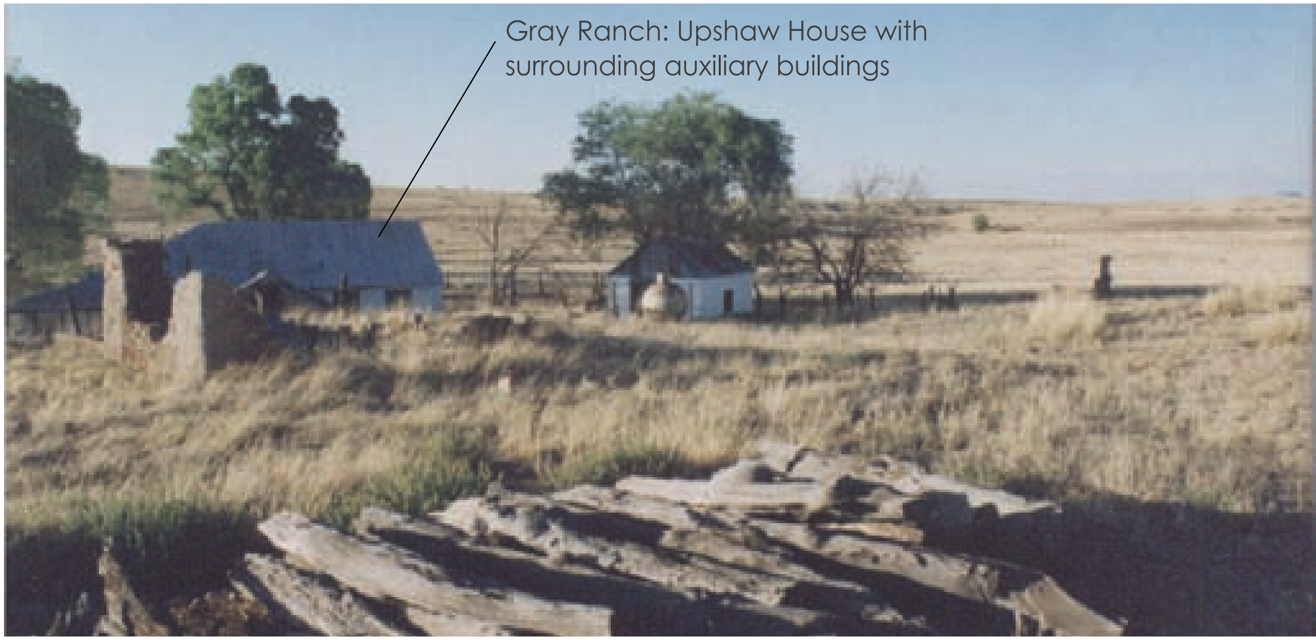
- *Vegetation:* The habitat of many rural locations in the US/Mexico border region is considered a semi-desert grassland, an arid form of the Great Plains grassland. Air temperatures drop as much as 10-14°F over grasses unlike the urban scenario where surface temperatures of black asphalt can be as much 25°F above ambient air temperatures (Moore, 59).
- *Wind speed:* The lack of large obstructions except perhaps trees means that wind speeds are a bit higher. In the case of this study, rural wind speeds are double that of urban being set at 15 m.p.h.
- *Elevation:* At an elevation of 5000 ft above sea level, the Upshaw House is twice as high as the urban examples. Due to adiabatic lapse rate, this rural site is naturally cooler.

## TEMPERATURE

NOAA 30 Year Monthly Averages, Sierra Vista, AZ

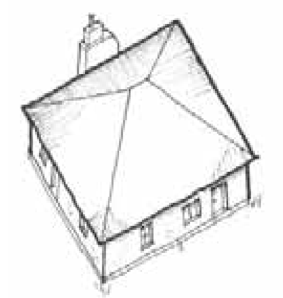



**Since no specific weather data was available for the actual site in Animas, NM, the information for Sierra Vista, AZ was substituted as it represents a very similar set of climatic and vegetative conditions*

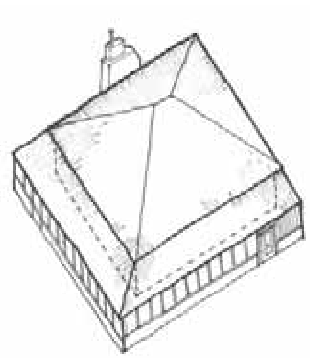


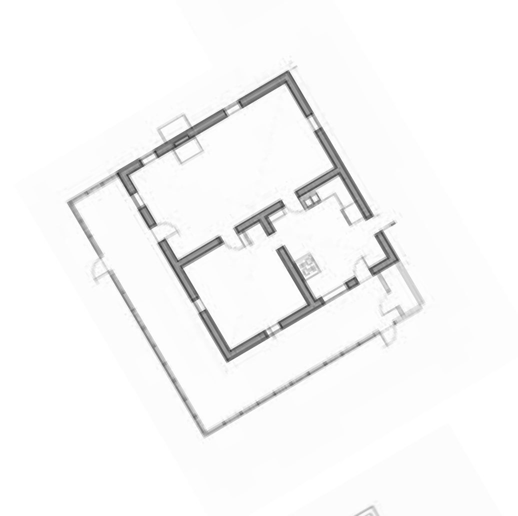

*View of Upshaw complex showing cluster of buildings surrounded by local vegetation. Photo: B.Vint*

The three cases below represent adaptations that the Upshaw House has undergone over its 80 year history since the 1920s. More information on this house can be found in the Gray Ranch feature of *Ch. 2: Design*. Phase 1 is a simple 630 s.f. rectangular structure built with 12" adobe walls and a hipped metal roof. The interior walls are 12" adobe as well. Phase 2 represents the addition of an 8' deep wood frame porch on the south and west sides of the house. This unconditioned porch is screened so it amply ventilates. Phase 3 is created when a 540 s.f. 8" concrete block addition is attached to the east side and a new metal roof was added. This is the present configuration of the house. The resulting area is almost double Phase 1 being 1170 s.f. All partition walls are frame in this addition and windows are single-pane double hung. The section on the next page shows in detail the material composition.

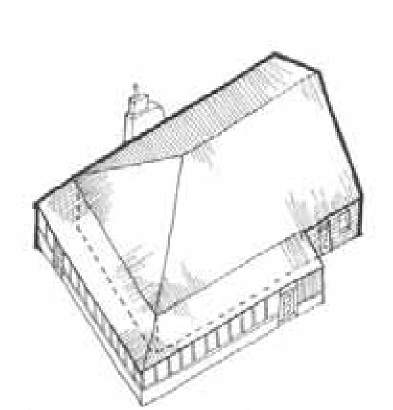


Upshaw House-Phase 1:
*simple square plan adobe*

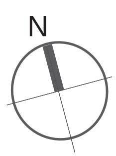




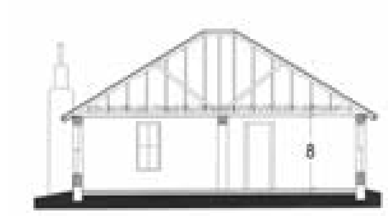
Upshaw House-Phase 2:
*simple square plan adobe with porch*



Upshaw House-Phase 3:
*square plan w/ porch and block addition*

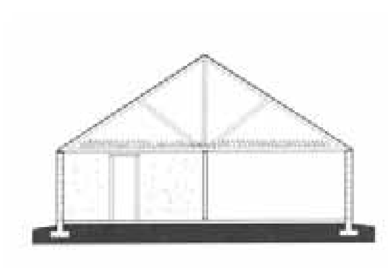



**For scaled house plans and additional supplemental information, such as area and volume, see Appendix.*



*Upshaw Phase 1 Section*

*Upshaw Phase 2 (with porch) Section*



*Upshaw Phase 3 (block addition) Section*

**U ROOF-** **METAL ROOFING ABOVE ROCK WOOL INSULATION**

| | BTWN RAFTER (90%) | @ RAFTER (10%) |
|---|---|---|
| OUTSIDE SURFACE | 0.17 | 0.17 |
| GALV. COR. MTL ROOFING | --- | --- |
| 3/4" PLYWOOD SHEATHING | 0.93 | 0.93 |
| ROUGH SAWN 2x6 RAFTER | -- | 6.11 |
| 3" ROCK WOOL INSULATION | 7.08 | 7.08 |
| 6" TIMBER BEAM | -- | 6.11 |
| INSIDE SURFACE | .62 | 0.62 |
| TOTAL R: | 8.34 | 21.0 |

AVE R = 10.0 **U= 0.1**

**U WALL-** **UNINSULATED PLASTERED ADOBE**

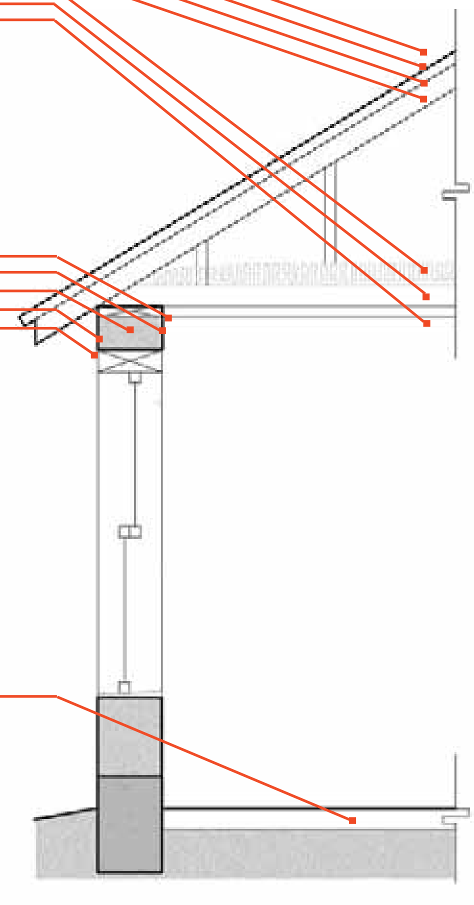
| | |
|---|---|
| INSIDE SURFACE | 0.62 |
| 1/2" LIME PLASTER SURFACE | 0.15 |
| 12" UNSTABILIZED ADOBE | ----- |
| 1/2" LIME PLASTER SURFACE | 0.15 |
| OUTSIDE SURFACE | 0.17 |
| TOTAL R: | 1.09 |

AVE R = 1.09 **U= 0.91**

ADOBE SPECIFIED HAS A VOLUMETRIC HEAT CAPACITY OF 25 BTU/CF-F AND CONDUCTIVITY OF 0.30 0 BUTH-FT/SF-F.
U-VALUE FOR SINGLE PANE VINYL WINDOW= 0.5
ACCOUNTED FOR IN CALPAS 3 AS SEPARATE ELEMENT FROM ROOF, WALL, OR FLOOR.

**U FLOOR-**

4" CONCRETE SLAB FACTORED AS MASS ELEMENT IN CALPAS 3 UNDER THE "SLAB" COMMAND. THE DENSITY OF THE STANDARD CONCRETE SPECIFIED IS 140 LBS/ CF. VOLUMETRIC HEAT CAPACITY IS 28 BTU/CF-F AND CONDUCTIVITY IS 0.980 BTUH-FT/ S.f.-F. NO CARPETING IS APPLIED TO THIS SURFACE.



0 1 2
scale 3/8" =1'-0"

## RURAL ADOBE TYPICAL WALL SECTIONS

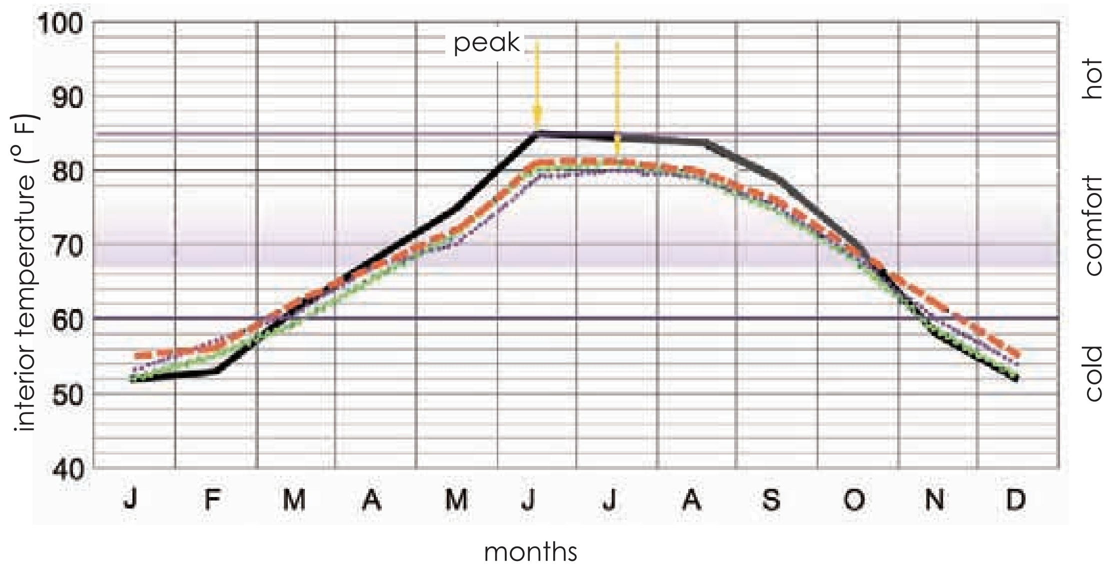
# EFFECT OF BUILDING FORM

■ *investigation summary:* Analyze thermal performance as a function of monthly mean interior temperature for manufactured housing base case and three rural adobe cases.

■ *investigation results:* In all cases, the need for passive heating predominates. 60-75 percent of the time, when the houses are predicted to be out of the comfort zone the need is for warmth. Phase 1 performs best in colder conditions, but becomes hottest in summer. The porch of phase 2 drops mean interior temperatures in summer an average of 1-2°F, but becomes a liability in colder months. The porch is too deep to allow solar gain to passively heat the house interior. In all, the historic cases performed better than the manufactured house, keeping temperatures 4-6°F lower in summer and 1-3°F higher in winter. As with the urban examples, the rural adobes are predicted to reach their peak interior temperature a month after the base case further demonstrating their adobe and block wall's ability to delay heat gain. Both adobe and block have a higher thermal heat capacity compared to wood.

## MEAN MONTHLY TEMPERATURE COMPARISON

Upshaw House, Phases 1-3 vs. Manufactured House

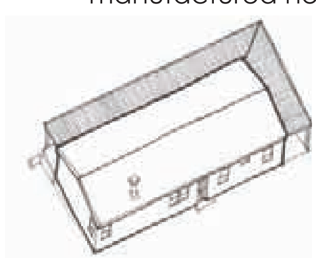



1659 s.f. s.v.r.= 17%
base case
manufactured house

630 s.f. s.v.r.= 38%
phase 1

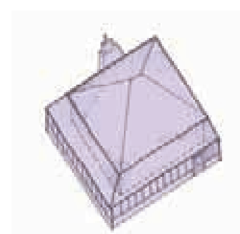
630 s.f. s.v.r.= 38%
phase 2

1170 s.f. s.v.r.= 19%
phase 3

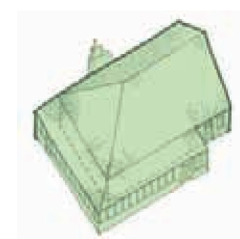


SUMMER HI: 102°F
WINTER LOW: 37°F
% YEAR - COMFORT ZONE : 22.5%
% YEAR - EXTENDED COMFORT ZONE : 66%

SUMMER HI: 89°F
WINTER LOW: 51°F
% YEAR - COMFORT ZONE : 33%
% YEAR - EXTENDED COMFORT ZONE : 75%



SUMMER HI: 87°F
WINTER LOW: 49°F
% YEAR - COMFORT ZONE : 33%
% YEAR - EXTENDED COMFORT ZONE : 75%

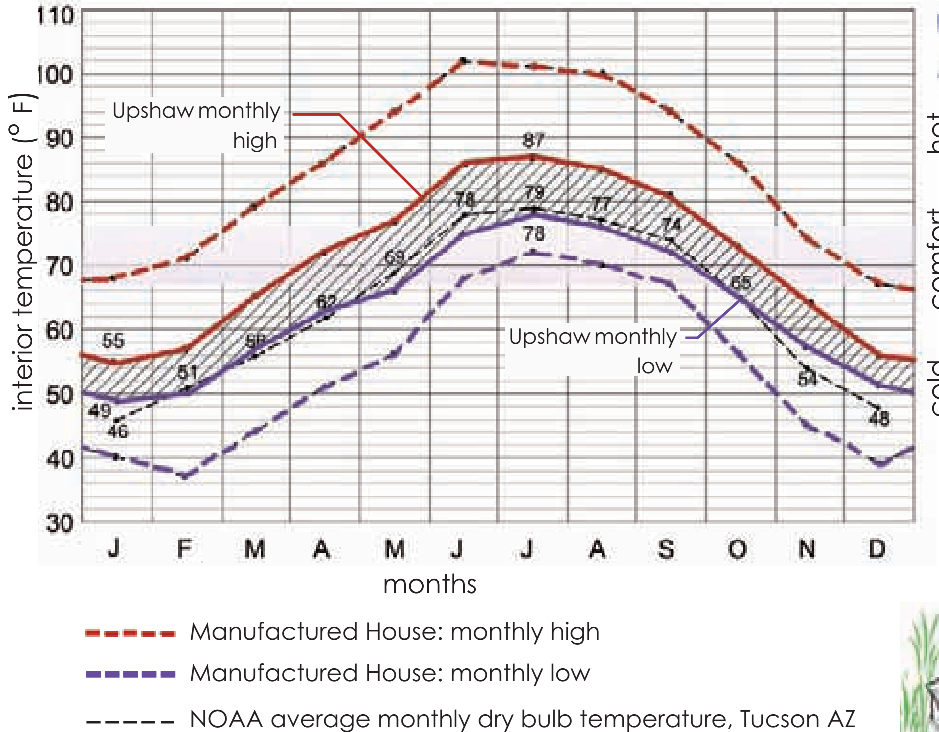


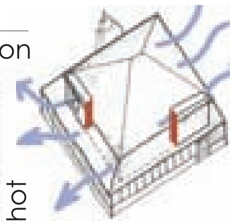
SUMMER HI: 88°F
WINTER LOW: 47°F
% YEAR - COMFORT ZONE : 23%
% YEAR - EXTENDED COMFORT ZONE : 66%

* *s.v.r. = Surface to Volume Ratio,* *see p. 129*

## MONTHLY HIGH AND LOW TEMPERATURES

Upshaw Phase 2 vs. Manufactured house Interior: natural ventilation



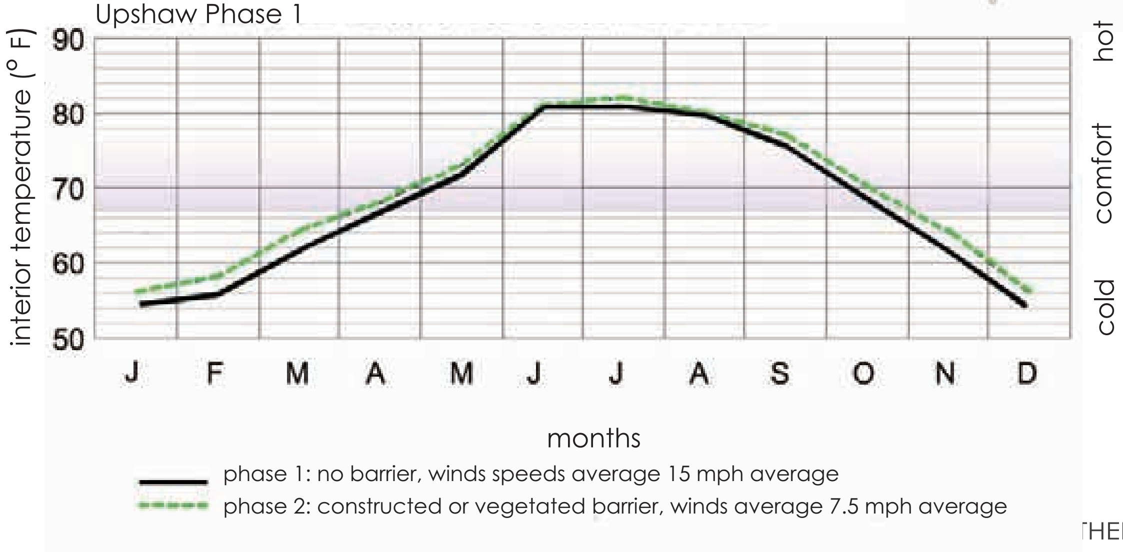
## EFFECT OF THERMAL MASS

■ *investigation summary:* Analyze extent of heat tempering effect in both high and low mass structures as a function of the difference between monthly high and low interior temperatures. This difference is represented by the diagonally hatched areas in the following graphs.

■ *investigation results:* The rural climate, being about 5°F cooler, creates greater concern for tempering both high and low exterior temperatures. The graph at left demonstrates the tempering effect of the high mass adobe Upshaw house and its constant ability to keep temperatures above exterior averages in the winter and at times below the same averages in summer as opposed to the low mass base case. Passive heating performance of the Upshaw house is not as successful since the 8' deep porch on the south and west sides blocks direct solar gain in winter. Additional heating was traditionally supplied by a wood burning stove.

## WINDBREAKS IN RURAL CLIMATES

Upshaw Phase 1




## EFFECT OF WINDBREAKS

■ *investigation summary:* Analyze the effect of wind speed as a function of mean monthly temperature on the Upshaw House, Phase 1.

■ *investigation results:* Reducing local wind speed by strategically placing barriers, such as auxiliary buildings, native trees/ shrubs or even lesser used vehicles can be an asset in passive heating in a rural climate. In this investigation, by reducing local wind speed to half, the Upshaw house is predicted to be much more effective in passive heating for all colder months, from November until April. Interior mean temperatures are predicted to rise an average of 2-4°F. In this colder climate, the reduction in wind speed does not have significant negative impact on passive cooling but a seasonal barrier may be a suggestion if a higher wind speed is desired in summer.

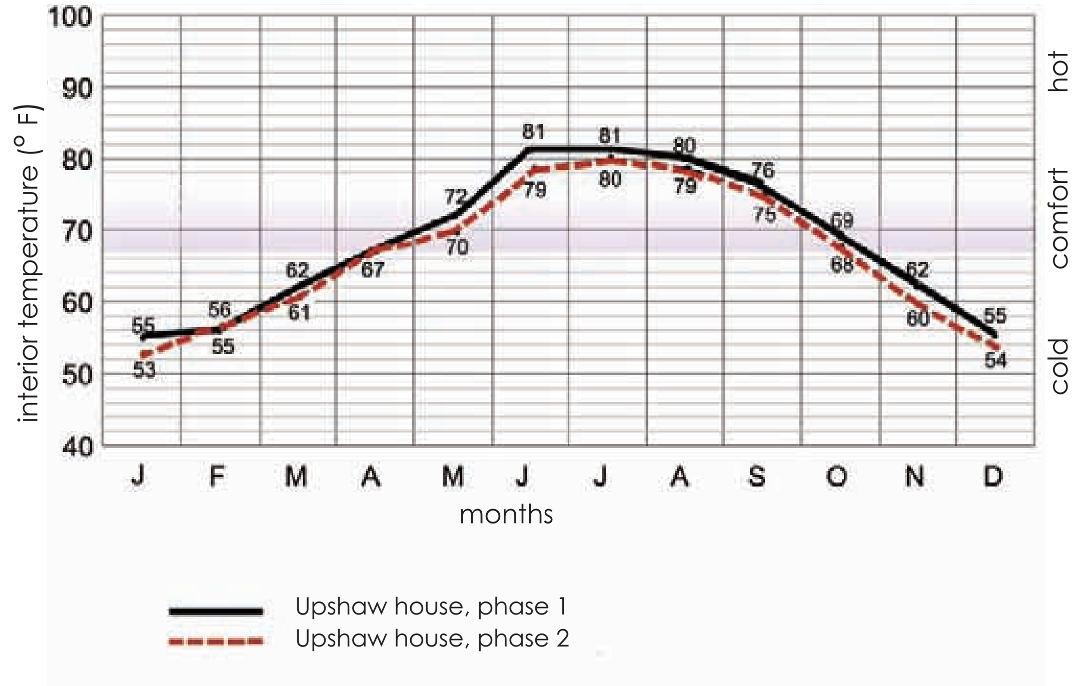
# EFFECT OF UNENCLOSED PORCH

■ *investigation summary:* Analyze the effect of the porch addition in Phase 2 upon thermal performance as a function of monthly mean interior temperature.

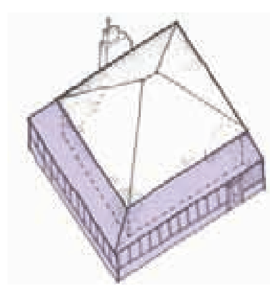
■ *investigation results:* The addition of the porch is more effective in passive cooling than in passive heating, as it is predicted to drop each monthly mean temperature by 1-2 °F. Phase 2 will remain in the comfort zone about 1-2 weeks longer as compared to Phase 1. Additional testing was done to investigate porch orientation when the house is rotated in 90 degree increments. The diagrams to the lower right demonstrate this rotation. Both position B and C were more efficient in passive heating without raising temperatures during the summer. Both were predicted to raise the mean monthly temperatures in winter by 1 °F. Another test with position A in which the porch depth was shortened to 4 ft. yielded similar results in summer and winter. In this case, passive heating was more successful since the adobe walls were more directly exposed to solar gains in winter.

## SCREENED PORCH

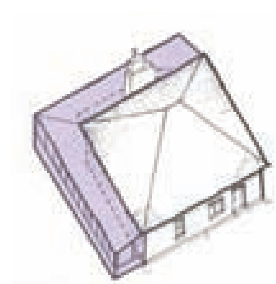
Upshaw Phase 1 vs. Phase 2



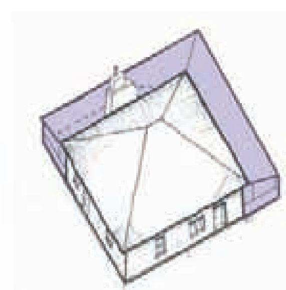

*The deep screened porch of the Upshaw house.*
*Photo: B. Vint*



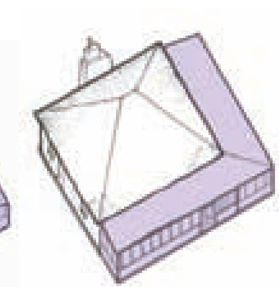
PORCH POSITION A (EXISTING):
ROTATION 0°



PORCH POSITION B
ROTATION 90°



PORCH POSITION C
ROTATION 180°

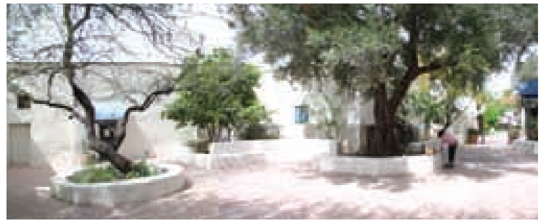


PORCH POSITION D
ROTATION -90°

## ANALYSIS HIGHLIGHTS

Rural Analysis
Upshaw House, Animas, New Mexico

Thermal comfort period elongated *0 - 9 %* over base case manufactured house



Urban Analysis
Fish Stevens Duffield House, Tucson AZ

Thermal comfort period elongated *21 - 29 %* over base case manufactured house

■ *High mass heat tempering* is a viable traditional passive cooling strategy in the arid Southwest.

- Peak mean interior temperatures for all high mass adobe cases are predicted to stay at least 4-6 °F below the low mass base case.
- High, low and mean interior temperatures of both rural and urban adobe cases stayed below the threshold of extended human thermal comfort unlike the base case which was well above this limit for June, July and August. The two psychrometric charts *p.150* further demonstrate these results.
- Peak interior temperatures of the adobe homes were predicted to be delayed one full month, from June with the base case to July .

■ *Natural ventilation*, particularly during cooler night hours, is a strategy that is vital for thermal mass cooling and southerly exposed operable glazing with appropriate shade allows passive solar heating in addition to ventilation cooling.

- For the urban adobes analyzed, the introduction of natural ventilation lowered temperatures by 5-8°F. This drop in summer is due to natural cross and stack ventilation and blackbody radiation to the clear night sky.
- The introduction of the casement window, with the most clear opening (90%) of all window types, was most effective in improving ventilation. In the Stevens House, temperatures drop 7°F in summer and rise 4°F in winter.
- Passive solar heating is as essential as cooling in the rural analysis due to higher wind speeds and cooler average exterior temperatures. The porch of the Upshaw house blocks direct solar gain and prevents the high mass building's ability to store precious solar heat which could be gained in cold periods.

■ *Seasonally vegetated courtyard* is potentially the most effective passive conditioning strategy for both heating and cooling.

- The shallow U-shaped form of the Fish House, with it's seasonally vegetated courtyard, was the most successful in passive cooling of all cases tested, as its mean interior temperature peaked at 83°F, staying 2-8°F lower than the other adobes and the base case.
- Summer shading via dense vegetation, significant depth of mass wall ( 18" window inset in urban adobe homes) and louvered shutters, permits a greater area of opening/glazing for enhanced natural ventilation in summer and solar gain in winter. In the case of the Fish House, while a south facing courtyard would be more ideal as opposed to the existing the east orientation, nonetheless, by increasing the area of open/glazing, mean interior temperatures increased by a few degrees in winter.
- Additional passive cooling effects due to evapotranspiration from plants or evaporation from a courtyard fountain were not accounted for in this study, but their common incorporation into traditional courtyards, such as that of the Cordova House, indicates that they also are integral in the creation of a thermally desirable courtyard microclimate. Using native seasonal trees and shrubs adapted to a hot arid climate aids in reduction of water consumption.

## CONCLUSIONS

Indigenous passive conditioning strategies, in particular *thermal mass heat tempering, controlled natural ventilation* and *seasonally vegetated courtyards,* are recommended as the basis for home conditioning in the hot arid Southwest. This study demonstrates the effectiveness of these strategies, as evidenced in the superior thermal performance of the two high mass vernacular cases when compared to a standard low mass contemporary manufactured house. The conventional wood stud and vinyl-sided manufactured house analyzed was designed specifically to be dependent on mechanical heating/cooling at all times and thus operates alien to its local climate.

Indigenous strategies for thermal control are effective in creating environments within a *reasonable range of human thermal toleration* which is particularly evident during times of extreme heat and cold. While these native structures don't consistently keep within the perfect bounds of thermal comfort (68-76°F), a feat only achieved by energy-intensive mechanical conditioning, they temper outside temperatures such that life is not threatened. The extremely high interior temperatures (averages in 100s) predicted for the unconditioned base case during the hot months simulate the grim reality of unconditioned housing not adapted to a hot and arid climate. This predicament is not uncommon for low-income people living in substandard housing units who cannot afford high air conditioning bills or conditioning system maintenance.

Further study is required to engineer floor, wall, and roof systems which utilize these passive strategies in conjunction with modern living patterns, construction methods and conditioning. Hybrid wall systems combining high insulation materials (straw bale, rigid insulation, etc.) in conjunction with thermal mass materials such as adobe, Concrete Earth Blocks (CEB) or Concrete Masonry Units (CMU) have potential to be the most energy efficient and regionally appropriate enclosures.

## CONCLUSIONS

The comparison at right again demonstrates the superior thermal performance of the high mass traditional case when compared to the low mass manufactured base case with regard to passive conditioning strategies in a hot arid climate. High and low monthly interior temperatures and their corresponding wet bulb temperatures were plotted on the psychrometric charts. The colors correspond with months of various seasons. They are as follows:

*summer months*
June, July, August

*fall months*
September, October, November

*winter months*
December, January, February

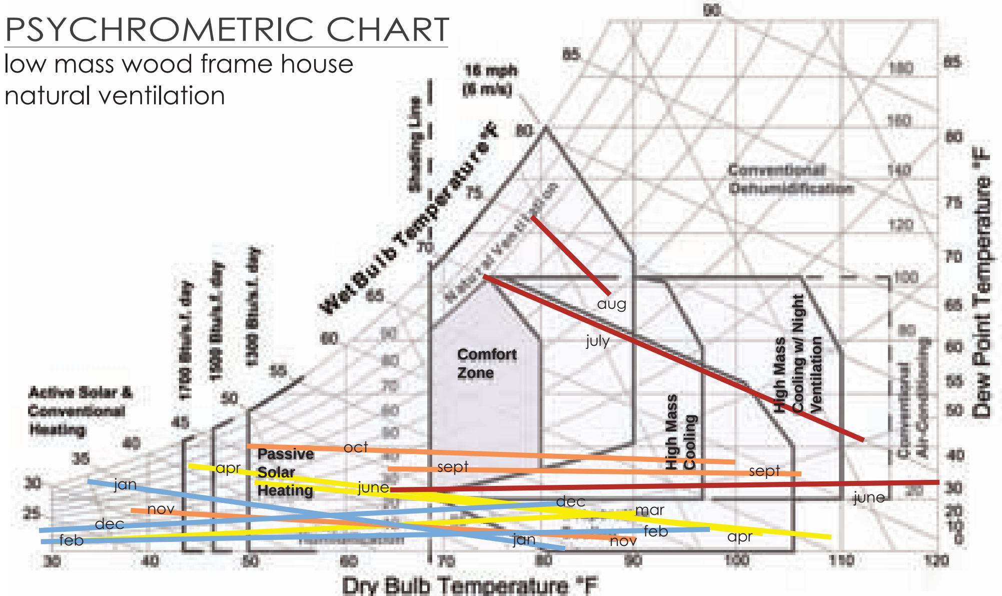
*spring months*
March, April, May

A comparison of these charts illustrates that the interior temperatures of the traditional high mass adobe house do not fluctuate as drastically as the low mass house. Temperatures also fall within the comfort zone (the purple region) more frequently with the high mass case. Of greatest interest is that, except in December, the high mass house is not out of range of the extended human comfort zone when passive solar heating and high mass cooling are considered. This extended high mass cooling zone does not apply to the low mass manufactured house. Even if mechanical conditioning were to be analyzed as well, it is apparent that if passive strategies for heating and cooling were applied and optimized before mechanical intervention, the high mass house would consume less energy to maintain comfortable interior temperatures resulting in homeowner cost savings.

From the Acoma Pueblo to the Gray Ranch, the vernacular architecture examples profiled in this book feature many regional building adaptations and energy conservation techniques that are as valid and effective for enclosure conditioning today as they were a thousand years ago.

## PSYCHROMETRIC CHART

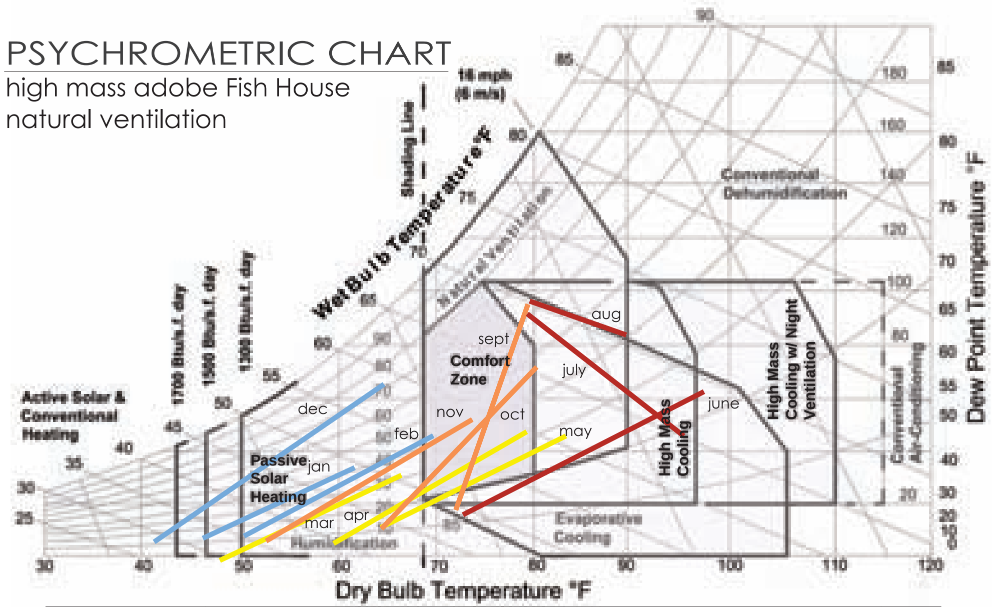
low mass wood frame house
natural ventilation




| extreme temperatures °F | jan | feb | mar | apr | may | june | july | aug | sept | oct | nov | dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| dry bulb low/ day | 35/ 5 | 27/ 21 | 31/ 22 | 45/ 23 | 51/ 6 | 65/ 16 | 73/ 10 | 72/ 15 | 65/ 28 | 49/ 20 | 38/ 27 | 27/ 29 |
| wet bulb low | 33 | 19 | 21 | 41 | 43 | 46 | 70 | 70 | 50 | 46 | 32 | 23 |
| dry bulb high/ day | 82/ 14 | 89/ 7 | 97/ 8 | 103/ 13 | 109/ 10 | 121/ 25 | 116/ 2 | 112/ 30 | 107/ 16 | 100/ 2 | 90/ 11 | 83/ 2 |
| wet bulb high | 49 | 52 | 53 | 58 | 60 | 68 | 64 | 70 | 65 | 66 | 53 | 54 |

## PSYCHROMETRIC CHART

high mass adobe Fish House
natural ventilation




| extreme temperatures °F | jan | feb | mar | apr | may | june | july | aug | sept | oct | nov | dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| dry bulb low/ day | 47/ 6 | 47/ 25 | 51/ 1 | 60/ 3 | 65/ 6 | 74/ 16 | 79/ 24 | 78/ 1 | 73/ 28 | 64/ 20 | 54/ 28 | 42/ 31 |
| wet bulb low | 32 | 30 | 36 | 39 | 43 | 49 | 68 | 68 | 48 | 46 | 31 | 29 |
| dry bulb high/ day | 62/ 24 | 67/ 8 | 70/ 10 | 79/ 14 | 84/ 12 | 97/ 21 | 96/ 5 | 90/ 7 | 89/ 1 | 81/ 2 | 76/ 1 | 67/ 7 |
| wet bulb high | 50 | 51 | 57 | 56 | 62 | 68 | 66 | 73 | 70 | 66 | 58 | 59 |