# RESIDENTIAL THERMAL MASS CONSTRUCTION

Jerry S. Thieken
Senior Customer Services Analyst
Salt River Project
Phoenix, Arizona

## ABSTRACT

The Southwest has long known the value of building homes with high mass materials. The ancient Pueblo Indians found that by using "adobe" they could capture the energy necessary to survive the harsh desert climate. Our ancestors knew that a heavy, dense wall (internal or external), or floor could store collected heat or coolness, retain it for long periods of time, and then slowly transfer it to its surrounding.

Due to rising construction costs and increased competition, modern homebuilders have completely shied away from high mass construction practices. In an attempt to revitalize the use of high mass in residential construction, we have designed a special "Thermal Mass Block." This new block incorporates the use of modern construction techniques with the value of high mass.

This paper describes the environment surrounding the development of this high mass block. It examines the research foundation used to validate the benefits of high mass construction.

## NOMENCLATURE

TME = Thermal Mass Effect

TOD = Time-of-Day Electric Rate

EST = Energy Savings Time (Salt River Project's Time-of-Day Electric Rate)

HVAC = Heating, Ventilating and Air Conditioning

## INTRODUCTION AND OVERVIEW

### THE THERMAL MASS CONCEPT

The interior of a low mass structure, like a light frame building, heats up and cools off as the outside temperature rises and falls over a 24-hour period. The interior of a building with mass, on the other hand, would not rise as high or fall as low. Also, the high and low peak temperatures would be greatly delayed. The reason for this moderating effect is that the mass absorbs the heat and delays its transfer.

In more technical terms, the thermal mass effect (TME) is the reduction in a building's heating and cooling energy caused by absolute reductions and shifting of dynamic heat fluxes through a massive envelope or interior materials. Figure 1 illustrates the general nature of the effect. It compares lightweight, wood-frame buildings with massive buildings--those with the mass inside the insulation.

Compared with the lightweight building, the massive buildings react more slowly to changes in outside temperatures. In addition, the amplitude of the daily inside temperature swing is reduced in the massive building.



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In buildings, we control the energy flow to and from thermal mass by accident or by design. We must appreciate both the charging and discharging cycles of the mass in order to put it to good use.

## PRELIMINARY RESEARCH DATA

### DEMAND-SIDE OBJECTIVE

In October 1983, Salt River Project began to investigate potential demand-side strategies. One such strategy involved residential thermal mass construction. The program that was developed had a primary objective of assessing the practicality of utilizing internal thermal mass to reduce or eliminate air conditioning demand on-peak and to shift energy consumption to off-peak.

A secondary objective was to develop practical construction methods that integrate internal thermal mass in subdivision or "tract" built homes.

The information gathered from this project was to be used to develop an aggressive demand-side marketing program.

### FIELD TESTING

In 1984, Salt River Project and Arizona Public Service Company participated in the construction and monitoring of three custom thermal mass homes. The three houses were designed to accomplish three different objectives.

Residence "A" was designed to shift the majority of the heating and cooling load off-peak. This test house provides a good example of a time-of-use rate strategy.

Residence "B" was designed to maintain an even heat pump demand across the 24 hours of the day. This test house is a good example of a demand rate strategy.

Residence "C" was designed to shift cooling off-peak and utilize solar heating to eliminate the winter load. Due to metering errors, the results gathered from this site are not reliable and should be used carefully.

### RESIDENCE "A"

The design characteristics of this house are as follows: 1) 2700 square feet, 2) R-15 walls filled block with 2 inches of external foam board insulation, 3) internal mass walls, 4) R-30 ceiling, 5) one 3-ton heat pump and one 2.5-ton heat pump and 6) time-of-day electric rate.

On an annual basis 91 - 100% of the heat pump load occurs off-peak. In July 1986 99.7% of the cooling load fell in the off-peak period. Figure 2 is a table showing the hourly energy use for this residence.

The first column of data shows the total kWh and heat pump kWh for a typical day in July. August results are similar to July's with 91% of the heat pump load falling in the off-peak period. For this customer, July and August represent the cooling season.

December 1985 is the only heating month and as Figure 3 shows 96.3% of the heat pump load is off-peak.

The remaining months are considered shoulder months with effectively no heating or cooling load.

### RESIDENCE "B"

The design characteristics of this house are as follows: 1) 5500 square feet, 2) R-19 walls filled block with 2.5" of external polyurethane rigid insulation, 3) R-30 ceiling, 4) one 3-ton heat pump, and 5) residential demand electric rate.

During the cooling season which occurs from early July through late August, this customer maintains a seasonal load factor of 60% (Demand computed on a monthly basis). "Typical day" load factor of the heat pump is 70 - 80%. Figure 4 shows August data in table form.

This customer's heating season occurs in December. A seasonal load factor of 43% and a heat pump load factor of 61% is achieved. Figure 5 shows December data in table form.

The remaining months represent the shoulder months where little or no heating or cooling occur.

The maximum kW demand for the peak day in July is 8.3. (Of this 3.7 kW is contributed by the heat pump.

**RESIDENCE "C"**

The design characteristics of this house are as follows: 1) 3400 square feet, 2) R-20 walls filled block with 2X4 frame and 1" foam, 3) R-38 ceiling, 4) two 2.5-ton heat pumps and one 2-ton heat pump, and 5) residential Time-of-Day with Demand electric rate.

The cooling season for this customer consists of June, July and August. During these months the heat pump runs off-peak 95% of the time. Cooling season data is represented in Figure 6.

Because of a metering error, no valid heating data are available.

April represents the shoulder months and is displayed in Figure 7.

**CUSTOMER ATTITUDE SUMMARY**

All three customers feel they are on the right electric rate for their lifestyle. Both time-of-day customers believe a good setup/setback thermostat is necessary. They all have a good feeling about thermal mass. They feel they have made modifications to the design of their homes that make them better equipped to live comfortably and economically in the Phoenix climate. They also feel that they have invested in something that will be working for the life of the home and will be an attractive selling point if they ever decide to move.

All three thermal mass homes have worked successfully. The customers have combined good building design, HVAC, and appropriate electric rates to minimize monthly utility costs while maintaining a comfortable environment.

**CURRENT MARKETING PROGRAM**

**INTRODUCTION**

Upon completion of the preliminary tests (construction of custom homes), and the positive findings from the data, we set out to promote this type of construction to the general building industry. Due to intense competition within the industry, "tract" builders were not willing to incorporate any new construction method that would raise the cost of their product. In short, the builders were selling the product they were building; so why change.

Our task then was to design a system that incorporated the use of internal thermal mass with existing construction methods.

**MASS BLOCK DEVELOPMENT**

In an attempt to revitalize the use of high mass in construction, we have designed a special "Thermal mass Block." The 8"x8"x16" nominal size of this block means that it does not require any special house design and, therefore, can be competitively utilized in track developments.

The block has been designed so that 3-1/2 inches of mass is exposed to the interior of the house. A polyurethane foam is then installed in a liquid form and provides an R-20 barrier between the internal mass and the 1-1/2 inch exterior face shell.

The wall is an engineered post tensioning system that does not require the blocks to have end caps or for the walls to contain grout columns. The cross-web between the interior and exterior face shell has also been reduced. Instead of the normal 8 inch height, it is now only 4 inches high. By eliminating the use of grout columns and end caps and reducing the height of the cross-web, we have dramatically reduced the heat bridges between the exterior and interior surfaces.

To allow for efficient storage in the mass, the surface of the mass walls will be finished with a filler coat of compound mud (to smooth out the surface) and sprayed on texture. Drywall will not be hung on these surfaces because of its insulating properties.

## RATIONAL FOR DEVELOPING THERMAL MASS PROGRAM

As our residential customer base increases, the need to control system peak becomes more important.[1] Residential "Thermal Mass" construction is one possibility for reducing kW requirements in new homes. The residential thermal mass program is designed to 1) drastically reduce the load imposed on the system during peak hours due to air conditioning and 2) reduce the amount the customer pays to operate his air conditioning system (through time-of-day rates).

## HOW THE PROGRAM IS IMPLEMENTED

To test the acceptance of thermal mass construction in both the building community and the buying public, we selected a builder that was currently building block homes in the $100,000 price range. To participate, the builder agreed to build one thermal mass house and position it within the subdivision's model home complex. An incentive was also offered by us to offset any additional construction costs incurred for this model (up to $2,000).

All the model homes at the subdivision, whether constructed out of high mass or not, are offered for sale using conventional block construction or the new thermal mass block system. The decision as to what system is built is left up to the customer.

To evaluate how effective each model design will be at storing cooling, we use a computer simulation program developed by the Environmental Research Lab in Tucson.[2] The simulation estimates the amount of air conditioning required at varying times of the day.

Since the thermal mass system is new, we expect the first several houses to cost a little more than conventional block (estimated overrun of about 3%). To remove this hurdle, we are also offering incentives for the first 12 thermal mass houses built and sold within the subdivision (up to $1,200 per house to offset additional costs). It is our belief that after these first houses are built, the thermal mass option can be offered for little or no increase in cost (1/2%-1% increase over cost). At these costs a simple payback would be 1 - 2 years.

To help the potential home buyer understand what is happening in a thermal mass house, we have installed instrumentation throughout the model. The customer will be able to see the temperature differences within the mass walls and understand the storage properties of mass (Figure 8).

**ACTUAL OR ANTICIPATED BENEFITS**

The potential benefits for this type of construction are numerous. The utility benefits from load shifting; the customer benefits from lower utility bills; and the public benefits from the utility's ability to meet existing loads without having to build new generation.

More specifically, SRP hopes to see a reduction somewhere around 3.8 kW per thermal mass customer during the summer peak, and 2.8 kW reduction during the winter peak. A net increase of 5% - 10% based on total consumption should result when the thermal mass house is operated for peak deferral. The result yields a 12 - 24 kWh per day peak reduction with a 13 - 26 kWh increase during the off peak hours of summer. Winter peak kWh reduction is 4 - 8 kWh per day and 5 - 9 kWh per day increase during off peak hours.

When billed according to SRP's Time-of-Day rate, the customer who utilizes the mass for pre-cooling can expect to save hundreds per year on heating and cooling costs (dependent upon how many degrees of pre-cooling are performed).

In the Phoenix climate, summer nighttime temperatures are not cool enough to provide the required storage. Mechanical refrigeration will be used to load the internal mass walls.

**CONCLUSION**

High mass construction is not new to the Southwest; however, modern building practices do not recognize it. Our first objective is to re-introduce this type of construction to this area and secondly, to share our experiences with other regions. Pre-cooling has the potential to benefit most of the power systems in the country. Since Salt River Project is a summer peaking utility, my discussions have focused around pre-cooling. The same potential exists for pre-heating. Thermal mass construction can benefit utilities who experience summer or winter peaks.

High mass construction gives the customer a tool with which to fit into a utility's valley or shoulder period. In the past utilities have asked their customers to use energy at certain times of the day. In order to do this our customers were forced to experience a certain degree of inconvenience. Building with high mass materials enables the customer to comply with our request in a more convenient and comfortable manner.

The key to high mass construction is thermal performance and customer acceptance. The mass block that we have developed possesses both attributes. It contains the appropriate storage capabilities and at the same time allows a house to be built that looks like any other house using conventional methods. These two properties give the system large scale acceptance potential and therefore can be used throughout a utility's customer base.

**REFERENCES**


1. Wood, Bion. <u>Performance Portrait of High-Mass Houses</u>.
   Solar Age, September 1984.

2. West, David; Watkins, James; and Thieken, Jerry. <u>Economic Evaluation of Proposed Thermal Mass Home Program for SRP.</u>
   October 31, 1983, Revised May 1984.

3. Lightfoot, L. J. Arizona Public Service Company Thermal Mass Project.

4. Peck, John F., Thompson, T. Lewis and Kessler, Helen J.
   <u>Off Peak Power Use in Solar Homes: Performance, Monitoring and Analysis of Periodic Heating and Cooling in High Mass Homes</u>.


**ATTACHMENTS**

1 Thermal Mass Effect
2 Table of July 1986 Data - Residence "A"
3 Table of December 1985 Data - Residence "A"
4 Table of August 1986 Data - Residence "B"
5 Table of December 1985 Data - Residence "B"
6 Table of June 1986 Data - Residence "C"
7 Table of May 1986 Data - Residence "C"
8 Data Collection Points
9 SRP Time-of-Day Electric Rate

FIGURE 1

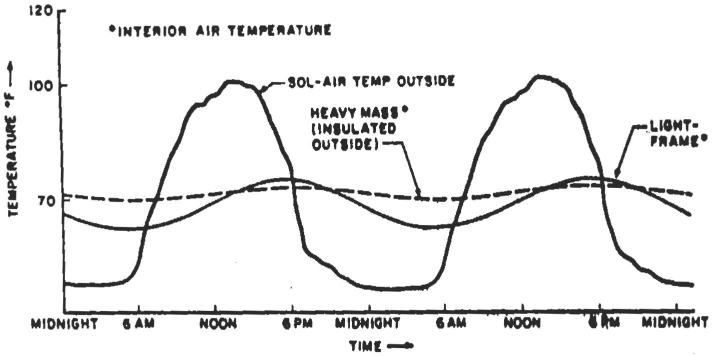



**Figure 1.** Based on 1975 NBS data, the graph shows the general nature of the mass effect during the swing seasons. Note two things: 1) The outside temperature has the largest swing (amplitude) followed by the light-frame house, and then the heavy-mass house. 2) The outside temperature peaks first, followed by the lightweight, and then the heavy mass. Inside-insulated mass (not shown) would appear between the light-frame and the outside-insulated mass walls.

FIGURE 2

HOURLY ENERGY USE

| HOUR | TYPICAL DAY 07/01/86 TO 07/31/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST TOTAL KWH 07/16/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST ON PEAK KWH 07/16/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST OFF PEAK KWH 07/20/86 TOTAL KWH | HEAT PUMP KWH |
|---|---|---|---|---|---|---|---|---|
| 1:00 | 6.0 | 3.7 | 6.7 | 3.7 | 6.7 | 3.7 | 6.9 | 3.9 |
| 2:00 | 5.1 | 3.7 | 5.1 | 3.7 | 5.1 | 3.7 | 5.7 | 3.9 |
| 3:00 | 5.0 | 3.6 | 5.5 | 3.7 | 5.5 | 3.7 | 5.2 | 3.8 |
| 4:00 | 5.0 | 3.6 | 5.1 | 3.7 | 5.1 | 3.7 | 5.5 | 3.7 |
| 5:00 | 4.9 | 3.6 | 5.4 | 3.6 | 5.4 | 3.6 | 5.1 | 3.7 |
| 6:00 | 4.8 | 3.5 | 4.9 | 3.6 | 4.9 | 3.6 | 5.0 | 3.6 |
| 7:00 | 4.8 | 3.5 | 4.7 | 3.6 | 4.7 | 3.6 | 5.3 | 3.6 |
| 8:00 | 4.7 | 3.3 | 5.4 | 3.7 | 5.1 | 3.7 | 7.2 | 3.8 |
| 9:00 | 6.2 | 3.7 | 7.1 | 3.8 | 7.1 | 3.8 | 7.2 | 3.9 |
| 10:00 | 1.8 | 0.0 | 3.3 | 0.0 | 3.3 | 0.0 | 2.6 | 0.0 |
| 11:00 | 1.0 | 0.0 | 2.3 | 0.0 | 2.3 | 0.0 | 0.8 | 0.0 |
| 12:00 | 0.7 | 0.0 | 1.5 | 0.0 | 1.5 | 0.0 | 0.7 | 0.0 |
| 13:00 | 0.7 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 1.8 | 0.0 |
| 14:00 | 0.8 | 0.0 | 0.6 | 0.0 | 0.6 | 0.0 | 1.1 | 0.0 |
| 15:00 | 0.7 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.9 | 0.0 |
| 16:00 | 0.7 | 0.0 | 0.6 | 0.0 | 0.6 | 0.0 | 0.9 | 0.0 |
| 17:00 | 0.7 | 0.0 | 0.8 | 0.0 | 0.8 | 0.0 | 1.8 | 0.0 |
| 18:00 | 0.9 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 | 2.2 | 0.0 |
| 19:00 | 1.0 | 0.0 | 5.1 | 0.0 | 5.1 | 0.0 | 1.4 | 0.0 |
| 20:00 | 1.1 | 0.0 | 4.1 | 0.0 | 4.1 | 0.0 | 1.8 | 0.0 |
| 21:00 | 1.4 | 0.0 | 4.4 | 0.0 | 4.4 | 0.0 | 2.0 | 0.0 |
| 22:00 | 1.5 | 0.1 | 4.3 | 0.0 | 4.3 | 0.0 | 2.0 | 0.0 |
| 23:00 | 5.5 | 3.8 | 6.2 | 3.6 | 6.2 | 3.6 | 5.3 | 3.5 |
| 24:00 | 7.7 | 3.8 | 8.6 | 3.6 | 8.6 | 3.6 | 8.4 | 3.4 |
| TOTAL KWH | 72.7 | 39.9 | 93.4 | 40.3 | 93.4 | 40.3 | 86.8 | 40.8 |
| % OF TOTAL KWH | | 54.9 | | 43.1 | | 43.1 | | 47.0 |
| ON PEAK: TOTAL KWH | 13.0 | 0.1 | 29.0 | 0.0 | 29.0 | 0.0 | 20.0 | 0.0 |
| % KWH | 17.9 | 0.3 | 31.0 | 0.0 | 31.0 | 0.0 | 23.0 | 0.0 |
| OFF PEAK: TOTAL KWH | 59.7 | 39.8 | 64.4 | 40.3 | 64.4 | 40.3 | 66.8 | 40.8 |
| % KWH | 82.1 | 99.7 | 69.0 | 100.0 | 69.0 | 100.0 | 77.0 | 100.0 |

**FIGURE 3**

HOURLY ENERGY USE

| HOUR | TYPICAL DAY 12/03/85 TO 01/03/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST TOTAL KWH 12/11/85 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST ON PEAK KWH 12/11/85 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST OFF PEAK KWH 12/11/85 TOTAL KWH | HEAT PUMP KWH |
|---|---|---|---|---|---|---|---|---|
| 1:00 | 2.9 | 1.4 | 7.7 | 3.4 | 7.7 | 3.4 | 7.7 | 3.4 |
| 2:00 | 2.6 | 1.6 | 4.5 | 3.4 | 4.5 | 3.4 | 4.5 | 3.4 |
| 3:00 | 2.6 | 1.7 | 4.4 | 3.4 | 4.4 | 3.4 | 4.4 | 3.4 |
| 4:00 | 2.4 | 1.6 | 4.9 | 3.3 | 4.9 | 3.3 | 4.9 | 3.3 |
| 5:00 | 2.9 | 1.9 | 4.4 | 3.4 | 4.4 | 3.4 | 4.4 | 3.4 |
| 6:00 | 2.7 | 1.8 | 4.4 | 3.5 | 4.4 | 3.5 | 4.4 | 3.5 |
| 7:00 | 2.7 | 1.7 | 5.6 | 3.5 | 5.6 | 3.5 | 5.6 | 3.5 |
| 8:00 | 3.9 | 1.7 | 4.4 | 3.4 | 4.4 | 3.4 | 4.4 | 3.4 |
| 9:00 | 3.8 | 1.6 | 5.7 | 2.5 | 5.7 | 2.5 | 5.7 | 2.5 |
| 10:00 | 1.0 | 0.0 | 0.8 | 0.0 | 0.8 | 0.0 | 0.8 | 0.0 |
| 11:00 | 0.8 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 |
| 12:00 | 0.6 | 0.0 | 0.6 | 0.0 | 0.6 | 0.0 | 0.6 | 0.0 |
| 13:00 | 0.8 | 0.0 | 0.7 | 0.0 | 0.7 | 0.0 | 0.7 | 0.0 |
| 14:00 | 0.8 | 0.0 | 1.4 | 0.0 | 1.4 | 0.0 | 1.4 | 0.0 |
| 15:00 | 0.8 | 0.0 | 6.4 | 1.6 | 6.4 | 1.6 | 6.4 | 1.6 |
| 16:00 | 0.8 | 0.0 | 2.7 | 0.0 | 2.7 | 0.0 | 2.7 | 0.0 |
| 17:00 | 0.7 | 0.1 | 5.9 | 1.7 | 5.9 | 1.7 | 5.9 | 1.7 |
| 18:00 | 1.1 | 0.0 | 2.7 | 0.0 | 2.7 | 0.0 | 2.7 | 0.0 |
| 19:00 | 1.6 | 0.1 | 4.3 | 1.7 | 4.3 | 1.7 | 4.3 | 1.7 |
| 20:00 | 1.8 | 0.0 | 2.2 | 0.0 | 2.2 | 0.0 | 2.2 | 0.0 |
| 21:00 | 1.7 | 0.1 | 3.7 | 1.4 | 3.7 | 1.4 | 3.7 | 1.4 |
| 22:00 | 2.6 | 0.4 | 3.7 | 1.1 | 3.7 | 1.1 | 3.7 | 1.1 |
| 23:00 | 6.9 | 2.0 | 9.8 | 3.5 | 9.8 | 3.5 | 9.8 | 3.5 |
| 24:00 | 3.8 | 1.3 | 9.3 | 3.5 | 9.3 | 3.5 | 9.3 | 3.5 |
| TOTAL KWH | 52.3 | 19.0 | 100.7 | 44.3 | 100.7 | 44.3 | 100.7 | 44.3 |
| % OF TOTAL KWH | | 36.3 | | 44.0 | | 44.0 | | 44.0 |
| ON PEAK: TOTAL KWH | 15.1 | 0.7 | 35.6 | 7.5 | 35.6 | 7.5 | 35.6 | 7.5 |
| % KWH | 28.9 | 3.7 | 35.4 | 16.9 | 35.4 | 16.9 | 35.4 | 16.9 |
| OFF PEAK: TOTAL KWH | 37.2 | 18.3 | 65.1 | 36.8 | 65.1 | 36.8 | 65.1 | 36.8 |
| % KWH | 71.1 | 96.3 | 64.6 | 83.1 | 64.6 | 83.1 | 64.6 | 83.1 |

**FIGURE 4**

HOURLY ENERGY USE

| HOUR | TYPICAL DAY 07/31/86 TO 08/29/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST TOTAL KWH 08/05/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST ON PEAK KWH 08/05/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST OFF PEAK KWH 08/05/86 TOTAL KWH | HEAT PUMP KWH |
|---|---|---|---|---|---|---|---|---|
| 1:00 | 5.6 | 2.1 | 7.5 | 3.3 | 7.5 | 3.3 | 7.5 | 3.3 |
| 2:00 | 5.3 | 1.9 | 7.2 | 3.2 | 7.2 | 3.2 | 7.2 | 3.2 |
| 3:00 | 5.1 | 1.9 | 7.2 | 3.2 | 7.2 | 3.2 | 7.2 | 3.2 |
| 4:00 | 4.9 | 1.8 | 7.2 | 3.2 | 7.2 | 3.2 | 7.2 | 3.2 |
| 5:00 | 4.7 | 1.6 | 6.9 | 3.2 | 6.9 | 3.2 | 6.9 | 3.2 |
| 6:00 | 4.6 | 1.6 | 7.3 | 3.2 | 7.3 | 3.2 | 7.3 | 3.2 |
| 7:00 | 4.6 | 1.5 | 7.4 | 3.2 | 7.4 | 3.2 | 7.4 | 3.2 |
| 8:00 | 4.7 | 1.5 | 7.2 | 3.2 | 7.2 | 3.2 | 7.2 | 3.2 |
| 9:00 | 5.0 | 1.6 | 7.2 | 3.3 | 7.2 | 3.3 | 7.2 | 3.3 |
| 10:00 | 4.6 | 1.8 | 7.7 | 3.4 | 7.7 | 3.4 | 7.7 | 3.4 |
| 11:00 | 4.9 | 2.1 | 6.7 | 2.4 | 6.7 | 2.4 | 6.7 | 2.4 |
| 12:00 | 5.0 | 2.3 | 7.9 | 3.5 | 7.9 | 3.5 | 7.9 | 3.5 |
| 13:00 | 5.2 | 2.4 | 7.6 | 3.6 | 7.6 | 3.6 | 7.6 | 3.6 |
| 14:00 | 5.4 | 2.6 | 7.9 | 3.6 | 7.9 | 3.6 | 7.9 | 3.6 |
| 15:00 | 5.4 | 2.7 | 7.9 | 3.6 | 7.9 | 3.6 | 7.9 | 3.6 |
| 16:00 | 5.4 | 2.7 | 7.7 | 3.7 | 7.7 | 3.7 | 7.7 | 3.7 |
| 17:00 | 5.4 | 2.7 | 7.7 | 3.6 | 7.7 | 3.6 | 7.7 | 3.6 |
| 18:00 | 5.5 | 2.7 | 7.6 | 3.6 | 7.6 | 3.6 | 7.6 | 3.6 |
| 19:00 | 5.2 | 2.5 | 7.6 | 3.6 | 7.6 | 3.6 | 7.6 | 3.6 |
| 20:00 | 5.3 | 2.5 | 7.6 | 3.5 | 7.6 | 3.5 | 7.6 | 3.5 |
| 21:00 | 5.6 | 2.5 | 7.6 | 3.5 | 7.6 | 3.5 | 7.6 | 3.5 |
| 22:00 | 6.2 | 2.5 | 8.1 | 3.4 | 8.1 | 3.4 | 8.1 | 3.4 |
| 23:00 | 6.2 | 2.3 | 8.3 | 3.4 | 8.3 | 3.4 | 8.3 | 3.4 |
| 24:00 | 5.8 | 2.2 | 7.9 | 3.3 | 7.9 | 3.3 | 7.9 | 3.3 |
| TOTAL KWH | 125.6 | 51.8 | 180.9 | 80.7 | 180.9 | 80.7 | 180.9 | 80.7 |
| % OF TOTAL KWH | | 41.2 | | 44.6 | | 44.6 | | 44.6 |
| ON PEAK: TOTAL KWH | 69.1 | 32.0 | 99.6 | 45.0 | 99.6 | 45.0 | 99.6 | 45.0 |
| % KWH | 55.0 | 61.8 | 55.1 | 55.8 | 55.1 | 55.8 | 55.1 | 55.8 |
| OFF PEAK: TOTAL KWH | 56.5 | 19.8 | 81.3 | 35.7 | 81.3 | 35.7 | 81.3 | 35.7 |
| % KWH | 45.0 | 38.2 | 44.9 | 44.2 | 44.9 | 44.2 | 44.9 | 44.2 |

FIGURE 5

HOURLY ENERGY USE

| HOUR | TYPICAL DAY 12/03/85 TO 01/03/86 TOTAL KWH | TYPICAL DAY HEAT PUMP KWH | DAY WITH HIGHEST TOTAL KWH 12/12/85 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST ON PEAK KWH 12/11/85 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST OFF PEAK KWH 12/13/85 TOTAL KWH | HEAT PUMP KWH |
|---|---|---|---|---|---|---|---|---|
| 1:00 | 2.0 | 0.7 | 3.6 | 1.3 | 2.2 | 1.0 | 4.2 | 2.0 |
| 2:00 | 2.0 | 0.8 | 3.2 | 1.6 | 2.2 | 1.1 | 3.8 | 2.1 |
| 3:00 | 2.0 | 0.8 | 2.9 | 1.0 | 2.5 | 1.3 | 4.4 | 2.3 |
| 4:00 | 2.1 | 0.9 | 2.9 | 1.3 | 2.5 | 1.4 | 4.6 | 1.8 |
| 5:00 | 2.0 | 0.9 | 2.9 | 1.2 | 2.3 | 1.3 | 3.3 | 1.5 |
| 6:00 | 2.1 | 0.8 | 3.8 | 0.8 | 2.7 | 1.4 | 3.0 | 1.0 |
| 7:00 | 2.4 | 0.9 | 3.9 | 0.8 | 2.7 | 1.4 | 3.3 | 1.6 |
| 8:00 | 2.6 | 0.8 | 3.5 | 0.3 | 3.2 | 1.3 | 4.3 | 2.1 |
| 9:00 | 2.6 | 0.8 | 4.5 | 1.9 | 3.2 | 1.3 | 2.7 | 1.3 |
| 10:00 | 3.0 | 0.7 | 5.2 | 1.9 | 3.7 | 1.2 | 4.2 | 1.6 |
| 11:00 | 3.9 | 0.7 | 5.1 | 1.4 | 6.0 | 2.6 | 5.8 | 1.9 |
| 12:00 | 3.8 | 0.6 | 5.5 | 1.7 | 5.8 | 2.2 | 5.7 | 1.8 |
| 13:00 | 3.8 | 0.4 | 6.1 | 1.5 | 5.8 | 1.9 | 4.9 | 0.9 |
| 14:00 | 3.4 | 0.2 | 4.9 | 0.9 | 5.1 | 1.5 | 4.7 | 0.9 |
| 15:00 | 2.9 | 0.2 | 5.0 | 0.9 | 6.1 | 1.8 | 5.2 | 0.9 |
| 16:00 | 2.9 | 0.2 | 4.8 | 0.8 | 5.9 | 2.0 | 4.2 | 0.7 |
| 17:00 | 1.7 | 0.2 | 3.4 | 0.9 | 4.6 | 1.7 | 2.5 | 0.7 |
| 18:00 | 1.8 | 0.2 | 2.7 | 0.9 | 4.2 | 1.4 | 3.3 | 0.8 |
| 19:00 | 1.9 | 0.3 | 3.5 | 0.9 | 4.3 | 1.1 | 2.6 | 0.9 |
| 20:00 | 1.8 | 0.2 | 1.9 | 0.0 | 3.1 | 1.0 | 2.5 | 1.0 |
| 21:00 | 1.9 | 0.3 | 1.9 | 0.0 | 2.9 | 0.5 | 2.7 | 1.0 |
| 22:00 | 2.0 | 0.4 | 3.6 | 1.0 | 2.2 | 0.2 | 2.4 | 0.6 |
| 23:00 | 2.1 | 0.5 | 3.2 | 1.6 | 2.9 | 0.8 | 2.5 | 0.7 |
| 24:00 | 2.0 | 0.6 | 3.6 | 2.0 | 4.1 | 1.0 | 2.5 | 0.8 |
| TOTAL KWH | 58.7 | 13.1 | 91.6 | 26.6 | 90.2 | 31.9 | 89.3 | 30.9 |
| % OF TOTAL KWH | | 22.3 | | 29.0 | | 35.4 | | 34.6 |
| ON PEAK: TOTAL KWH | 34.8 | 4.6 | 53.6 | 12.8 | 59.7 | 18.6 | 50.7 | 13.7 |
| % KWH | 59.3 | 35.1 | 58.5 | 48.1 | 66.2 | 58.3 | 56.8 | 44.3 |
| OFF PEAK: TOTAL KWH | 23.9 | 8.5 | 38.0 | 13.8 | 30.5 | 13.3 | 38.6 | 17.2 |
| % KWH | 40.7 | 64.9 | 41.5 | 51.9 | 33.8 | 41.7 | 43.2 | 55.7 |

FIGURE 6

HOURLY ENERGY USE

| HOUR | TYPICAL DAY 06/11/86 TO 07/11/86 TOTAL KWH | TYPICAL DAY HEAT PUMP KWH | DAY WITH HIGHEST TOTAL KWH 07/04/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST ON PEAK KWH 07/04/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST OFF PEAK KWH 06/28/86 TOTAL KWH | HEAT PUMP KWH |
|---|---|---|---|---|---|---|---|---|
| 1:00 | 6.6 | 2.4 | 6.7 | 2.8 | 6.7 | 2.8 | 7.0 | 2.9 |
| 2:00 | 6.0 | 1.9 | 6.7 | 2.8 | 6.7 | 2.8 | 7.2 | 2.9 |
| 3:00 | 5.3 | 1.6 | 6.3 | 2.5 | 6.3 | 2.5 | 7.3 | 2.9 |
| 4:00 | 4.8 | 1.3 | 6.6 | 2.6 | 6.6 | 2.6 | 7.0 | 2.8 |
| 5:00 | 4.4 | 1.4 | 5.8 | 2.1 | 5.8 | 2.1 | 6.5 | 2.5 |
| 6:00 | 4.6 | 1.5 | 5.6 | 2.0 | 5.6 | 2.0 | 6.8 | 3.7 |
| 7:00 | 5.1 | 1.6 | 7.5 | 2.9 | 7.5 | 2.9 | 8.3 | 3.3 |
| 8:00 | 4.7 | 1.3 | 5.3 | 1.4 | 5.3 | 1.4 | 5.4 | 1.2 |
| 9:00 | 3.7 | 0.5 | 4.0 | 0.4 | 4.0 | 0.4 | 4.3 | 0.4 |
| 10:00 | 0.8 | 0.0 | 1.2 | 0.0 | 1.2 | 0.0 | 1.0 | 0.0 |
| 11:00 | 0.5 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 | 0.5 | 0.0 |
| 12:00 | 0.5 | 0.0 | 0.7 | 0.0 | 0.7 | 0.0 | 0.3 | 0.0 |
| 13:00 | 0.6 | 0.0 | 0.6 | 0.0 | 0.6 | 0.0 | 0.3 | 0.0 |
| 14:00 | 0.7 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.4 | 0.0 |
| 15:00 | 0.8 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 | 0.5 | 0.0 |
| 16:00 | 0.8 | 0.0 | 1.7 | 0.0 | 1.7 | 0.0 | 0.6 | 0.0 |
| 17:00 | 0.8 | 0.0 | 1.4 | 0.5 | 1.4 | 0.5 | 0.7 | 0.0 |
| 18:00 | 0.8 | 0.0 | 1.4 | 0.0 | 1.4 | 0.0 | 1.0 | 0.0 |
| 19:00 | 0.8 | 0.0 | 1.9 | 0.0 | 1.9 | 0.0 | 0.5 | 0.0 |
| 20:00 | 1.0 | 0.0 | 2.3 | 0.0 | 2.3 | 0.0 | 0.8 | 0.0 |
| 21:00 | 1.5 | 0.1 | 1.5 | 0.2 | 1.5 | 0.2 | 0.8 | 0.0 |
| 22:00 | 1.7 | 0.9 | 1.5 | 0.3 | 1.5 | 0.3 | 1.5 | 1.0 |
| 23:00 | 5.0 | 2.6 | 5.0 | 1.9 | 5.0 | 1.9 | 4.4 | 1.9 |
| 24:00 | 6.6 | 2.7 | 6.8 | 2.8 | 6.8 | 2.8 | 6.9 | 2.8 |
| TOTAL KWH | 68.1 | 19.5 | 82.5 | 25.2 | 82.5 | 25.2 | 80.0 | 28.3 |
| % OF TOTAL KWH | | 28.6 | | 30.5 | | 30.5 | | 35.4 |
| ON PEAK: TOTAL KWH | 11.3 | 1.0 | 16.2 | 1.0 | 16.2 | 1.0 | 8.9 | 1.0 |
| % KWH | 16.6 | 5.1 | 19.6 | 4.0 | 19.6 | 4.0 | 11.1 | 3.5 |
| OFF PEAK: TOTAL KWH | 56.8 | 18.5 | 66.3 | 24.2 | 66.3 | 24.2 | 71.1 | 27.3 |
| % KWH | 83.4 | 94.9 | 80.4 | 96.0 | 80.4 | 96.0 | 88.9 | 96.5 |

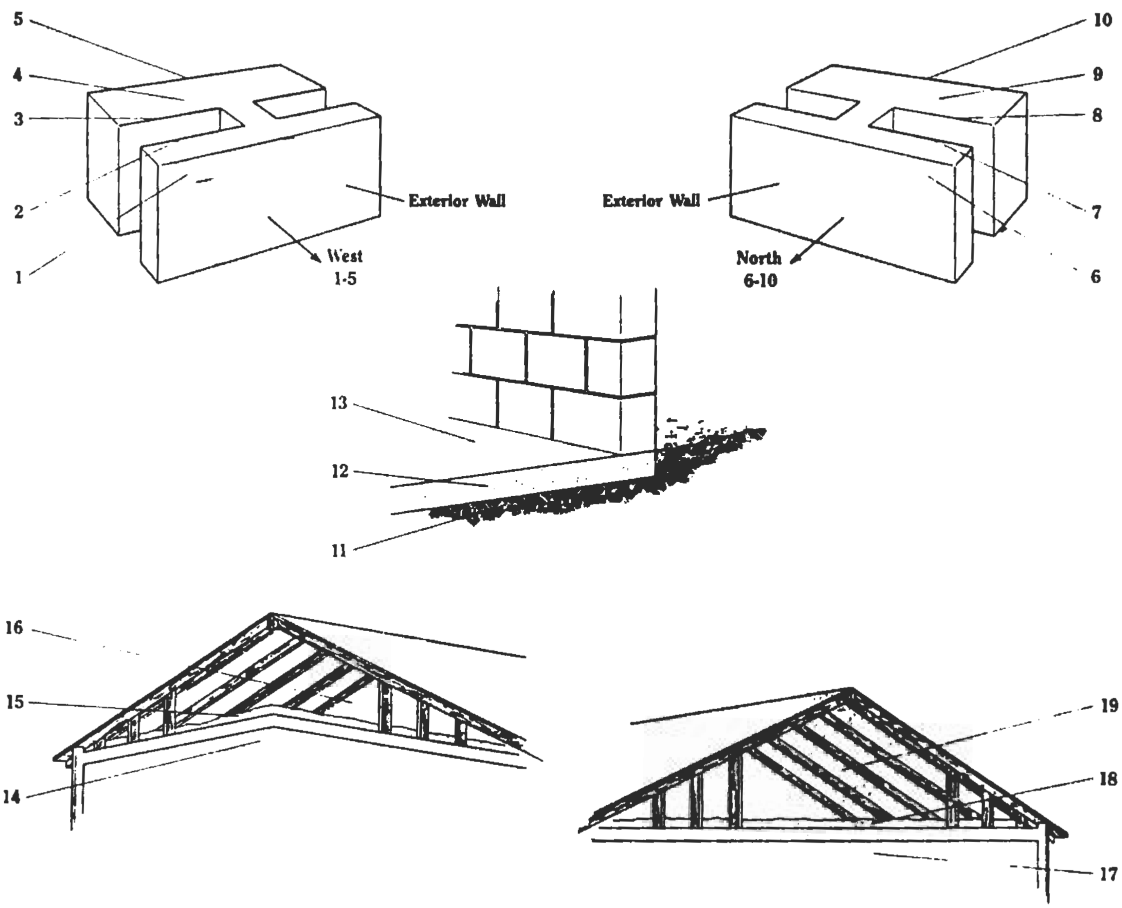
FIGURE 7

HOURLY ENERGY USE

| HOUR | TYPICAL DAY 04/11/86 TO 05/12/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST TOTAL KWH 05/03/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST ON PEAK KWH 04/19/86 TOTAL KWH | HEAT PUMP KWH | DAY WITH HIGHEST OFF PEAK KWH 05/03/86 TOTAL KWH | HEAT PUMP KWH |
|---|---|---|---|---|---|---|---|---|
| 1:00 | 0.5 | 0.1 | 2.2 | 1.6 | 0.4 | 0.1 | 2.2 | 1.6 |
| 2:00 | 0.5 | 0.1 | 1.8 | 1.2 | 0.4 | 0.1 | 1.8 | 1.2 |
| 3:00 | 0.5 | 0.1 | 1.4 | 0.9 | 0.5 | 0.1 | 1.4 | 0.9 |
| 4:00 | 0.5 | 0.1 | 1.0 | 0.6 | 0.8 | 0.1 | 1.0 | 0.6 |
| 5:00 | 0.5 | 0.1 | 1.1 | 0.5 | 0.4 | 0.1 | 1.1 | 0.5 |
| 6:00 | 0.7 | 0.1 | 0.9 | 0.5 | 0.7 | 0.1 | 0.9 | 0.5 |
| 7:00 | 0.5 | 0.1 | 1.5 | 1.0 | 0.5 | 0.1 | 1.5 | 1.0 |
| 8:00 | 0.5 | 0.1 | 0.4 | 0.1 | 0.4 | 0.1 | 0.4 | 0.1 |
| 9:00 | 0.5 | 0.1 | 0.5 | 0.1 | 0.5 | 0.1 | 0.5 | 0.1 |
| 10:00 | 0.5 | 0.1 | 0.4 | 0.1 | 0.6 | 0.1 | 0.4 | 0.1 |
| 11:00 | 0.5 | 0.1 | 0.4 | 0.1 | 0.8 | 0.1 | 0.4 | 0.1 |
| 12:00 | 0.6 | 0.1 | 0.4 | 0.0 | 0.9 | 0.1 | 0.4 | 0.0 |
| 13:00 | 0.6 | 0.1 | 0.3 | 0.0 | 0.7 | 0.1 | 0.3 | 0.0 |
| 14:00 | 0.6 | 0.0 | 0.7 | 0.0 | 1.5 | 0.1 | 0.7 | 0.0 |
| 15:00 | 0.6 | 0.1 | 0.5 | 0.0 | 1.4 | 0.1 | 0.5 | 0.0 |
| 16:00 | 0.6 | 0.1 | 0.4 | 0.0 | 1.1 | 0.1 | 0.4 | 0.0 |
| 17:00 | 0.8 | 0.0 | 0.4 | 0.0 | 1.9 | 0.1 | 0.4 | 0.0 |
| 18:00 | 0.7 | 0.0 | 0.3 | 0.0 | 0.7 | 0.0 | 0.3 | 0.0 |
| 19:00 | 0.8 | 0.0 | 1.1 | 0.0 | 1.1 | 0.1 | 1.1 | 0.0 |
| 20:00 | 1.2 | 0.1 | 1.4 | 0.0 | 1.0 | 0.1 | 1.4 | 0.0 |
| 21:00 | 1.2 | 0.1 | 1.3 | 0.0 | 1.0 | 0.1 | 1.3 | 0.0 |
| 22:00 | 1.0 | 0.1 | 1.6 | 0.0 | 1.1 | 0.1 | 1.6 | 0.0 |
| 23:00 | 0.7 | 0.1 | 1.5 | 0.0 | 0.6 | 0.1 | 1.5 | 0.0 |
| 24:00 | 0.6 | 0.2 | 0.7 | 0.0 | 0.4 | 0.1 | 0.7 | 0.0 |
| TOTAL KWH | 15.7 | 2.1 | 22.2 | 6.7 | 19.4 | 2.3 | 22.2 | 6.7 |
| % OF TOTAL KWH | | 13.4 | | 30.2 | | 11.9 | | 30.2 |
| ON PEAK: TOTAL KWH | 9.7 | 0.9 | 9.2 | 0.2 | 13.8 | 1.2 | 9.2 | 0.2 |
| % KWH | 61.8 | 42.9 | 41.4 | 3.0 | 71.1 | 52.2 | 41.4 | 3.0 |
| OFF PEAK: TOTAL KWH | 6.0 | 1.2 | 13.0 | 6.5 | 5.6 | 1.1 | 13.0 | 6.5 |
| % KWH | 38.2 | 57.1 | 58.6 | 97.0 | 28.9 | 47.8 | 58.6 | 97.0 |

FIGURE 8

# THERMAL MASS CONSTRUCTION




## Channels

1-5 West Facing Block
6-10 North Facing Block
11-13 Slab
14-16 Attic (vault)
17-19 Attic (8' ceiling)
20 Indoor Temperature NW Bedroom
21 Indoor Temperature Central Hall
22 Outside Temperature
23 Outside Humidity
24 Heat Pump Power Draw (WATTS)
25-27 Research Data