Proceedings of the 35 Annual Conference of American Solar Energy Society. ISBN 0-89553-178-X July 11 2006

DESIGN AND EVALUATION OF PASSIVE HEATING AND COOLING STRATEGIES IMPLEMENTED IN A DESERT CLIMATE

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ABSTRACT

A 137.20 m^2 foot house was designed, built and finalized in August 2005, specifically to respond to the climate in northern New Mexico. Specific passive cooling and heating strategies were applied to reduce energy consumption and increase thermal comfort. The aim of this research was to assess that performance and evaluate the use of mass and applied passive heating and cooling design strategies.

This design was predicted to use over 60% less energy than a traditionally designed stick frame house. Current performance showed energy savings on heating of up to 52%. This performance was the result of using passive heating that according to calculations saved 15 to 20% of gas consumption. Thermocouples at 20 points in the house monitored temperatures at floor, wall, roof and inside and outside air levels.The overall energy and thermal comfort performance was assessed only for the winter season. Further research will continue to determine summer performance.

1. INTRODUCTION

Nageezi is located within the Navajo Reservation limits in San Juan County, New Mexico, 164.47 km NW from Albuquerque. At 2,120.00 m. in altitude and a Latitude of 36.27 N, the climate in this region can be quite unpredictable and fluctuate by up to 20 to 40 degrees in 24 hours. Climatic data was used primarily to assess maximum and minimum design temperatures. Although not frequent, temperatures can reach highs of over 40 ^{O}C in the months of June and July and lows that drop to -17 degrees Celsius from December to February. The high desert of Nageezi NM receives an average rainfall of 200 mm per year. Humidity is nearly always in the low levels and does not represent a problem when designing home environments. Frequently and especially on some hot summer days, rainfall will evaporate before striking the grounds of Nageezi. Around 36 percent of the total precipitation occurs in July through September, when temperatures start to decrease considerably.

2. PASSIVE DESIGN AND MATERIALS

Specific passive heating and cooling design strategies were implemented in the Nageezi house. A fly-ash 30 cm thick light concrete block was selected to be use as the primary construction element for the walls. This block featured bearing strength, a 35 (6.2 metric/cal) R-value and mass that was use to store energy during the winter and summer seasons.

2.1 Heating and cooling strategies

- Orientation, the design was placed on an east-west axis to maximize solar exposure to take advantage of passive heating during the winter cold season. Over 12% of the south façade is glazing which allows this unit to collect enough energy to stay warm until early evening. Clerestory windows facilitate direct solar incidence while the lower windows are protected with a trellis that will shade the same façade in the summer.

Fig. 1 Floor plan

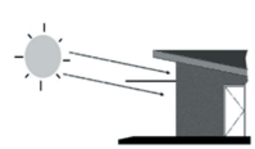

Fig. 2 South façade

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- This unit was design to be cooled entirely through natural ventilation. According to our simulations there is no need to use any artificial system to maintain inside temperature within the comfort zone. Clerestory windows allow during the day exhaustion of warm air while introduces cool air from the central east facing courtyard. At night the same clerestory windows allow free cross ventilation. And taking advantage of the cool night in high deserts we can store enough energy to avoid mechanical cooling.

Fig. 3 Daytime ventilation   Fig. 4 Nightime ventilation

- The house is equipped with a 1,200 gallon underground cistern to harvest rainwater. This water will be use for gardening, watering animals and farming.

3. RESULTS

3.1. Unit Description and Considerations

The single family residence of 137.20 m^2 in question has twenty windows and four regular 0.90X2.1 m. glass doors and one glass French door. Seven of those windows are located on the south façade, four on the east façade, three on the north façade and six on the west façade, three doors on the east façade, one on the north façade and the French door on the south façade. In addition to our basic design we added one trellis-shade of 13.10wX2.00d m. to control solar heat gains on the south façade. For practical purposes, the house roof is to be considered flat on this project. The climate in Nageezi is not as hot as the one in Phoenix, yet the roof was designed to have a resistance of 35 at minimum. Our concentration was focused on maximizing thermal comfort and energy savings by manipulating the composition of walls and glazing and to make educated material selections.

The orientation of the building affected the energy performance and thus its energy loads. The front of the house had to be facing east and this characteristic was not negotiable for cultural reasons, for this same reason we oriented our design at 0 degrees azimuth.

3.2 Electrical Energy Simulation

Two programs were used in order to make the most educated energy analysis. Energy 10 (E-10) is an excellent tool that can provide essential information with respect on material selection and natural ventilations.   E-QUEST (E-Q) from the Department of Energy is a powerful tool that breaks energy consumption and performance by use and item.

The main purpose of this analysis is to determine the best performance of different wall thicknesses, construction, as well as the location and use of glazing per façade. Natural ventilation was an excellent option for this climate, as cold nights and hot days make perfect combination.

3.3 Optimization

The first step was to optimize the glazing exposed per wall following Energy 10's recommendations of 12 percent of floor area of glazing on the south wall, 4 percent on the east and north walls and a maximum of 2 percent of the same gross square floor footage on the west wall. Our building's energy consumption for the whole year, utilizing 8" flex-Crete blocks, was 94.5 kWh/m^2 or 71.67 percent compared to our baseline case. Utilizing 10" block the overall energy consumption was reduce by only 3.49 percent to 91.20 kWh/m^2. Finally, when simulating 12" blocks our results showed an additional decrement of 2.52 percent or 88.90 kWh/m^2.

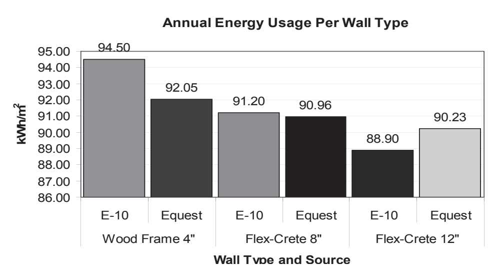

Fig. 5 Energy performance per wall type

Based on the area of the house 137.2 m2 (1470 ft2) and the use of 12" thick walls the lowest annual energy usage calculated by Energy 10 would be 88.80 kWh/m^2 or 12,197.08 kWh. According to eQUEST utilizing the same parameters the annual energy usage would be 12,380.00 kWh. Both calculations were very close one to another. At this point it was safe to recommend the use of *flex-crete 12"* for external walls and 6" flex-crete blocks for partition walls.

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3.4 Electrical consumption

Electrical energy consumption varied from month to month, these variances respond mainly to daylight hours, number of weekends and total days per month. The total energy consumption for the month of January was 1.06 kWh and for the month of February 0.94 kWh, with a differential usage of 11.32 percent between the two months. This large difference of electrical energy usage is related to the number of days in February. However, if a day by day average energy consumption used, it is practically the same at 0.03419 kWh for January and 0.03357 for February, with a difference of only 1.8 percent.

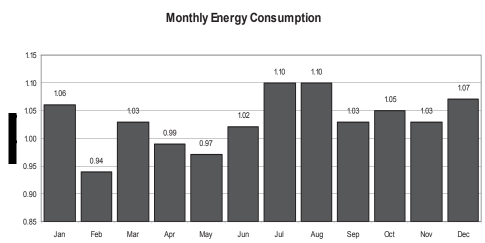

Fig. 6 Monthly electrical usage

Electrical energy usage is expected to remain almost the same all year round. The Nageezi residence does not have any mechanical cooling devices. Therefore any additional electrical usage is not contemplated at all. Perhaps during the summer time the Augustine family may decide to make more use of the bedroom and public area electrical ceiling fans. During the hot season natural ventilation should offset daytime temperatures with the use of night cooling.

The following charts will illustrate the actual electrical usage and the consumption projected by Energy 10 and eQUEST. These projections and actual consumption correspond to the period of January 23 to February 23.

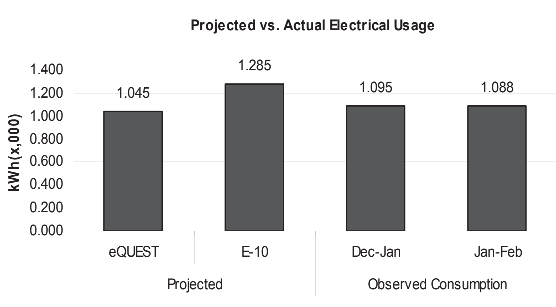

Fig. 7 Electrical usage for January, 2006

Electrical usage pertains only to lighting, washer, dryer, ceiling fans and boiler pumps. No major changes are expected to show every month. However, we notice than the energy consumption for the same months according to the records of Jemez Mountains Electric Cooperative, Inc. were almost 50 percent of what they are now. The highest projected usage by E-10 was1.285 kWh, and for the same period actual consumption in 2005 was 0.672 kWh. This represents an increment of 47.70 percent, which may correspond to the fact than this family didn't have washer and dryer, additional lights including night security lights, and a boiler that runs with a water pump.

4. GAS CONSUMPTION AND ANALYSIS

For the winter perhaps the most important parameter to assess is heating energy usage during the cold months. These calculations will be assesses using predicted BTU consumption, maintaining temperatures within the comfort zone. On the other hand the data collected will show actual temperatures compared to actual gas and BTU consumption. It is important to mention that the heating system that was simulated with eQUEST was a traditional furnace and the system used in Nageezi is a hydronic PEX coil radiant floor heating. The previous comparison was made with the sole purpose of demonstrating that radiant hydronic system performs better.

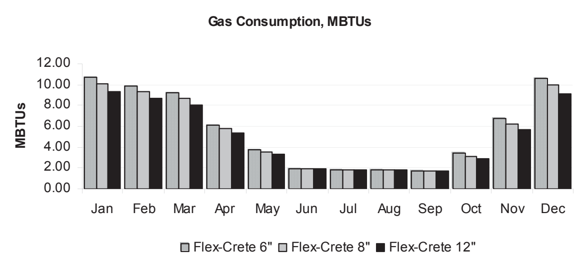

Fig. 8 Predicted gas usage

The energy savings calculated between Flex-Crete 15 cm and 30 cm rose 13.27 percent between the months of October to April. The difference in energy consumption between 8" and 6" walls was only 6.35 percent, with the 20 cm walls performing the best, based only on the winter season. As expected, gas consumption started increasing in October which is when temperatures start to decrease dramatically to zero degrees Celsius. Most of the gas for heating is expected to be burned during the early morning when the night cooling has lowered the building's stored mass temperature.

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Gas usage for the month of September is predicted to be 1,740,000 BTU's for all needs. This usage increases dramatically over the next months until it reaches it maximum energy consumption in the month of January with 9,280,000 BTU's. This represents a total energy increment of 81.25 percent. Most of the gas consumption during the months of June through September is only for water heating and cooking.

It is rather complicated to show in a one week graph the pattern of inside temperatures and outside temperatures in relation to the energy needed to maintain inside temperatures within the 20 and 27^{O}C (ASHRAE 90.1). In order to understand in more detail this relationship, it is necessary to analyze a 24 hour window. Within 24 hours it is clear and easy to make an analysis of energy consumption compared to thermal performance.

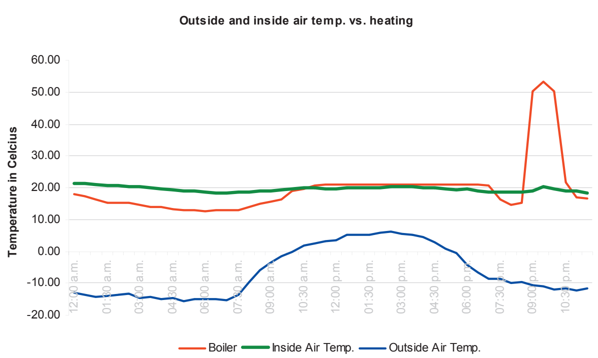

Fig. 9 Jan 10, Boiler activity trend

January 10 shows the typical trend of space heating activity, although the number of heating hours varied from day to day. On January 10 the boiler operated for two hours and 30 minutes and the previous day the boiler was on for one hour and 45 minutes. Most days the system works an average of three to fours hours per every 24 hours, burning approximately 5.8 liters of propane (180,000 BTU's) maximum. The radiant floor heating system performs very well. However, sometimes the inside air temperature drops under the comfort zone for more than the recommended time. On January 17, the outside temperatures reached record lows for the month with -17.40 ^{O}C and our indoor temperatures went down to 10 degrees Celsius.

This rather unusual problem was solved by adjusting the thermostat and instructing the client that in such cases when temperatures went down below freezing levels and the heater was not responding automatically, it should be activated manually

Unusually the boiler had to work twice the amount of typical time to bring temperatures to the comfort level zone. In total the boiler had to work for three hours and a half, burning 6.5 liters of propane, 157,500 BTUs and $3.08 dollars. According to the eQUEST modeling calculations, heating loads were penalized by 1 percent with the addition of the south trellis to control solar heat gain during the summer season.

January 17 was one of the coldest mornings in Nageezi, and due to a lack of a better thermostat the system did not keep temperature within the recommended temperatures. However, it took the radiant floor heating only three hours and a half to bring temperatures above 18 ^{O}C. Notice than the boiler goes off even before the temperatures reached 18 ^{O}C, with thermal mass storage keeping comfortable temperatures until 9:30 pm when the boiler went on again for one and a half hours.

5. THERMAL PERFORMANCE

5.1 The wall

Passive heating raised the temperatures to 48.88 ^{O}C on the outer face of the south wall. While the outer face of this wall raised its temperature to over 37 degrees, the inside air temperature went up only 3 degrees Celsius by 2:00 pm. The space water heater was not activated until 8:30 pm which is when outside temperatures dramatically went down to less than -12 ^{O}C. Theoretically this proves than the glazing facing south is bringing enough solar heating to avoid mechanical conditioning. According to calculations, this heating is saving the home user between 15 and 20 percent of gas usage during the coldest winter months. The savings are expected to increase as winter temperatures keep going up.

The high outer temperatures of the south wall didn't affect the mid and internal wall temperatures. This poor heat flow through the wall demonstrates the good insulation properties of the Flex-Crete block

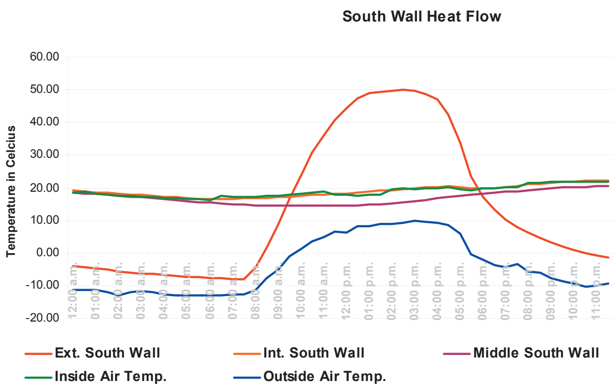

Fig. 10 South wall heat flow

5.2 The slab

The concrete slab in combination with the use of the high efficiency lonchivar water heater performed as expected with slight variances in schedule. Initially according to calculated predictions the mechanical system was going to be heating the house during the early hours of the day. Even though passive heating was expected to start complementing mechanical heating in the morning, it was not expected to eliminate all heating loads during that time. A traditional day for mechanical heating for this house is during the night for an average of 2.5 to 4 hours of total heating for every 24 hours. The heater usually comes on between 8:00 and 9:00 pm. The following graph shows in detail how the systems comes on at 8:30 pm and stays on for 2.5 hours heating the slab enough for this to stay warm for the next 5 to 6 hours. It is important to mention that even after the systems goes off the slab continues warming up. The slab temperatures started to warm up from 21.91 ^{O}C to 23.58 ^{O}C from 10:30 pm on January 12 to 2:30 am on January 13, 2006. At 3:00 am the temperature started to drop gradually until the early sun hours when they start to gradually go up with passive heating.

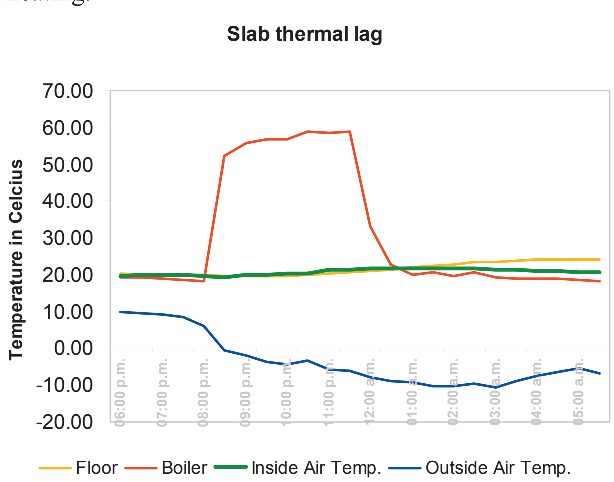

Fig. 11 Slab Thermal Lag

6. CONCLUSIONS

Initially it was predicted that our heating system would be heating the unit during the morning due to the heat loses during the night. This prediction was not met and most of the mechanical heating was happening during the night. As explained before passive heating was not expected to eliminate all the heating loads during the day and passive heating is saving more energy than expected. According to eQUEST passive heating is saving us 15 to 20 percent which through all the winter season could represent big savings for home users. In combination with our mechanical heating system the overall saving raised to almost 50 percent or 3.5 dollars daily during the coldest months.

The thermal mass in concrete the floor helps indoor temperature to remain stable during the night and retains enough energy to keep the house indoor temperatures within the comfort zone for over 5 hours. All this energy that is store in the concrete slab helps the unit to remain at stable indoor temperatures all night until passive heating start warming up the house. Around 8:00 pm the mechanical heating comes on again and the slab will be rising its temperature even after the heater goes off until 2 or 3:00 am.

In summary the unit's performance responded even better than calculated and expected. Further research will continue during the summer to determine natural ventilation performance and efficiency. The following are the highlights of winter performance.

- Overall space heating gas consumption presumably is saving the client nearly 50 percent or High desert temperature swings are ideal for designers to use thermal mass as part of their projects.
- Passive heating can be the difference between a high energy bill or unhealthy indoor ambient temperatures.
- Passive strategies should be the first alternative followed by the optimization of mechanical systems.
  Design does not necessarily have to increase the price of housing units.
- Sustainability targets long term affordability by decreasing the actual maintenance cost of utilities.

Affordable housing and highly efficient architectural design seem to be the beginning to target long-term affordability. The Navajo Nation has been battling all its history to provide a better life for the Navajo people. Yet they are not the only ones with limited access to affordable and efficient housing units. Millions across the United States and across the world are not even able to live in a house, even less in a

 ISBN 0-89553-178-X July 11 2006

highly efficient unit. The Nageezi house sets the groundwork for potential future housing projects. Perhaps a lesson has been learned and those individuals in positions of power embrace sustainability as a symbol of wellness for their people and their land.

The Augustine's residence gave all of us a great opportunity to learn and envision a better future for upcoming generations. Efficiency does not have to be expensive. Design by itself will dramatically affect energy consumption and user satisfaction. The Nageezi house was the first experimental project from the ASU Stardust Center for Affordable Homes and the Family. Yet, this experiment was designed under very strong educated analysis, calculations and architectural design considerations. The design addresses the cultural background of the Navajo family and their needs. In addition to this it responds and interacts with the regional climatic conditions.

A cost-benefit analysis remains to be completed. Nonetheless, construction of this 140 square meters home did not exceed $140,000. The systems installed in this new construction were conventional as those used by the mainstream construction industry. The design of this unit is what makes it highly efficient. The improvement of mechanical systems simply complements the design.

Many more housing developments are in the making. Hopefully we will continue to see a change that will benefit our most needed sectors of our societies and our natural environments.

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