PASSIVE SOLAR CONSTRUCTION METHODS: LESSONS LEARNT FROM THE EXPERIMENTAL SOLAR HOUSE

Petros Lapithis, Anna Papadopoulou

University of Nicosia, Department of Architecture, Sustainable Architecture Unit, Nicosia (Cyprus)

1. Introduction

The discipline of Solar Architecture, which has been gaining popularity and momentum in geometric rates, is unique in its direct and immediate connection to the characteristics of its designated site. Although most architectural forms gain validity via their site-specificity, none does more so than Solar Architecture. Site characteristics range from geomorphology, local energy resources and potential, micro- and macro-climatic conditions as well as a breadth of social parameters.

Cyprus' climate lies within the temperate Mediterranean zone, with average hottest peak reaching 41°C in the summer and dropping to an approximate of 5°C in the winter. Relative humidity ranges from 40-60%, and a considerable daily temperature fluctuation is observed, with up to 18°C difference between day and night temperatures. Thus Cyprus' climate calls for effective, efficient and ecological means of cooling in the summer and heating in the winter months.

The Experimental Solar House is a private initiative whose construction was completed in 2000 and whose mission statement was to investigate and implement best practices in passive solar design in Cyprus. Its spatial and aesthetic characterises were derived from the basic typology of a middleclass, Cypriot dwelling of the late twentieth century.

Passive solar design, as it pertains to architecture and construction, describes the general practice of exploiting natural, renewable energy sources to maintain steady, comfortable indoor temperatures. It mainly entails using solar energy for winter heating and natural wind for summer cooling in the northern hemisphere. The implementation of passive solar design ranges from simple actions (like opening the blinds of a house during the morning hours to allow heat to enter and be absorbed internally and the slowly released after the sun sets) to more forms like shading mechanisms whose design and orientation allows winter sun to enter while protecting against summer sun. A full account of passive solar design is not within the scope of this paper.

2. Planning the Experimental Solar House

It was decided early on in the stages of the design that the house shall have an area in the region of 200-250m^2 so as to approximate the average size of a contemporary, middleclass house in Cyprus. At the end of the design process, the area of the house was settled at 223m^2. The construction costs were planned so as not to exceed 140,000 Euro, by considering construction costs of a typical middleclass house (Stavrou, 1998). Similarly, the final product, i.e. the house, is comprised of all of the common components of a two-storey, Cypriot house (Lapithis, 2002).

At the initial stages of designing the Experimental Solar House, several passive solar systems were considered. Taking into account all advantages and disadvantages at hand, it is concluded that the best systems to be implemented for the Experimental Solar House were the following:

- Thermal storage by increased interior mass. The simplest heat storage approach is to construct the building of massive structural materials insulated on the exterior, to couple the mass of the indoor space.
- Thermal insulation
- Direct solar gain, i.e. allowing sun to enter internal spaces with no interference
- Solar control: orientation and shading devices
- Glazing: Low emmisivity glazing, argon-filled, double-glazed, special glass panes. Vertical glazing surfaces would intercept almost as much radiation during heating season as optimally sloped surfaces. Shading can be easily controlled during the non-heating season.
- Natural ventilation: cross ventilation, stack effect, night ventilation and ceiling fans

Vertical and horizontal louvers, although considered, were deemed not appropriate due to their associated high construction cost and permanent obstruction of surrounding view on the east and west façade of the house. The second floor bedroom windows located on the southeast and south walls were recessed so as to prevent summer sun from entering, but allowing winter solar warmth to enter. These recesses also act as permanent shading devices. Roof fans are used to ensure against overheating during periods of high temperatures.

The house is supported by a concrete frame, and it is furnished with concrete floors and roof slabs. Exterior walls are made of 250mm ceramic clay bricks, locally produced and are dressed on the exterior with 70mm of expanded polystyrene and plaster. In fact, the entire building, including concrete beams and columns is fully covered by the expanded polystyrene so as to eliminate thermal bridges.

The ground floor beams of the structure are reversed into the first floor slab so that they do not appear in the interior of either floor. The top of the roof slab, i.e. the terrace, is dressed with wood beams and metallic sheets, 600mm in overall thickness, so as to create an extra 600mm of air cavity enhancing insulation. The top surface of the roof is then covered by 100mm of expanded polystyrene, on top of which lies a layer concrete which forms the water drainage canals. It should also be noted that the concrete foundations are constructed according to local anti-seismic regulation. Monitors have been installed in various locations of the house to record temperatures and humidity.

Constant, comfortable winter indoor temperatures have been achieved successfully. Enough solar heat storage was collected and stored during daytime and released with the appropriate rate during the night hours in order to maintain pleasant nightly temperature. The fireplace was used to top up the heat on occasions when winter evening temperatures dropped below the norms. In the winter of 2000 this occurred only eight times and in the winter of 2001 this occurred ten times. The fireplace was lit on average three to four hours per night and the warmth was retained until well into the next morning.

The monitoring results of the Experimental Solar House have indeed demonstrated that by employing an understanding of the principles of environmental physics, appropriate use of available technology and judicious use of materials and resources, it is indeed possible to achieve comfortable living conditions in the summer months and low energy use.

Figure 2.1 summer design considerations (north-south section through the staircase)

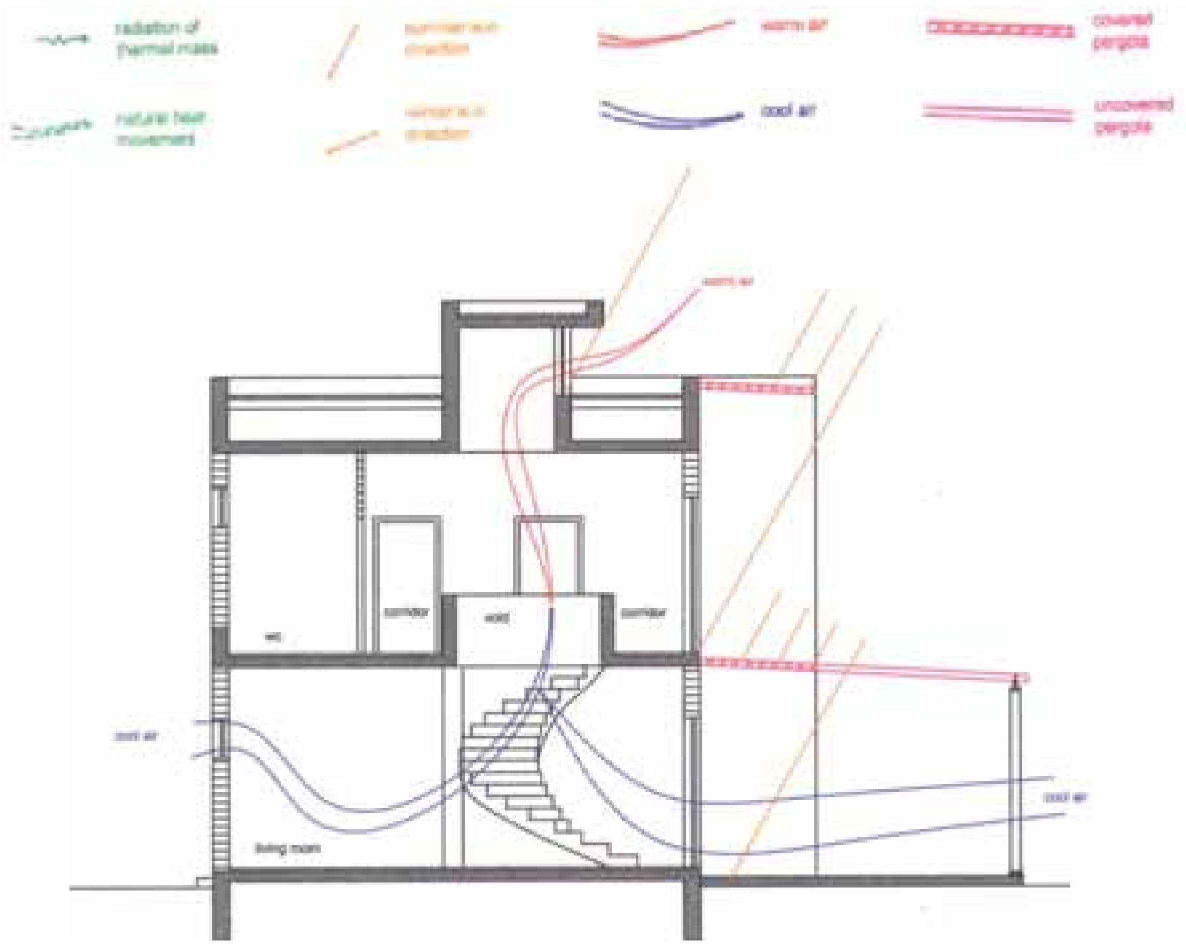
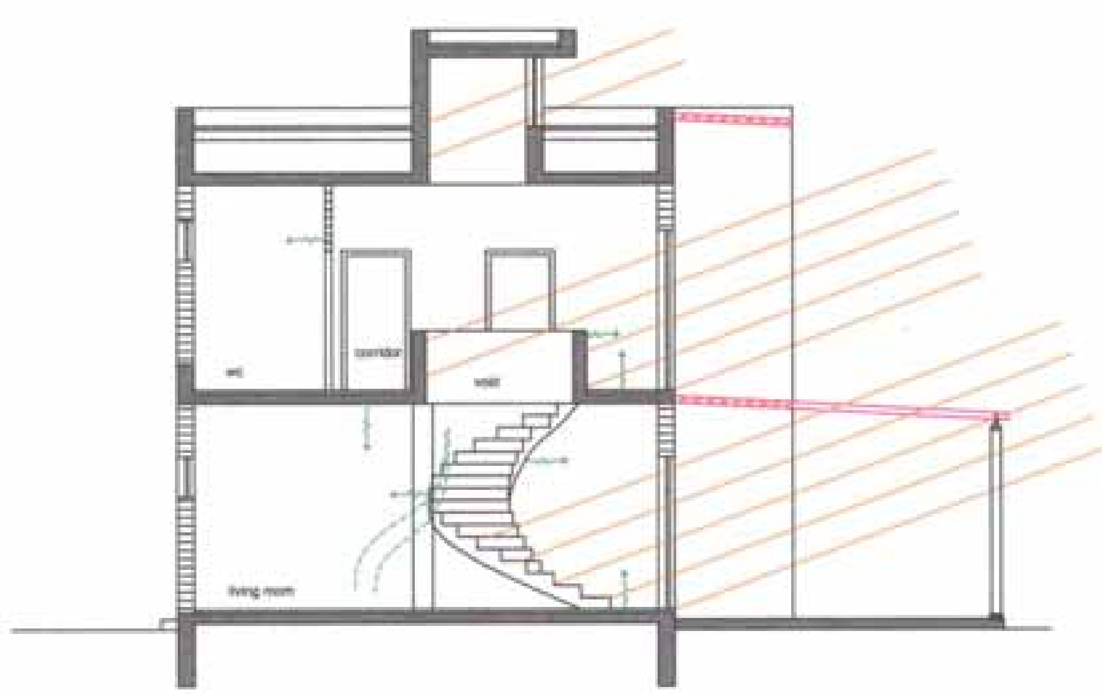


Figure 2.2 winter design considerations (north-south section through the staircase)



3. Mass Applications

The thermal mass of a building is of particular significance for Cyprus due to the large diurnal fluctuations (15 to 25 ºC) and the potential possessed by mass for large solar contribution in winter and cooling in summer (Sergides, 1991). This implies that heat admitted during the day in winter could be stored for slow release during the evening hours. Therefore, addition of internal mass incurs energy conservation (Sergides 1991). It appears that the extent of mass increase is a critical factor concerning the effect on the energy loading. Specifically, extensive increase of thermal mass could act adversely, requiring more time to cool it in the summer nights or indeed to accumulate heat in the winter.

The purpose of internal thermal storage resulting from increased mass, whether provided by masonry walls, Phase Change Material (PCM), water, or the use of smaller windows on the south facades is to take advantage of "free mass," while eliminating the possibility of overheating and providing comfort and energy savings. Thermal mass use can also temper increased solar gain. Adding thermal capacity reduces temperature swings if the mass is well distributed in the direct gain space.

Placement of thick carpets over heat-storage floors and hanging too many plants in sunspace windows are some examples of elements introduced in interior spaces which do not bear positive effects on comfort. The elements on a building inclined to absorb heat must not be shielded from effective solar heat absorption. Occupants of passive buildings must be well informed of the necessity for exposure of thermal storage components to direct sunlight, or to secondary gains via reflection and convection. There have been examples of subsequent owners covering over heat-storage walls with insulation and wallboard to "hide" block or brick exposed on the interior, thereby eliminating its storage capacity and function. One way to prevent this kind of intervention is to provide a storage mass that is aesthetically pleasing or acceptable. Also, an operator's manual for the building explaining the functions and requirements for the mass to work well can be helpful.

Other options of thermal mass include possibilities where the exterior walls may be lightweight and highly insulated and interior separating walls are constructed with ceramic clay bricks or with poured concrete. Both these cases offer high thermal effusivity. In these cases, the thermal mass can be located on the floor or on the ceiling. A thickness of 100mm of a massive material (concrete or brick) is quite suitable for providing coolness for the span of one day or for storing passive heat during a winter day. However, it should be noted that should the house be indeed well insulated, the importance of passive heat absorption lies in the surface area of wall that is in contact with air, rather than the actual thickness of the wall.

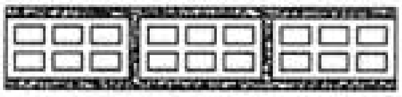
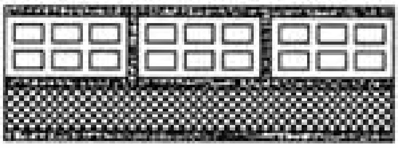
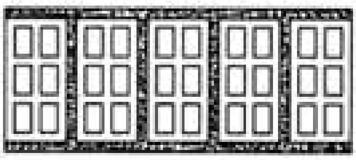
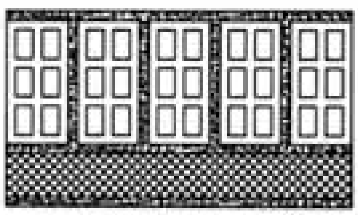
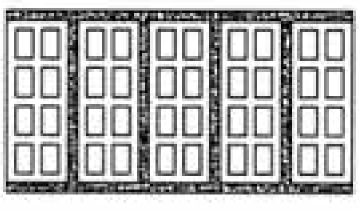
Construction of passive solar heat storage ranges from simple to quite complex. The simplest heat storage method is to construct the building in question with massive structural materials insulating the exterior to couple the mass to the indoor space. Multiple functions of the components can increase cost efficiency.

4. Wall Construction Methods

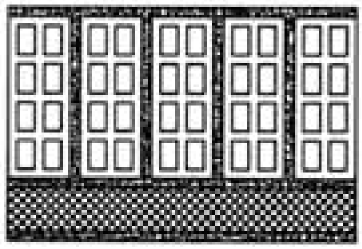
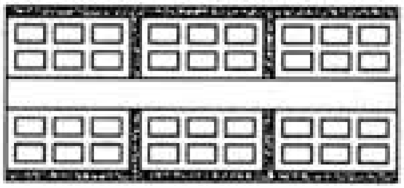
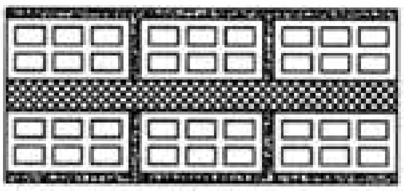
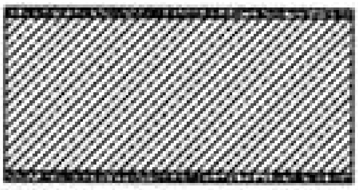
In the construction of the Experimental Solar House thirteen methods of wall construction were taken under consideration. The following solutions exhibited in Table 6.1-6.3 for a masonry-insulated wall were considered.

For plastering the external wall were polystyrene is placed, a special plaster is being used. It is a brand commercially known as Adesilex FIS 13 and it is especially designated to be applied on insulation panels. Special plastering is required because the customary plaster used on brickwork (mixture of water, cement and sand) will quickly form cracks when placed on polystyrene.

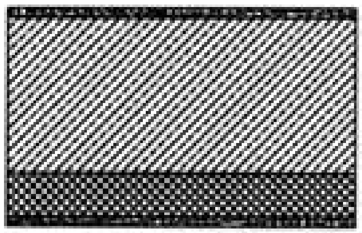
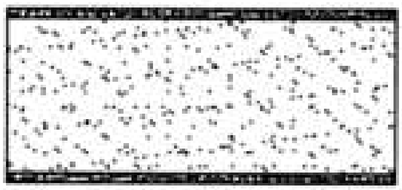
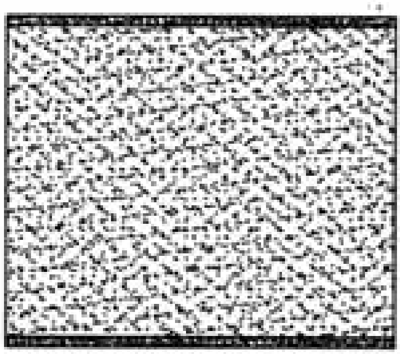
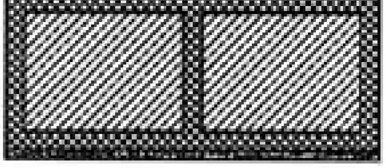
Tables 4.1 Wall construction consideration methods

1. 100x100x300 brick, with three layers of plaster on both the interior and the exterior sides. U-value 1.66 W/m²k	
2. 100x100x300 brick and 70mm of expanded polystyrene on the exterior, with three layers of plaster on the interior and Adesilex FIS 13 on the exterior sides. The plastering on the exterior will be layered on a fibreglass mesh. U-value 0.36 W/m²k	
3. 100x200x300 brick, with three layers of plaster on both the interior and the exterior sides. U-value 1.47 W/m²k	
4. 100x200x300 brick and 70mm of expanded polystyrene on the exterior, with three layers of plaster on the interior and Adesilex FIS 13 on the exterior sides. The plastering on the exterior will be layered on a fibreglass mesh. U-value 0.31 W/m²k	
5. 100x250x300 brick, with three layers of plaster on both the interior and the exterior sides. U-value 1.37 W/m²k	

Tables 4.2 Wall construction: methods and options

6. 100x250x300 brick and 70mm of expanded polystyrene on the exterior, with three layers of plaster on the interior and Adesilex FIS 13 on the exterior sides. The plastering on the exterior will be layered on a fibreglass mesh. U-value 0.296 W/m²k	
7. 250mm cavity brick wall. 100x100x300 brick on both sides and 50mm of air gap in between the walls, with three layers of plaster on both the interior and the exterior sides. U-value 0.9 W/m²k	
8. 250mm cavity brick wall. 100x100x300 brick on both sides and 50mm of expanded polystyrene in between the walls, with three layers of plaster on the interior and Adesilex FIS 13 on the exterior sides. U-value 0.314 W/m²k	
9. 250mm concrete wall, with three layers of plaster on both the interior and the exterior sides. U-value 3.22 W/m²k	

Tables 4.3 Wall construction: methods and options

10. 250mm concrete wall and 70mm of expanded polystyrene on the exterior, with three layers of plaster on the interior and Adesilex FIS 13 on the exterior sides. The plastering on the exterior will be layered on a fibreglass mesh. U-value 0.4 W/m²k	
11. 62.5x25x20 Ytong blocks with two layers of special plaster on the inside wall and on the outside with a total price of 37.00 Cyprus pounds per square meter. U-value 0.29 W/m²k.	
12. 500mm adobe wall, with three layers of plaster on both the interior and the exterior sides. The plastering on the exterior will be layered on a fibreglass mesh. U-value 1.45 W/m²k	
13. Isorast, which is a lego type block made of polystyrene the cavities are then filled with concrete. 250mm cavity polystyrene wall. 30mm expanded polystyrene on both sides and 190mm of concrete in between the walls, with Adesilex FIS 13 on both the interior and the exterior sides. U-value 0.46 W/m²k	

Since in a passive building, the walls require thermal mass in order to retain heat, type 11 and 13 as exhibited above are immediately rejected in the case of the solar house. Types 11 and 13 can be used for passive buildings as long as the walls will not be used as thermal mass.

Since the U-value of the wall is an important factor, types 1, 3, 5, 7 and 9 are rejected, as they have an unacceptable U-value.

Type 10 and 12 have an acceptable U-value, but the prohibitive manufacturing cost does not make them an efficient choice.

The types 2, 4, 6, 7 and 8 are viable options. Type 6, 7 and 8 appear to be the most appropriate options for a 250mm thick wall to match the thickness of the concrete frame of the building. A wall that has the same thickness as the concrete skeleton is preferred so as to avoid the 50mm gap between the external walls and the columns and beams, making for a better architectural detail.

With these comparisons in mind, the chosen type of wall construction for the Experimental Solar House is type 6, since it effectively insulates the entire structure and avoids thermal bridges where the columns and beams occur.

5. Polystyrene as Thermal Insulation

Research on extruded and expanded polystyrene for the application on exterior surfaces of buildings has been conducted by the authors. The research findings conclude that expanded polystyrene is a more cost effective option than extruded polystyrene. Fortunately, expanded polystyrene is produced locally, whereas the extruded kind has to be imported from abroad. This renders the use of expanded polystyrene an even more sustainable option than the alternative.

A comparison of different densities of expanded and extruded polystyrene was performed. The U-values of the polystyrene were compared versus the thickness and cost which was applied on a number of elements of a building (see Figure 5.1 showing applications on the walls, columns, beams and overhangs)**:**

- Brick wall
- Roof
- Overhangs (on exterior floors)
- Columns and beams

Expanded polystyrene considered, supplied by the Cypriot company *Leopol Manufacturers Ltd*:

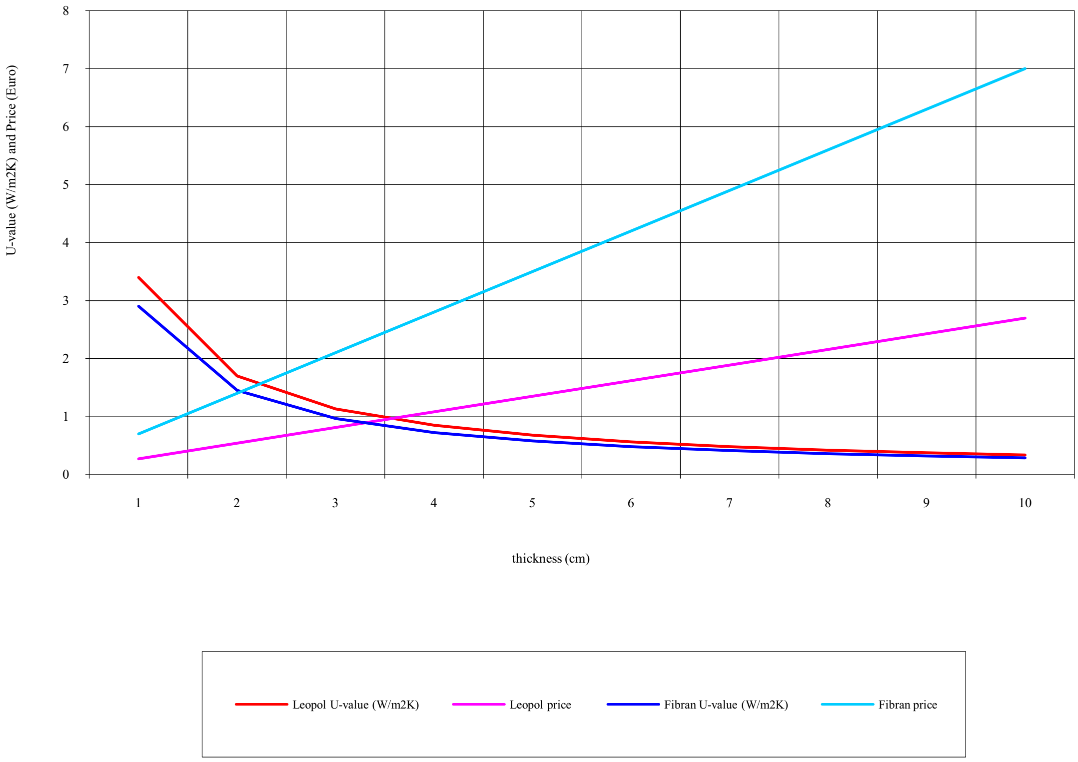
1. Density (ρ) of 15 kg/m³ and thermal coefficient (λ) of 0,036
2. Density (ρ) of 20 kg/m³ and thermal coefficient (λ) of 0,035
3. Density (ρ) of 25 kg/m³ and thermal coefficient (λ) of 0,034
4. Density (ρ) of 30 kg/m³ and thermal coefficient (λ) of 0,033
5. Density (ρ) of 40 kg/m³ and thermal coefficient (λ) of 0,033

Extruded polystyrene considered, supplied by *Fibran Bulgaria AD*:

1. Polystyrene used for walls of density (ρ) of 28-30 kg/m³ and thermal coefficient (λ) of 0,025
2. Polystyrene used for concrete of density (ρ) of 28 kg/m³ and thermal coefficient (λ) of 0,029

With respect to the type of polystyrene used, considerations considered included the comparative research of the required structural thickness compared to the unit price for several different polystyrene densities. From this comparison, it was determined that in order to meet the required proposed Cyprus Standards, polystyrene of weight 25kg/m^3 is to be used. Figure 5.1 shows the U-values and prices of the Extruded (Polystyrene used for concrete of density (ρ) of 28 kg/m³ and thermal coefficient (λ) of 0,029) and Expanded (Density (ρ) of 25 kg/m³ and thermal coefficient (λ) of 0,034) polystyrene.

Figure 5.1 Expanded (Leopol) versus Extruded (Fibran) polysteryne

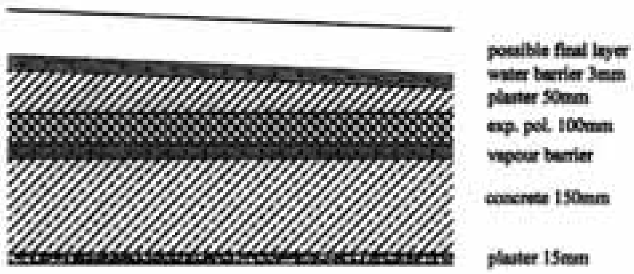
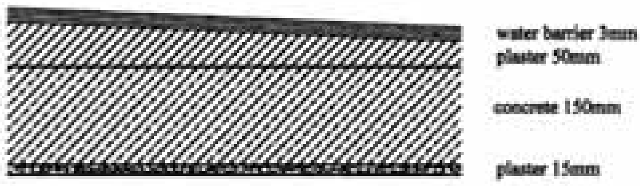
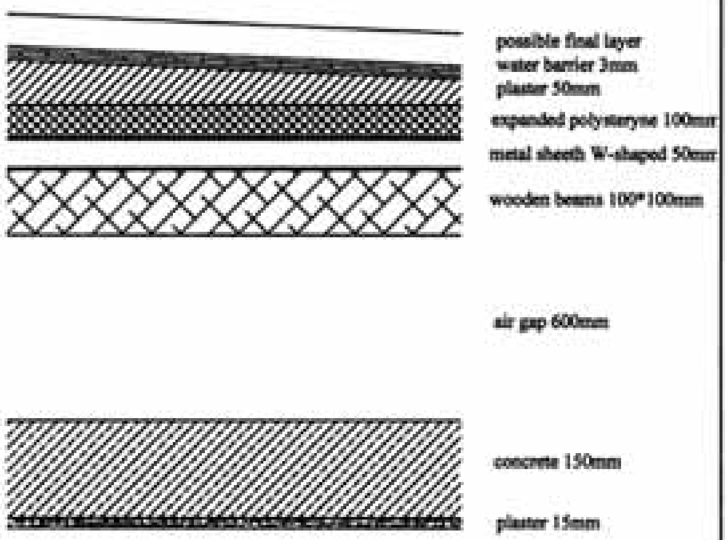


6. Roof Construction Methods

In the construction of the Experimental Solar House, two methods of roof construction were taken under consideration. These options are presented in Table 6.1.

As discussed earlier, a passive building requires thermal mass in order to retain heat. With that in mind, all three roof types are indeed viable options. However, type 1 and 3 seem to stand out because of the lower U-values they posses. Eventually, type 3 is selected because the reverse beam structure of the roof provides aesthetically better interior architectural space. Also, better insulation results are achieved while avoiding a 50mm gap between the external walls, columns and beams.

Table 6.1 Roof construction: methods and options

1. 150mm concrete, 3mm water insulation and 100mm of expanded polystyrene on the exterior, with three layers of plaster on the interior and 50mm on the exterior. U-value - 0.29 W/m²k.	
2. 150mm concrete, 3mm water insulation, with three layers of plaster on the interior and 50mm concrete on the exterior sides. U-value 3.03 W/m²k.	
3. 150mm concrete, 600mm air gap, 3mm water insulation and 100mm of expanded polystyrene on the exterior, with three layers of plaster on the interior and 50mm on the exterior. U-value - 0.28 W/m²k.	

7. Monitoring the Experimental Solar House

The house was inhabited in May 2000. In the first month of habitation, it was observed that daytime external temperature reached approximately 28°C and the nighttime temperature was 14°C. Indoor temperatures, however, remained steady at around 22°C. Hourly temperature and relative humidity readings were taken all year round. As it transpired from the readings, the temperatures acceptable for comfort level range from 19°C to 29°C for Cyprus (Lapithis, 2002).

Overall, the twenty-four hour indoor readings indicate a fluctuation of 0-2ºC. Considering that the external temperature swing is 10-15ºC, it is proven that a constant temperature is preserved throughout the day.
Energy supplies in the Experimental Solar House are electricity, potable water and wood for auxiliary heating. The house rewarded the inhabitants with a low winter and summer utility bill, considering that no air conditioning system is required. Overall, there is an annual energy saving of 85% between the Experimental Solar House and an average contemporary house in Cyprus that falls within the specific typology.

8. List Summarizing Lessons Learned

- It is necessary to consider the total usage of energy in a building, and not to isolate, for instance, space or water heating alone. In the same spirit, in attempting a holistic approach to a passive solar house, it is crucial to consider remedies for both summer and winter circumstance. Additionally, it transpired reducing cooling loads was often a greater challenge than reducing heating loads.

- The building ought to be considered as a system, where individual technologies act as integral parts of the greater whole. The order in which the technologies are introduced into the design is of importance. In general, energy-conservation technologies are considered first, passive solar are second, and active solar are considered third. However, in most cases all of these technologies are used as a synergistic combination of systems.

- Energy conservation, using high levels of insulation and highly insulated windows, should be the first option considered. High levels of insulation in all building members are beneficial in the climatic conditions of Cyprus, as well as in countries where cooling is a major issue.

- It was been proven that passive solar gains can contribute to indoor space heating in the climatic conditions of Cyprus and do not lead to overheating if counteracted by proper solar protection. Passive solar cooling was also proven to be effective. In both the heating and the cooling scenarios, it was necessary to include thermal mass in direct gain passive solar design, as it extended the usability of the systems by increasing the time constant and slowing down heat build-up in the summer.

- Designing new, innovative building concepts requires a multi-disciplinary design team. The extensive uses of solar technologies, which are often integral parts of the design, make the design process unique against traditional methods. It requires the energy aspects to be considered early on in the design stage and it also requires architects, engineers and the clients' collaboration from the onset of the project.

- Training of constructors and on-site supervision is particularly important in low-energy buildings. In very low-energy or zero-energy buildings, the energy consumption is strongly influenced by construction practices and by user behavior than it is in conventional buildings.

9. Conclusion

There are a number of choices of solar techniques from which a design professional can select, each with its own set of advantages and disadvantages. These options must be weighed in terms of the local climate, construction practices and competing fuel costs and overall construction expenses. However, the above-mentioned passive solar system would not guarantee comfort levels in summer and winter months unless a proper assessment is carried out to include calculations that involve a suitable prediction method of indoor air temperatures and numerical external and internal design data.

Currently, most buildings in Cyprus are constructed with little or no insulation. In the few instances where insulation does occur in Cypriot houses, it is generally isolated in the wall members. This is fact the leading cause of large instances of summer and winter discomfort. The Experimental Solar House is designed in accordance to comfort zone calculations so as to ensure the maximum comfort of its occupants. It is important not to neglect insulation of building members such as the skeleton and the roof.

When a Cypriot contemporary house was compared to a traditional house (Lapithis 2004), the energy performance of the original insulated traditional house was proven to be superior to the contemporary house, which has no energy-efficient considerations. Therefore, since the Experimental Solar House was designed and constructed using researched material of traditional houses, once compared with a contemporary house the results were easy to assume. The Experimental Solar House proved to be far superior in its energy-saving performance. Thus the construction of the solar house has a purpose that is multifaceted. It is an environmental success as well as an architectural one. The house itself is able to provide excellent indoor air quality and natural lighting.

10. References

Lapithis, P, 2002, **Solar Architecture in Cyprus**, PhD thesis, University of Wales, Cardiff
Lapithis, P, "Traditional vs. Contemporary vs. Solar Buildings," **International Solar Energy Society Conference Proceedings**, International Solar Energy Society, 20-24 June 2004
Sergides, D, 1991, "Zero Energy for The Cyprus House," The Architectural Association
Stavrou, N, 1998, **Energy Conservation in New Residential Buildings in Cyprus: Cost Comparative Study**, School of the Built Environment, University of Glamorgan, Cardiff