PLEA 2017 EDINBURGH
Design to Thrive

# New insight on passive ice making and seasonal storage of the Iranian Yakhchal and their potential for contemporary applications

**Hareth Pochee[1], John Gunstone[1], Oliver Wilton[2]**

[1] Max Fordham LLP, London, UK, h.pochee@maxfordham.com
[2] The Bartlett School of Architecture, UCL, London, UK, o.wilton@ucl.ac.uk

**Abstract:** The Yakhchals of Iran are a type of ancient structure and system used to produce, harvest and store ice for cooling uses later in the year. In this paper, the authors present an explanation of how Yakhchals are understood to have operated and then go on to present analyses of aspects of the ice making and storage processes. A transient 1D heat transfer model is used to predict of how much ice could be made over the course of a year. A second transient heat transfer simulation is used to predict the amount of ice that could be retained (not melt) over the storage season. Finally, the potential for a modern day application of passive ice making and storage for space cooling in an ultra-low energy office is explored.

**Keywords**: Yakhchal, ice, passive, cooling, simulation

## Introduction

The Yakhchals of Iran are relatively well-known (Hosseini & Namazian, 2012) and their method of making and storing 'ice in the desert' via passive means has influenced the current generation of passive and low energy designers. The use of ice from Yakhchals for cooling drinks and food was reported to be common in Iran by John Fryer in the late seventeenth century (Beazley, 1977) and some Yakhchals were reportedly still in active use as recently as the 1960s (Jorgensen, 2010). Yakhchals are found across Iran in areas where the climate enables the freezing of ice on site in winter, or where ice and snow could be brought from nearby mountainous areas (Hosseini & Namazian, 2012).

Figure 1 illustrates a particular large, dome type Yakhchal in Meybod, in the province of Yazd on the Iranian plateau, which is reported to be around 400 years old and has

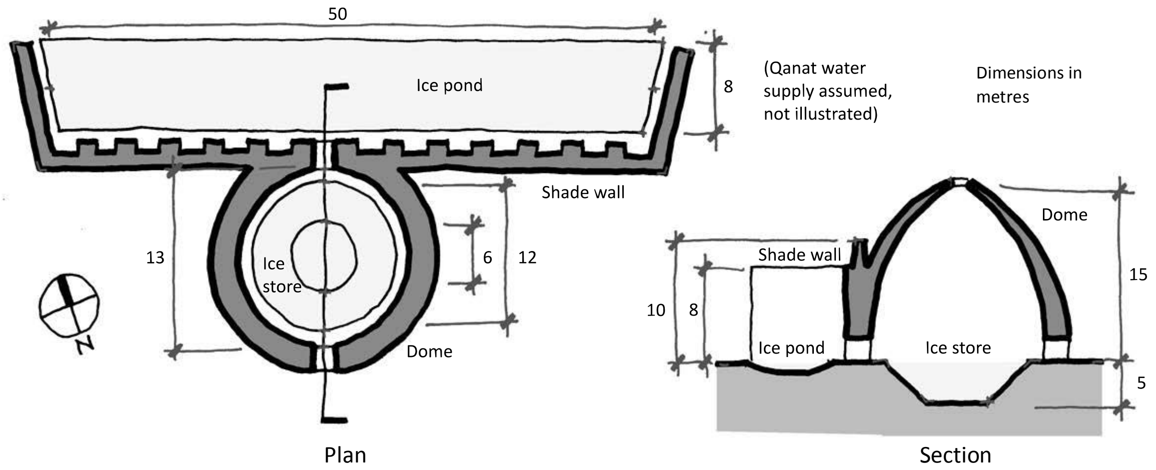



Figure 1. Meybod Yakhchal. (Adapted from Ghobadian, 2001 as referenced in Hossieni and Namazian, 2012)

recently been partially restored. The complex includes an ice production pond, which is protected from the low winter sun by a shade wall, and a store where ice is kept for use in the warmer months. The shade wall and dome structures are typically made of mud bricks or adobe, sometimes made using soil extracted from the local ice pond and store excavations (Jorgensen, 2010).

In this paper we present the results of analyses of several building physics aspects of the large dome type Yakhchal and ice pond structures within Yazd climatic conditions. There are several aims; to understand and simulate the heat transfers used to form ice; to make predictions of the amount of ice that could be produced; to understand and simulate the physics of the ice storage process; to make predictions of the amount of ice that could be retained (not melt) from winter to summer; to understand how the architectural designs of the structures contributed to these effects; and to investigate if passive ice making and storage could be made use of in a modern architectural context.

Anecdotal evidence from historical accounts regarding quantities of ice production vary, CJ Wills describes the ice production process in Shriaz in 1891; “A few inches of still clear water is collected in the pond, by morning it is frozen; at night the water is again admitted, and another inch or two of ice made. When three to six inches thick, the ice is broken and collected for storage in a deep well on the spot : and so day by day the process goes on during the short winter until the storehouses are full” (Wills, 1891).

Other physics based analyses have been carried out; Jorgensen presents an ice yield estimate from the Abarqu ice pond in Yazd district of 100cm/yr. However, having reviewed this work we feel that the work over estimates both the ice formation rate at a given temperature and the extent that Yazd’s climate resides at sub-zero temperatures leading to a gross over prediction of ice yield. Zare et al derived an expression for the thickness of pond ice produced based on climatic conditions (Zare & Davoodmoosavian, 2015). The same paper presents an analysis of dome shaped stores concluding that dome shaped stores absorb less solar radiation than flat roofed equivalents.

**Climate Data**

The climate of Yazd is very dry, with hot summers and cool winters. The average annual precipitation is less than 100mm/yr. A TMY hourly climate data set (IRN_Yazd.408210_ITMY) is available for Yazd (Energy_Plus_Weather_Data, 2005). Figure 2 illustrates the hourly dry bulb temperature for this set showing that summer temperatures occasionally exceed 40°C and winter temperatures occasionally drop below -5°C. TMY data sets use a cut and paste approach from many years of data to synthesize a “typical” year’s climate data. The Yazd TMY year uses data from 1961 to 2004.

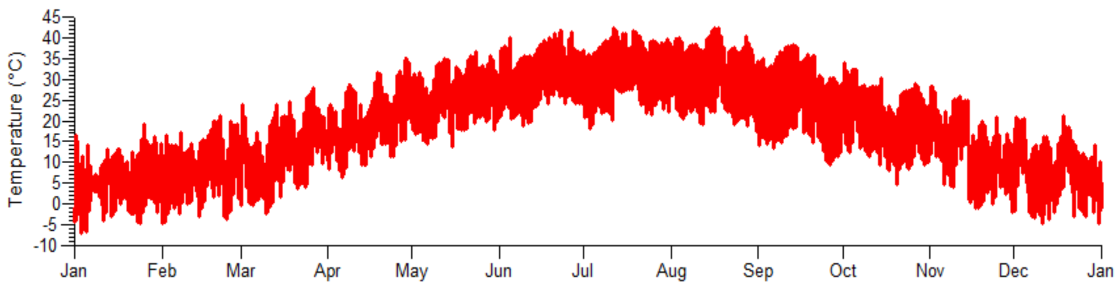


Figure 2. hourly dry bulb temperature from the Yazd TMY (Typical Meteorological Year).

**Ice Production Modelling**

A 1D numerical model (the "MF Pond Ice Model") was created to simulate the heat transfer processes in the Meybod ice pond.

Figure 3 illustrates the pertinent model parameters. The model uses the Yazd TMY hourly climate data set for the external variables. The convection, sky radiation, and evaporation models implement the methods proposed by Tang and Etzion (Tang & Etzion, 2005) and Hamza (Hamza, 2007).

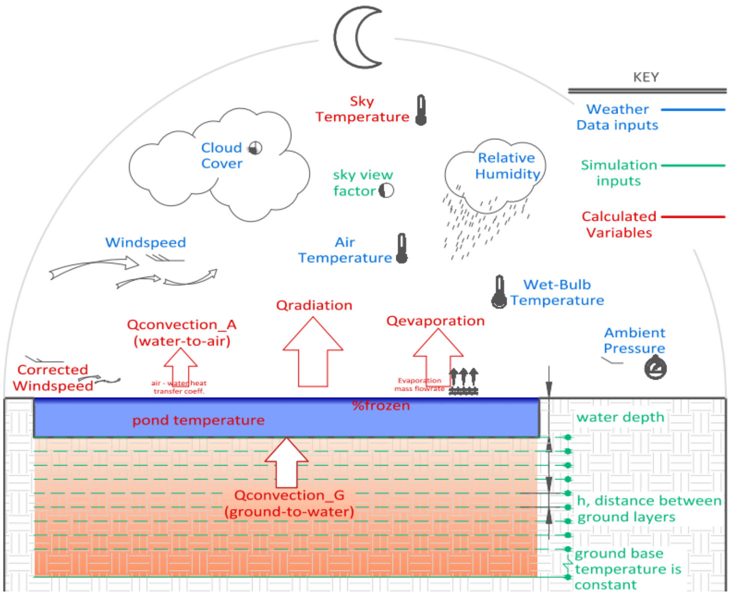



Figure 3. Ice making model features and parameters. "Q" is used to represent heat transfer

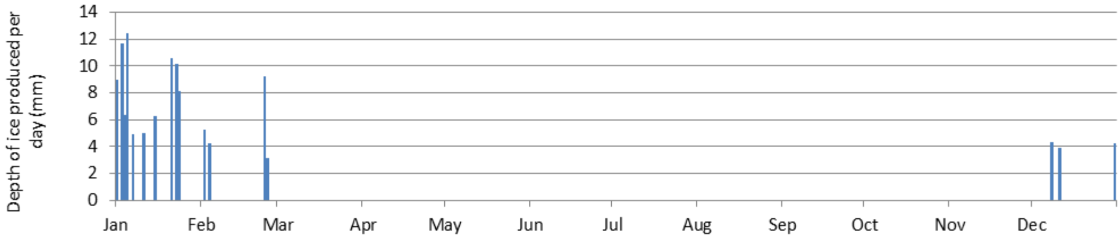
The ground below was modelled as 5m thick layer with a base temperature fixed at 19°C (the annual average air temperature). The ground thermal conductivity used was 0.3$Wm^{-1}K^{-1}$, a value for dry clay soil 5% m.c. proposed for Yazd by (Dehghani-sanij & Sayigh, 2016). The ground initial temperature was modelled with a spatial distribution defined by the method provided by Kasuda (Kusuda & Achenbach, 1965) which results in a temperature of about 4°C at the pond base and 19°C at 5m depth.

The pond itself was modelled as a homogeneous medium 100mm thick with the thermal properties of either liquid water, or ice depending on its temperature. The freezing (or melting) phase change was modelled by keeping track of the amount of energy in a theoretical "latent store" Using this procedure, when the pond reaches 0°C and receives further cooling the temperature of the water is fixed to remain at 0°C and energy is subtracted from the latent energy store, which when fully depleted signifies a complete phase transition from water to ice for the whole pond. For intermediate states, the thickness of ice layer is assumed to be equal to the total pond depth multiplied by the % that the latent store is empty.

The pond area was assumed to be 416$m^2$, estimated from drawings of Meybod (Figure 1). It was assumed that each evening in winter, at 9pm the pond is filled with 100mm of water with temperature equal to the external air temperature at that time. The ground temperatures below the surface are calculated from the results of the previous day. After 11 hours of simulation any ice >3mm thickness predicted to have formed is "harvested" and the process repeats again for the next day. The assumed view factor from the pond to the sky was 0.7. The simulation was run for 3 years using a 5 minute time step. The results presented are for the final year of the run.

### *MF Pond Ice Model Results*

Figure 4 illustrates the predicted daily ice yield. The maximum predicted ice yield is 12mm/day. The total predicted yield is $49m^3$/yr, equivalent to a total thickness of 120mm and a latent coolth store of 4.3MWh. Figure 5 shows the predicted average hourly heat transfers for the coldest week of the winter (in January). Radiation heat loss to the sky is found to be the dominant cooling mechanism, but the modelling shows that evaporation is also significant, much more so that convection to the external air. Convection heat gains from the relatively warm ground are also small in comparison to the losses from radiation and evaporation.



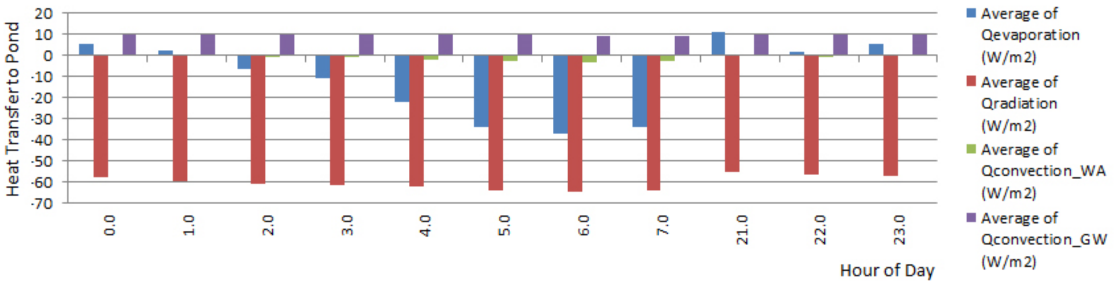




Figure 5. Model results of heat transfers in the Meybod ice pond. The values are the average value at the stated time for all the days of the coldest week.

### *Ashton Ice Formation Model*

The Ashton Ice Model is an empirical model proposed for thin layers of ice on open fresh water bodies (Ashton, 1989). It depends only on the duration of cold air temperatures, expressed as freezing degree days (FDD) and empirical constants. The Yazd TMY data set has 20 FDD, for which the Ashton Ice Model predicts 70mm of ice.

## Ice Storage Modelling

Heat transfers within a typical dome Yakhchal have been modelled using a 3D dynamic thermal simulation with the Virtual Environment software by IES (IES VE, 2015) using the hourly Yazd TMY climate data. The model geometry and pertinent model parameters are illustrated in Figure 6. For the walls and the ground the model implements a layered 1D transient conduction model, allowing temperature penetration depth and time lag effects to be represented.

(Hosseini & Namazian, 2012) report that straw, or thatch insulation was placed around and within the ice packs and also on the outside of the dome. They also state that the layer of straw insulation over the icepack top surface could have been 1 to 2m thick. The model material properties are given in Table 1. The initial run used 0.5m of thatch insulation in all locations.

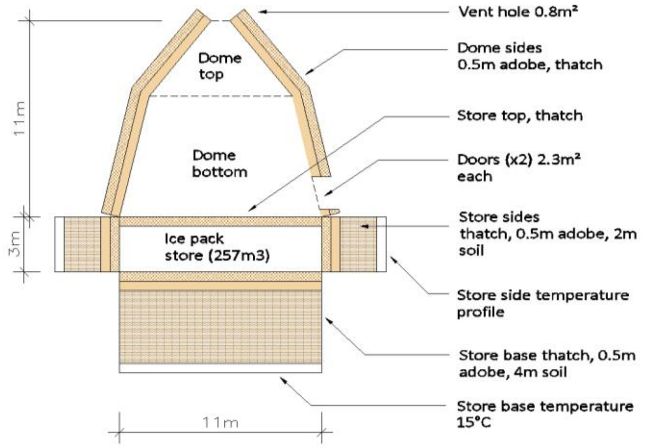



Figure 6. Ice storage model parameters

Table 1: Ice storage model material properties

| Material | Thermal Conductivity (W/mK) | Density (kg/m$^3$) | Specific Heat Capacity (J/kgK) |
|---|---|---|---|
| Adobe | 0.6 | 1700 | 900 |
| Thatch | 0.1 | 250 | 1800 |
| Soil | 0.3 | 1000 | 1900 |

The store side and base temperatures were estimated using the Kasuda equation for ground temperature with an estimated correction for the long term cooling effect of the presence of the ice store. The base temperature was kept fixed at 15°C. The store side temperature profile was set to vary according to the season in the following way J,F,M: 8°C; A,M,J: 16°C; J,A,S: 30°C; O,N,D: 16°C. The model was started with an initial temperature of 10°C. The IES model uses the climate data to simulate the effects of solar radiation, longwave sky radiation and convection to the dome external surfaces.

The ice pack was modelled as a zone with a (variable as needed) cooling load applied to keep the temperature at 0°C. The store volume was assumed to be full of ice. The model calculates the conduction heat gains into the store from the dome and surrounding ground. The amount of ice melted is calculated from the total seasonal heat gains (cooling load) into the ice pack store.

***Ice Storage Modelling Results***

Figure 7 shows the predicted internal dome (bottom) temperature for a scenario called Store_10 which has the doors closed, the top vent unshaded and open for ventilation and the thatch 0.5m thick. The annual total heat gain (cooling load) of the ice store is predicted to be 4.6MWhrs which equates to 52m$^3$ of ice melt or 20% of the total store volume.

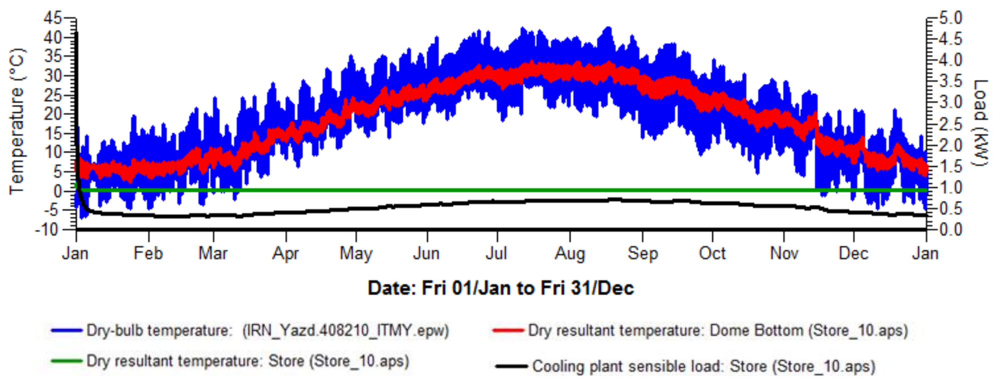



Figure 7: Store_10 scenario ice storage modelling results.

The distribution of annual heat gains into the store for Store_10 is found to be 15% through the floor, 15% through the sides and 60% through the top surface to the dome; which shows that the dome's ability to keep cool could significantly affect how much ice melts. However, it should be noted that this work assumes soil with a very low thermal conductivity, which keeps the heat gains from the ground to a low fraction of the total.

Several other scenarios have been simulated to investigate how the system could perform in both the past and the present. It was found that adding shading to the top vent so that the dome solar gain is zero has negligible effect on the store heat gains. However, employing a ventilation manager (in either human or machine form) to open the doors whenever the external temperature is lower than the internal dome temperature reduces the melt losses by 1%. Removing the thatch on the dome exterior causes melt losses to increase by 1%. Most benefit can be gained by investing in store insulation; if 1m of thatch is used at the base, sides and top of the store the melt losses are reduced to 13%. If 0.5m thick of polyurethane foam (with k=0.02W/mK) is used the melt losses are predicted to be 6%.

**Contemporary Application: An Ultra-Low Energy Office**

A concept ultra-low energy office has been modelled using IES VE with the Yazd TMY climate data. The concept design is one that minimises the cooling load. The model geometry is illustrated in Figure 8. Other key features of the model were: 10m$^2$/person occupancy from 8am to 6pm. High thermal mass floor, walls and ceiling. Windows sized to provide 2% daylight factor with solar control glazing and external shading that automatically deploys to block 80% of direct sun. Lighting and computer heat gains of 4W/m$^2$ and 5W/m$^2$ during occupied hours; an additional heat gain of 2W/m2 all the time and ventilation at 8l/s/p of fresh air when occupied. The design and model also included additional free cooling ventilation providing 20ac/h of external air whenever beneficial. A cooling system is included that attempts to cool to 26deg C but is limited to 8W/m$^2$ (1kW) peak output.

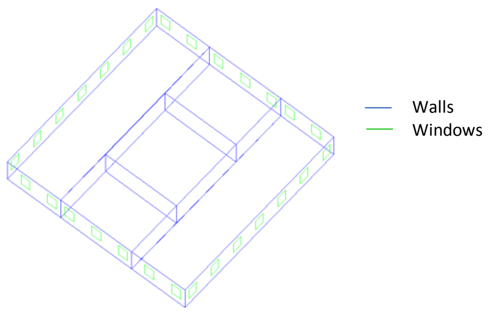



Figure 8: Ultra low energy office model. Single storey with 400m$^2$ floor and roof areas.

***Ultra-Low Energy Office Model Results***

The results of the modelling for the west facing side of the building are illustrated in Figure 9. The peak cooling output is limited and results the internal temperatures shown. The model predicts that a typical hot day has an internal temperature of about 33°C when the external temperature is 40°C. The total annual cooling demand is 3.5MWhrs.

An assesment of thermal comfort was made using the adaptive thermal comfort method descibed by (Mohammad & Shea, 2013) which, for the Yazd climate data defines the following monthly comfort temperatures; May 28°C, Jun 30°C, Jul 31°C, Aug 30°C, Sep 29°C. The results showed that comfort temperarures were exceeded in 20% of occupied hours.

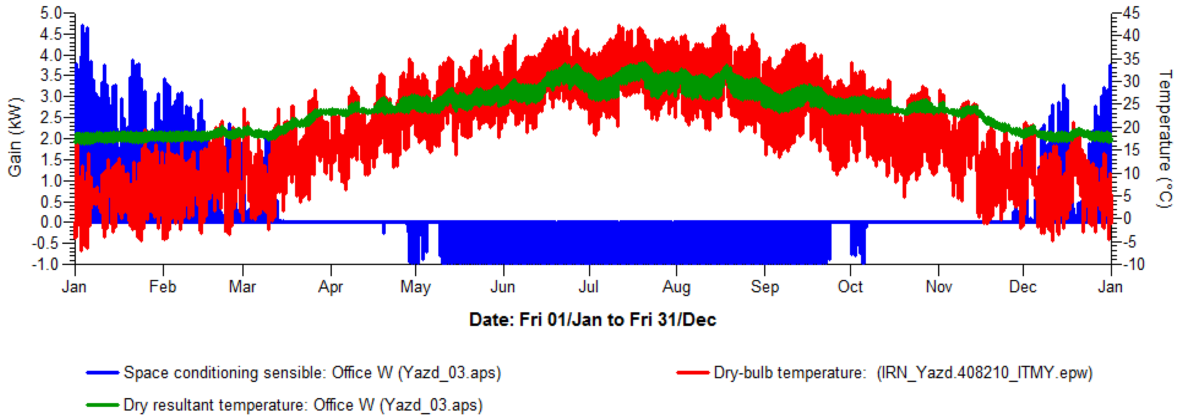



Figure 9: Ultra low energy office model results

## Discussion, Insights and Conclusions

### *Ice Production*

A 1D transient heat transfer MF Pond Ice Model was developed. When used with Yazd TMY climate data the model predicts the amount of ice that could be made in a sun shaded pond over one winter to be 120mm total thickness. This was in general agreement with the Ashton Thin Ice Model which predicts 70mm for the same climate data. A lower yield from the Ashton method is expected since the Ashton empirical constants were measured for lakes subjected to solar radiation. Whereas, due to their operation at night and shading structures, the Yahkchal ice ponds receive little or no solar radiation.

As expected, sky radiation was found to the dominant cooling mechanism but evaporation was also found to be significant. For the coldest week in the data set The MF Model predicts typical night time average pond heat losses of 60W/m$^2$ for sky radiation, 20W/m$^2$ for evaporation, 1W/m$^2$ for convection to air and 8W/m$^2$ heat gain from the ground. The MF Model assumes that evaporation effects are always active (even when ice has formed), in this respect it probably over predicts the ice formation rate. However, including evaporation always is a reasonable approximation if the water is gradually applied in layers on top of an existing ice sheet. This is mode of operation is therefore recommended to maximise yield and there are historical reports in the literature that suggest this was indeed done.

The simulation work also showed that harvesting ice each morning was more beneficial that leaving it out. This was because, even with the shading wall in place the amount of diffuse solar radiation heat received was greater than additional available daytime cooling.

The estimated size of the Meybod ice store is 200m$^3$. The predicted winter ice yield from the 416m$^2$ production pond was 49m$^3$, 25% of the size of the store. There are several possible explanations for the predicted low fill fraction including one or more of the following; the pond may be genuinely undersized compared to the store; the physics model may be deficient; the assumptions for model inputs may have been flawed; the TMY climate data may not provide a good representation of ice making conditions compared to reality (either now or in the past).

### *Ice Storage*

A numerical model was used with the Yazd TMY climate data to simulate the heat transfers within a large dome type Yakhchal similar to the one at Meybod. The model used a 1D approximation of heat transfers from the below ground store into the surrounding soil. The model assumed a $257m^3$ underground store packed full of ice surrounded by a layer of insulation. The modelling results predicted annual melt losses of 20% for 0.5m thatch insulation, 13% for 1m thatch and 6% for 0.5m of modern polyurethane foam insulation.

### *Potential Contemporary Application*

A concept single storey $400m^2$ ultra-low energy office in Yazd was modelled using a dynamic thermal simulation. The model included very high standards of passive design along with a maximum active cooling output of $8W/m^2$ resulting in an annual cooling load of 3.5MWh ($9kWhr/m^2/yr$). The Ice Production analysis predicted an annual ice yield of 120mm/yr. Therefore, siting a pond over the whole $400m^2$ office roof could produce $48m^3$ of ice per year which could be stored in an insulated pit under the building. Allowing for 10% melt losses, the avaialble latent coolth from the ice store would be 3.7MWh, i.e. slighly more than the annual space cooling demand. However, it was found that internal condictions within the office were not always comfortable; comfort temperatures were exceeded in 20% of occupied hours. Convieniently ignoring cost or any other feasibility issues, the work has shown that using passive ice making and seasonal storage alone can, in principal meet a significnt fraction, but not all of the space cooling demand in a contemporary single storey ultra-low energy office. The cooling capacity of the system could be enhanced by also making use of summer roof pond cooling such as the type descibed in (Tang & Etzion, 2005) which, when combined with the seasonal ice harvesting might be possible to meet 100% of the building cooling load.

## References


Ashton, G., 1989. This Ice Growth. *Water Resources Research,* 25(3).

Bahareh Hosseini, A. N., 2012. An overview of Iranian ice repositories, an example of traditional indigenous architecture. *METU Journal of the Faculty of Architecture, v.29, no.2.*

Beazley, E., 1977. Some Vernacular Buildings of the Iranian Plateau. 15(1).

Dehghani-sanij, A. & Sayigh, A. S., 2016. *Cisterns: Sustainable Development, Architecture and Energy (River Publishers Series in Earth and Environmental Sciences).* s.l.:s.n.

Energy_Plus_Weather_Data, 2005. *Weather Data by Location - Yazd 408210 (ITMY).* [Online]
Available at: https://energyplus.net/weather-location/asia_wmo_region_2/IRN//IRN_Yazd.408210_ITMY

Hamza, H., 2007. Passive cooling of water at night in uninsulated open tank in hot arid areas. Volume 48.

Hosseini, ,. B. & Namazian, A., 2012. An Overview of Iranian Ice Repositories, an Example of Traditional Indigenous Architecture. *METU Journal of the Faculty of Architecture, v.29, no.2.*

IES VE, 2015. *IES VE User Guides.* [Online]
Available at: https://www.iesve.com/support/userguides

Jorgensen, H., 2010. *Ice Houses of Iran. 1st ed..* s.l.:University of Copenhagen.

Kusuda, T. & Achenbach, P., 1965. Earth Temperatures and Thermal Diffusivity at Selected Stations in the United States. 71(1).

Mohammad, S. & Shea, A., 2013. Performance Evaluation of Modern Building Thermal Envelope Designs in the Semi-Arid Continental Climate of Tehran. *Buildings,* Volume 3.

Tang, R. & Etzion, Y., 2005. Cooling performance of roof ponds with gunny bags floating on water surface as compared with a movable insulation. Volume 30, p. 1373–1385.

Wills, C., 1891. *The land of the lion and the sun (Modern Persia), being experienced of life in Persia from 1866-81.* London: Ward Lock and Co.

Zare, M. & Davoodmoosavian, S., 2015. A Scientific Study on the Performance of Iranian Ice-Pits. Volume 4(6).