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Freezing at the Iranian Yakhchal / یخچال

Yakhchal is a type of ancient structure and system used to produce, harvest and store ice during the winter for cooling uses later in the year; today I am going to be discussing how this engineering wonder works and showcase the techniques used to construct the Yakhchal.

This article uses a study by The Max Fordham Group to analyze the engineering marvel, numerical modelling methods to simulate the various heat transfers that control the ice making and ice storage processes. This allows us to make estimates of the amount of ice that could be made and the amount of ice that could be retained over the course of the year.

The Yakhchals:

Yakhchals are ancient Persian refrigerators used to store ice and food, dating back to around 400 BCE. The term "yakhchal" means "ice pit" in Persian. These structures were a marvel of engineering and sustainability, using natural cooling techniques in the desert.

Structure:

- Yakhchals are dome-shaped buildings made of mud bricks, often with an underground storage chamber.

- The thick walls, made of a special water-resistant mortar called *sarooj*, provided insulation to keep the interior cool.

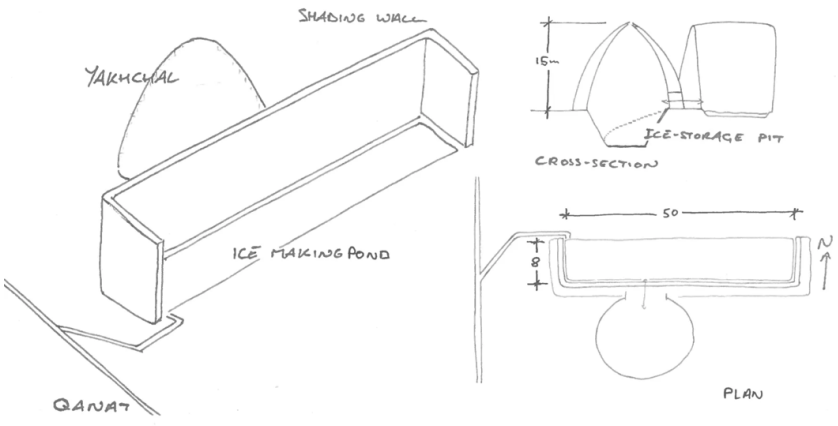
How They Worked:

- During winter, ice from nearby mountains or frozen water channels was collected and stored in the yakhchal.
- The underground chamber and the dome shape helped maintain low temperatures even during hot summers.
- Some yakhchals also had windcatchers (بادگیر) to circulate cool air and improve ventilation.

Uses:

- They were primarily used to store ice, water, and perishable food items.
- Ice was used in summer for cooling drinks or preserving food, showing how people adapted to the harsh desert climate.

Yakhchals are a testament to the ingenuity of ancient Persian engineers, combining environmental knowledge and architectural skills to create sustainable solutions long before modern refrigeration.



The dome-type Yakhchal at Meybod, Yazd Province, Iran

The drawing above 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.

The complex comprises of a shallow ice making pond which is filled each night from a qanat (قنات), a fresh water canal. A shading wall shields the pond from the heat of low-angle winter sun.

Ice is harvested from the pond and transferred into the Yakhchal ice store. These types of Yakhchals are reported to have been constructed from locally sourced adobe containing mud and binding materials such as animal hair and egg white.

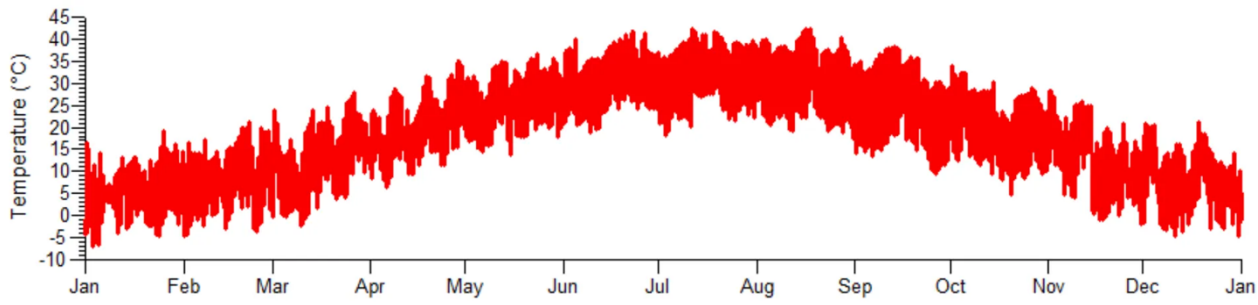
The height of the dome at Meybod is around 15m tall and pit about 5m deep. The dome walls are estimated to be around 2m thick at the base and 0.5m thick at the top where there is a vent hole.

An aspect perhaps not often visualised is that (at least in summer) the domes may not have displayed the smooth, red-brown finish seen in all Yakhchal photographs. Some sources report that they were covered in a thick layer of straw thatch to insulate them from the heat of the sun, in which case they would have resembled giant hairy haystacks.

The Yazd climate:

Yazd experiences a very arid climate, characterized by scorching summers and mild winters. The region receives minimal rainfall, with an average annual precipitation of under 100 mm.

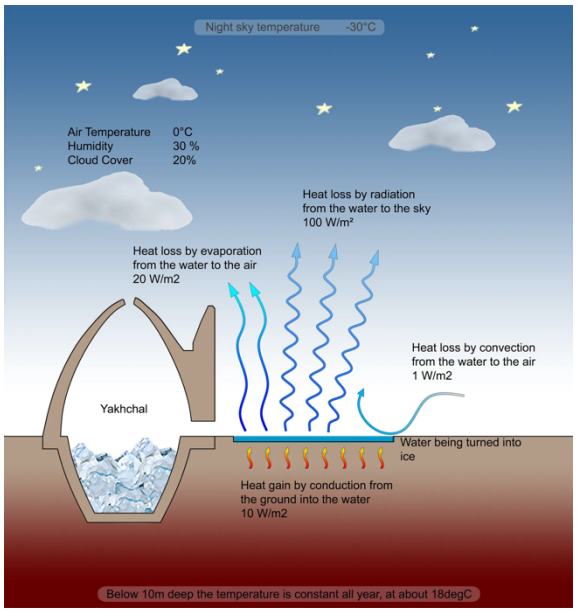
The accompanying graph displays Yazd's typical hourly air temperature over a year. During winter, temperatures can occasionally dip to -5°C, while in summer, they frequently surpass 30°C and may even peak at 40°C.



Ice Production:

The rate at which ice forms in a shallow pond is influenced by several factors, including climate conditions, ground temperature, the initial water temperature, and the methods used to manage the process.
To analyze the ice-making process, we developed a heat transfer physics model. Our unique approach includes the following features:

- The pond is represented as a series of thin layers that can be water, slush, or ice. The model simulates how ice forms on the pond's surface and gradually expands inward.
- The model accounts for changes over time and incorporates hourly climate data specific to Yazd, such as air temperature, humidity, and cloud cover. These factors are used in heat transfer calculations, with the effective sky temperature being particularly crucial.



This method enables us to numerically predict the amount of ice that can be produced during the entire ice-making season.
Over several years of simulation, our results revealed that the primary cooling mechanism was radiative heat loss from the pond to the cold night sky, a process enhanced by Yazd's frigid winter nights. Significant heat loss through evaporation, driven by the region's low winter humidity, also played a key role.
The ice-making pond in Meybod has a surface area of approximately 400 m^2. Simulations indicated that this pond could produce 50 m^3 of ice in one winter season, equivalent to 3 million modern ice cubes. This volume represents about 20% of the storage capacity of the ice pit beneath the dome. However, the predicted ice quantity appears somewhat low. Potential reasons for this discrepancy include:

- The model may have inaccuracies (though this seems unlikely).
- The climate data, which averages conditions from 1960 to 2004, may not reflect colder winters, during which more ice could form.
- Historical climate conditions might have been significantly cooler.
- Additional ice could have been collected from other sources and brought to the storage pit.

These factors highlight the complexities of modeling the historical ice-making process in Yazd.