Introduction

In small cities on periphery of deserts whose historical textures are not yet lost among the new parts of city , one is often confronted with tremendous cone-like structures called Yakh-chal (the ice-house), resembling mountains rising above the level surface of the desert . The existence of ice-house as a response to the need for ice in these cities (where temperature can rise up to 50 degrees Celsius in summer) is a sign of climate conformity of historical cities to the hot and arid climate .these cities have succeeded in using the great temperature fluctuation round the clock and throughout the year as a source of energy. in residential buildings, materials with high heath transmission delay time have been utilized. Nighttime coolness is used during the day and day time heath at night.

Thus, prior to analyzing Yakh-chals, and because of their climatic behavior, “thermal mass” and “earth-sheltered structures” will be shortly introduced. Therefore following article will contain three main topics: Thermal mass, Earth-sheltered structures and Yakh-chals.

Thermal mass

Thermal capacity is the ability of a material to store heat, and is roughly proportional to a material’s mass or its weight. A large quantity of dense material will hold large quantity of heat. Light, fluffy materials and small pieces of material can hold small quantities of heat. Thermal capacity is measured as the amount of heat required to raise the temperature of a unit (by volume or weight) of the material one degree. Water has a higher thermal capacity than any other common material at ordinary air temperatures. Consequently, the heat from the sun retained by a large body of water during the day will only gradually be lost to the air during the cooler night. This is why, once a lake or ocean warms up, it will stay warm even after the air cools off [1].

Thermal mass is the ability of a material to absorb heat energy for extended periods. It has slow change in temperature during warm-up or cool-down periods. It stores and re-radiates heat thus; it acts as a thermal battery.

Thermal mass is effective in improving building comfort in any place that experiences daily temperature swings—both in winter as well as in summer (Fig. 1 and Tab.1).

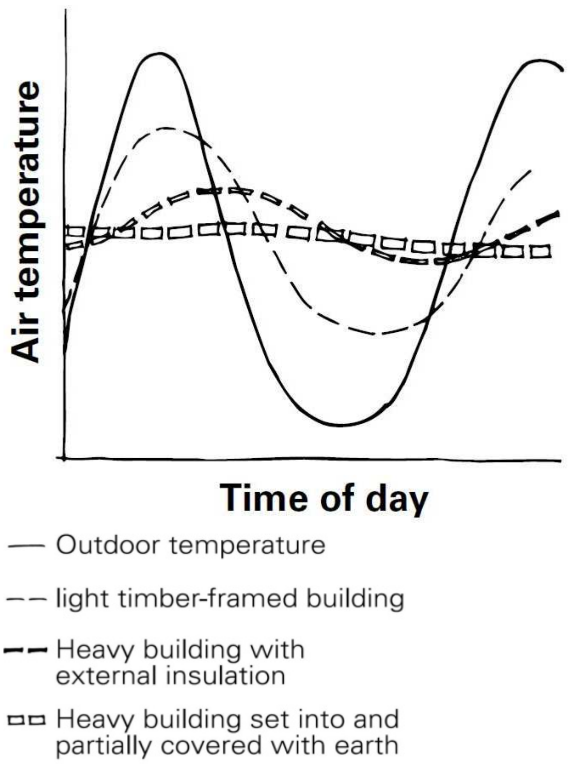
In winter, thermal mass absorbs heat during the day from direct sunlight or from radiant heaters. It will re-radiate this warmth back into the home throughout the night.

During summer, cool night breezes and/or convection currents pass over the thermal mass, drawing out all the stored energy. During the day protect thermal mass from excess summer sun with shading and insulation if required [2] (Fig. 2).

Thermal mass is particularly beneficial where there is a big difference between day and night outdoor temperatures. Heavy mud or stone buildings with high thermal mass work well in hot desert climates with extreme changes in temperature from day to night.

Passive TES [Thermal Energy Storage] systems utilize precooling strategies of the building thermal mass during nighttime to shift and reduce peak cooling loads. Simulation analyses of various precooling strategies have shown that energy cost savings of 10% to 50% and peak demand reductions of 10% to 35% are possible by utilizing a preconditioning control strategy. Experimental studies have also shown comparable levels of cost savings and peak demand reduction. Control optimization geared toward specific outcomes can generally increase cost savings or peak demand reduction [3].

To be effective, thermal mass must be integrated with sound passive design techniques. This means having appropriate areas of glazing facing appropriate directions with appropriate levels of shading, insulation and thermal mass.



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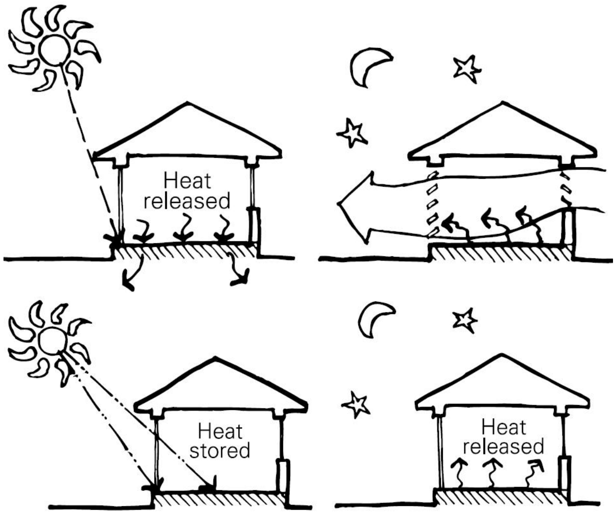
ass [2].

Tab. 1. Thermal mass act during a day

☼	Daytime	Reducing cooling load: absorb heat gains
☾	Night	Reducing heat load: release the heat



rmance during winter

Types of thermal mass

There are two types of thermal mass:

1- Traditional
2- Phase change materials (PCMs)

Traditional thermal mass includes common materials such as brick, concrete, stone, adobe and earth. Meanwhile, PCMs act differently; heat is absorbed or released when the material changes from solid to liquid and vice versa. This type of thermal mass, Store and release large amounts of energy. As can be seen in chart below, PCM’s heat capacity is more than 4 times bigger than water that is estimated as material with highest amount of heat capacity among traditional materials (Fig. 3).

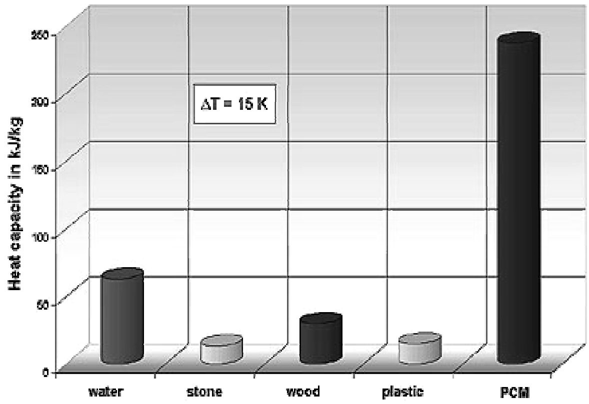
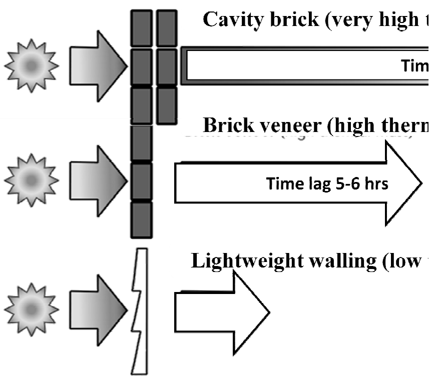


Fig. 3 Heat capacity in traditional materials and PCMs [12].

One development of this technology uses thousands of plastic capsules filled with a wax that absorbs and releases energy by melting and solidifying within the temperature range of human comfort. This increases the effective thermal capacity of the material which contains the capsules and dampens temperature fluctuations, acting like thermal mass. At least one company manufactures building products that integrate phase-change microcapsules into their structure, including plasterboard and aerated concrete (AAC) blocks. Gypsum plasters, paints and floor screeds have the potential to contain phase change materials and many such applications are likely to appear on the market over the next few years as the technology offers the prospect of lightweight buildings that can behave with characteristics associated with 'traditional' thermal mass – for instance, the thermal capacity of a 13mm thick plaster layer with 30 per cent microcapsule content is claimed to be equivalent to that of a six-inch thick brick wall [2].

Yakh-chals are mostly made of adobe or brick, thus; performance of brick is analyzed here for instance (Fig.4-6):

On a hot day, brickwork can slow the passage of heat from the outside for up to eight hours by storing it in its mass. Before the heat reaches the interior, the peak of the day has passed, the outside cooled and the stored heat starts to flow back out (heat flows from hot to cold). In winter, internal mass absorbs, stores and slowly releases any heat generated internally or gained through the day [13].



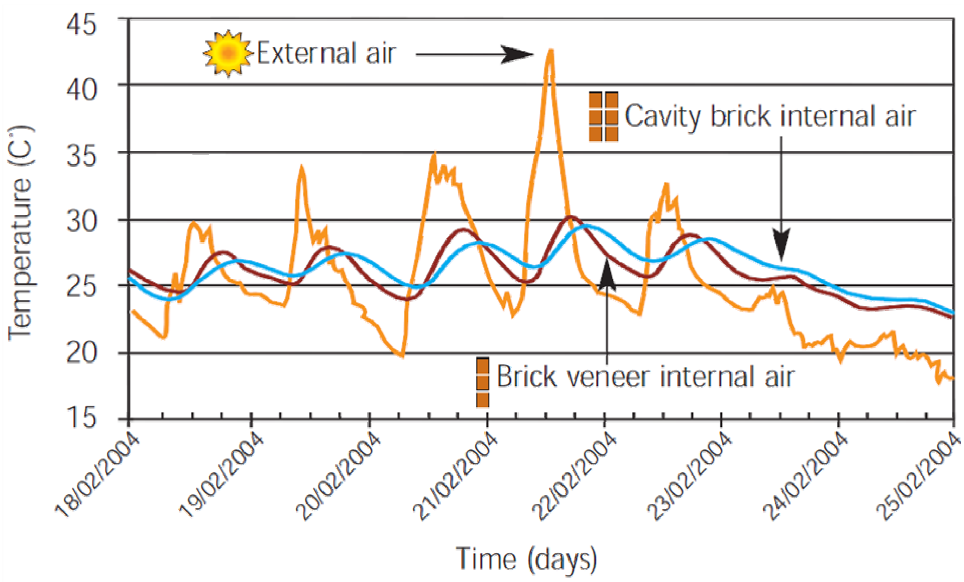
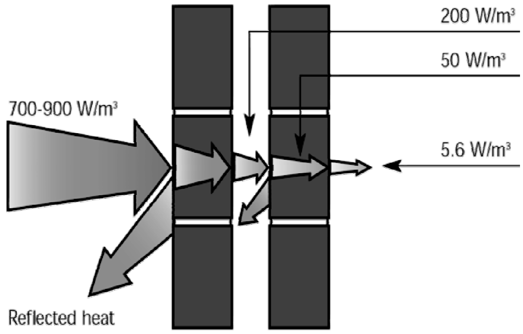


Fig. 4. Thermal behavior of brick walls, compare with lightweight walls [13].



ıore able to moderate ıt walls [13].

Three basic properties are required for a good thermal mass:

1- Density (p),
2- Specific heat (c_m),
3- Conductivity (k).

Water has the highest amount of specific heat among common materials. however, its density is much lower than heavy materials such as stone and concrete. These properties can be compared between a range of materials as can be seen in (tab. [2]).

Insulating materials have low thermal capacity since they are not designed to hold heat; they prevent heat from passing through them by incorporating lots of air spaces between their thin fibers [1].

Material	Density (Kg/m3)	Specific heat (kJ/kg.K)	Volumetric heat capacity Thermal mass (kJ/m3.K)
Water	1000	4.186	4186
Concrete	2240	0.920	2060
AAC	500	1.100	550
Brick	1700	0.920	1360
Stone (Sandstone)	2000	0.900	1800
FC Sheet (compressed)	1700	0.900	1530
Earth Wall (Adobe)	1550	0.837	1300
Rammed Earth	2000	0.837	1673
Compressed Earth Blocks	2080	0.837	1740

High thermal mass materials can be an integral part of the building envelope, or may be incorporated into the furnishings of the space. For maximum benefit, they must be within the insulated part of the building. The building's envelope will store heat if it has a large amount of mass (Fig. 7). This will delay the transmission of heat to the interior, resulting in a thermal lag that can last for several hours or even for days; the greater the mass, the longer the delay. Where thermal mass is used inappropriately, excessively high temperatures or cooling loads may result on sunny days, or insufficient storage may occur overnight. Low thermal mass is a better choice when the outside temperature remains consistently above or below the comfort temperature. Heavy mud or stone buildings with high thermal mass work well in hot desert climates with extreme changes in temperature from day to night.

In a cold climate, a building that is occupied only occasionally (like a ski lodge) should have low thermal capacity and high thermal resistance. This will help the building to warm up quickly and cool quickly after occupancy, with no stored heat wasted on an empty interior.

Fig. 7. High thermal mass works well in hot desert climates [14].

Massive walls

Four basic material configurations are considered for massive walls:

- Exterior thermal insulation, interior mass (Intmass)
- Exterior mass, interior thermal insulation (Extmass)
- Exterior mass, core thermal insulation, interior mass, and (CIC)
- Exterior thermal insulation, core mass, interior thermal insulation (ICI).

The four types of massive walls above approximate most of the currently used multilayer massive wall configurations. For example, the first two wall configurations may represent any masonry block wall insulated with rigid foam sheathing. The last wall configuration may represent Insulated Concrete Forms (ICF) walls. Therefore, results presented in this work can be used for approximate energy calculations of most massive wall systems [4].

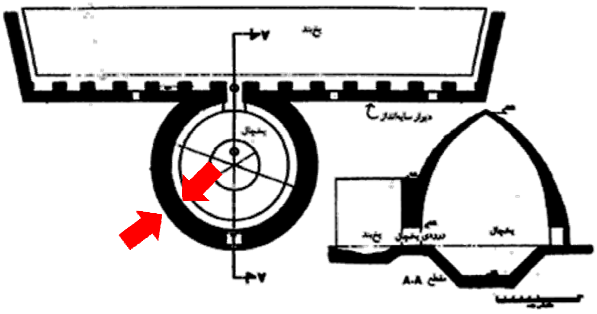


Fig 8. Plan and Section of a Yakh-Chal, Meibod, Iran – Ground Floor plan: massive wall [11].

Earth-Sheltered Structure

The high thermal capacity of soil ensures that basement walls and walls banked with earth stay fairly constant in temperature, usually around 13°C to 15°C (mid-fifties in degrees Fahrenheit) year-round. Earth-bound walls are not exposed to extreme air temperatures in cold weather [1].

The large thermal inertia of the soil cover causes the temperature in the surrounding soil to be higher/lower than the outdoor air temperature during winter/summer. This way, the temperature differences between the interior and exterior are reduced, which means that the heat transmission is lower compared to conventional above-ground houses. The application of soil cover thus potentially cuts the required heating and cooling loads [3].

For a better understanding the performance of earth-sheltered structures, here, we show a resent research from Maja and Henryk [5]. The authors have undertaken the analysis of the influence of soil cover thickness, thermal insulation thickness, glazing area of exposed elevations and type of soil on heating and cooling loads of earth-sheltered buildings with one or two elevations exposed. The results were then compared to the respective above ground buildings as shown in Fig.8.

Heat losses/gains

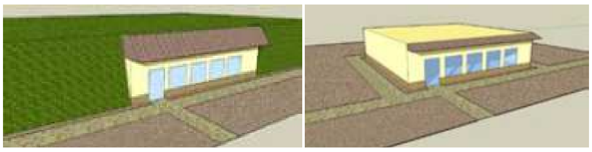


Fig. 9. The analyzed schemes of earth-sheltered and above-ground buildings [5].

Conditions and hypothesis of this research is as shown below:

- Simulations were focused on the influence of soil cover and the thermal insulation of building envelope thickness
- Earth-sheltered building, with one (southern) elevation exposed
- Simulations were done for "Poznan, Poland" climate conditions.
- Floor area: 12x12 m (144 m^2).
- Glazed with 60 % of wall area.
- Both buildings have a concrete construction
- Climate conditions (Tab: 3).

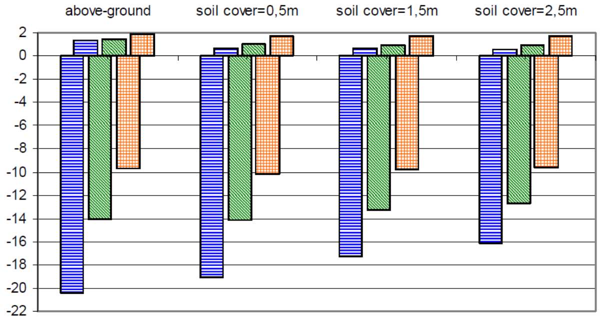
Tab. 3. Climate conditions of the example research [5].

Latitude (N):	52º25'
Longitude (E):	16º49'
Maximum air temperature:	+ 35,6°C
Annual air temperature:	+ 9,8°C
Minimum air temperature:	- 16,0°C
Annual direct sun radiation:	1 865 [Wh/m^2]
Annual diffusive sun radiation:	1 679 [Wh/m^2]
Annual total sun radiation:	2 692 [Wh/m^2]
Annual air humidity:	78 %
Annual wind speed:	3,3 [m/s]
Annual clouds cover:	0,61 [-]

Simulation results

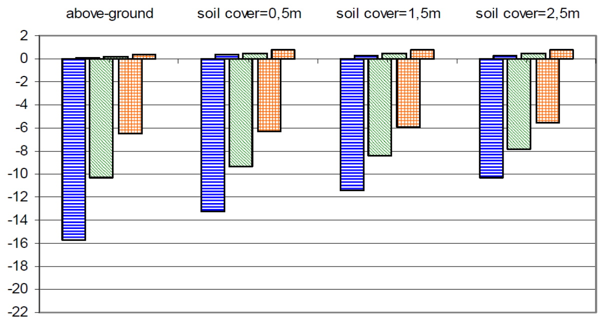
Figure 10 shows heat losses/gains from analyzed earth-sheltered and above-ground buildings for annual values and separately for heating and cooling seasons. Because of linear dependence heat losses to the ground from buildings, they are presented for 0.5 m, 1.5 m and 2.5 m of soil cover thickness. Results are presented for 5 cm, 10 cm and 20 cm of thermal insulation. Analyzing annual values of heat losses/gains of earth-sheltered and above-ground buildings it may be noticed that the differences between them are not significant. A clear difference is seen when analyzing values separately for heating and cooling season (Fig. 10 and Tab. 4). It is caused by the fact that heat losses from earth-sheltered buildings are smaller than from aboveground ones but only during winter (heating season) [5].

During heating season, heat losses from earth-sheltered buildings are about 14%, 8% and 5% smaller for: 5cm, 10cm and 20cm of thermal insulation thicknesses respectively. Increasing soil cover thickness over 0,5m decreases heat losses about 20-25%, 10-15% and 5% for 5cm, 10cm and 20cm of thermal insulation comparing to buildings with 0.5m of thermal insulation. In above-ground houses heat gains are 3% of heat losses, while, in earth-sheltered houses heat gains are up to about 15% of heat losses. Heat gains during heating season are about 40% higher in earth-sheltered houses than in aboveground ones. In above-ground buildings the thickness of thermal insulation does not have a significant influence on heat gains. However, in the earth-sheltered houses heat gains are greater with increasing thermal insulation thickness. Each 5 cm of thermal insulation increases heat gains about 40%.



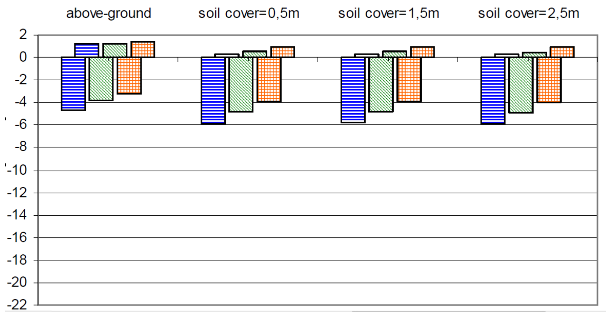
a)

Annual Values



b)

Heating Season



c) Cooling Season

- thermal insulation 5 cm
- thermal insulation 10 cm
- thermal insulation 20 cm

Fig. 10. Heat losses/gains from analyzed earth-sheltered and above-ground buildings [5].

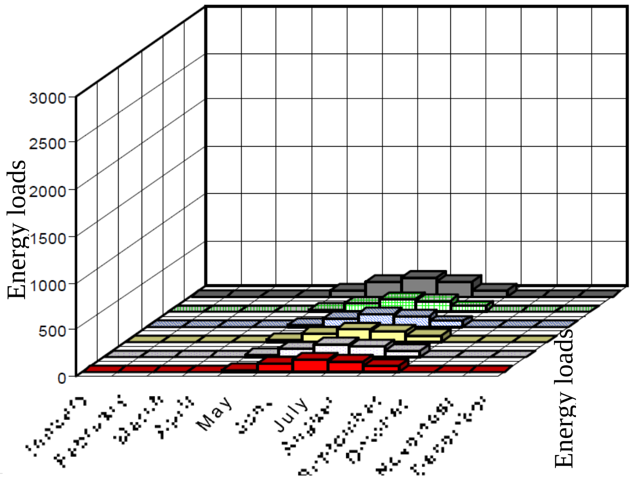
During cooling season, heat losses from earth-sheltered buildings are about 20-35% greater than from above-ground buildings, while, heat gains are nearly 80% lower. In the summertime each 5cm of thermal insulation lowers the heat losses by about 20%. In earth-sheltered houses, If heat losses are 100 % then heat gains are only 5 %, Which is why earth sheltered buildings need less cooling energy. As it will be explained, Yakh-chals use this property to prevent ices from melting.

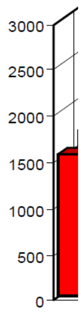
When analyzing the monthly values (Fig. 11) it can be noticed that earth-sheltered buildings require longer heating periods than conventional above-ground ones, while total heating loads are still smaller. This is due to the lower temperature of the soil surrounding earth-sheltered houses. The cooling period is nearly the same [5].

Tab. 4. Earth-sheltered house performance in Cooling and Heating Seasons.

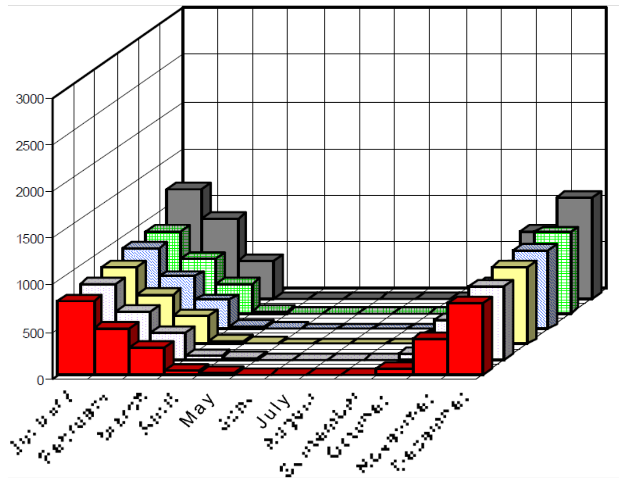
Summer (Cooling Season)	Winter (Heating Season)
The temperature of soil is higher that of external air Heat losses from earth sheltered buildings are smaller than from aboveground ones Causes lower heating loads for earth-sheltered buildings.	The temperature of soil is lower that of external air which naturally cools down a building Heat losses from earth-sheltered buildings are higher Earth-sheltered buildings require less cooling energy than above-ground ones.

a-1) 5 cm of thermal insulation heating energy:

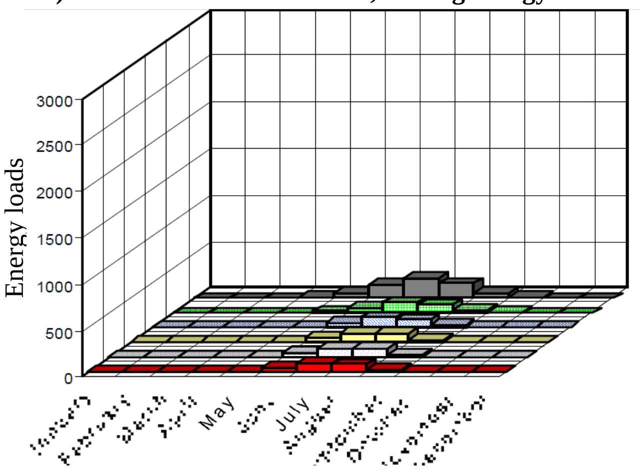




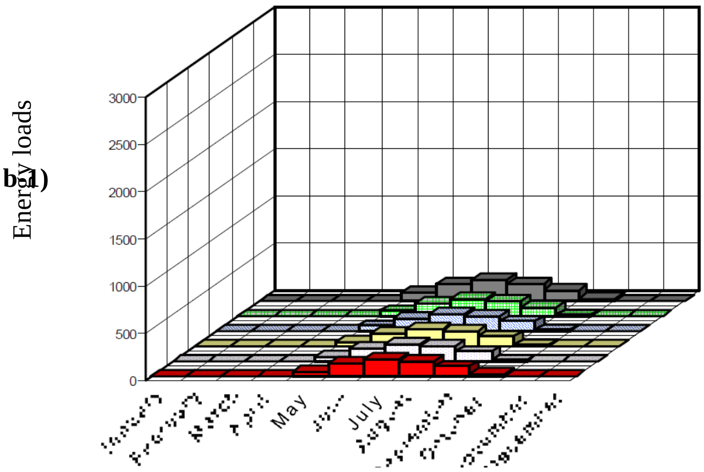
c-1) 20 cm of thermal insulation, heating energy:



a-2) 5 cm of thermal insulation, cooling energy:



c-2) 20 cm of thermal insulation, cooling energy:



b-1) 10 cm of thermal insulation, heating energy:

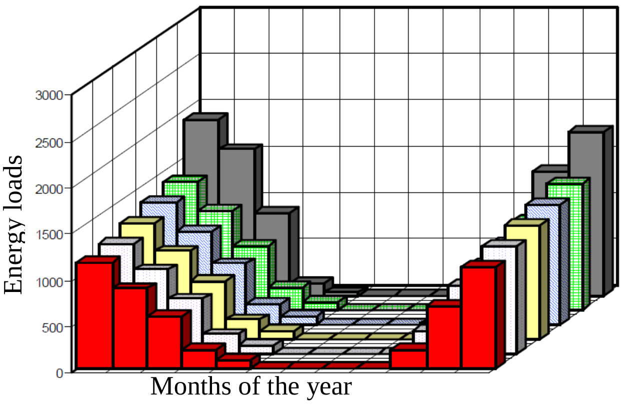
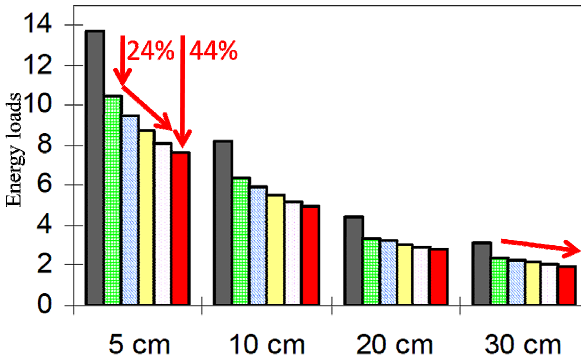


Fig. 11. Monthly values of heating and cooling loads of earth-sheltered and above-ground buildings, with 5, 10 and 20 cm of thermal insulation [5].

b-2) 10 cm of thermal insulation, cooling energy:

It can be easily noticed that the heating and cooling consumption of analyzed earth-sheltered buildings is definitively smaller that of above-ground ones. The difference between them gets smaller with the increase of the thermal insulation thickness (Fig. 11).
Because the interpretation of the results presented in monthly values would be very complicated, annual values are discussed;

a) Heating energy:



b) Cooling energy:

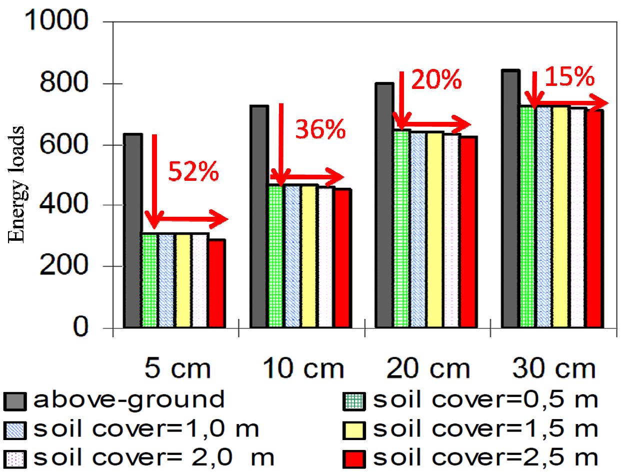


Fig. 12. Annual heating and cooling energy loads of earth-sheltered and above-ground buildings, with 5, 10 and 20 cm of thermal insulation.

The earth-sheltered buildings with exposed southern elevations, which are covered with a soil cover of 0.5 m have heating energy consumption reduced by about 25 % compared to the respective thicknesses of above-ground buildings. Each next 0.5 m soil cover thickness reduces heating loads about:
- 8 % for 5 cm of thermal insulation,
- 7 % for 10 cm of thermal insulation,
- 5 % for 20 cm of thermal insulation,
- 4 % for 30 cm of thermal insulation.

The earth-sheltered buildings with southern elevation exposed, which are covered with a soil cover of 0.5 m have cooling energy consumption reduced by about:
- 52 % for 5 cm of thermal insulation,
- 36 % for 10 cm of thermal insulation,
- 20 % for 20 cm of thermal insulation,
- 15 % for 30 cm of thermal insulation.

During heating season (winter), the thicker soil cover and insulation are both above-ground and earth-sheltered buildings naturally consuming less heating energy. With increasing thermal insulation thickness the influence of soil gets smaller, which causes insignificant differences between above-ground and earth-sheltered buildings for large insulation thickness. Meanwhile, during cooling season (summer), for cooling loads, the soil cover thickness does not have a significant influence. Both kinds of buildings consume more cooling energy with increasing thermal insulation thickness. Thus the thinner the thermal insulation is the greater the cooling energy savings are compared to the above-ground ones. This is due to the fact that thermal insulation acts like a coat, and during wintertime protects a building from colder outside soil temperatures but during summertime does not allow the soil to naturally cool a building down.

Yakh-chal Definition

Ice houses originally invented in Persia were buildings used to store ice throughout the year, prior to the invention of the refrigerator. The most common designs involved underground chambers, usually man-made, which were built close to natural sources of winter ice such as freshwater lakes.
During the winter, ice and snow would be taken into the ice house and packed with insulation, often straw or sawdust. It would remain frozen for many months, often until the following winter, and could be used as a source of ice during summer months. The main application of the ice was the storage of perishable foods, but it could also be used simply to cool drinks, or allow ice-cream and sorbet desserts to be prepared.

Yakh-chal History

An inscription from 1700 BC in northwest Iran records the construction of an icehouse, "which never before had any king built." In China, archaeologists have found remains of ice pits from the seventh century BC, and references suggest they were in use before 1100 BC. Alexander the Great around 300 BC stored snow in pits for that purpose. In Rome in the third century AD, snow was imported from the mountains, stored in straw-covered pits, and sold from snow shops. The ice formed in the bottom of the pits sold at a higher price than the snow on top.

Fig. 14. a) An ancient ice house, called a Yakh-chal, built in Kerman, Iran during the middle ages, for storing ice during summers. b) Boboli Gardens, Florence: domed icehouse (ghiacciaia) half-sunk into a shaded slope.

Yakh-chal functions

1- Producing and Storing Ice: The main purpose of Yakh-chal was keeping ice from winter to be used in summer . In cold season at night which the temperature degree was descended they produced ice and stored it, in hot season when they needed ice they extracted ice from thesaurus for ice-cream and fruit juices.
2- As a Fruits Fresh-keeper: Some Yakh-chal-owners poured pomegranate s seeds into ice and in summer they had fresh pomegranate.
3- As an Urban Element: Yakh-chals are huge buildings , so they play an iconic role for the cities, a role which they have still preserved.

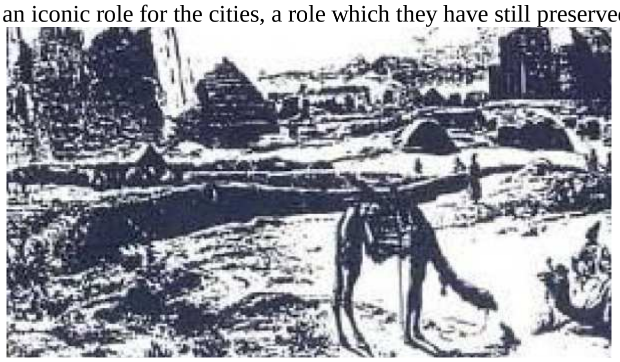
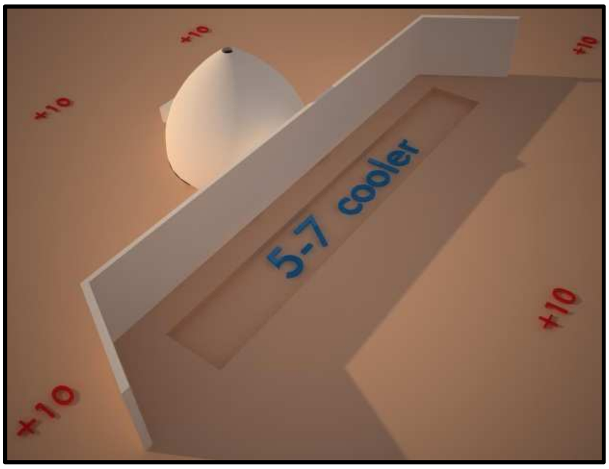


Fig. 15. Ice-house and Caravan-sera in Safavie period, designed by Jules Lawrence

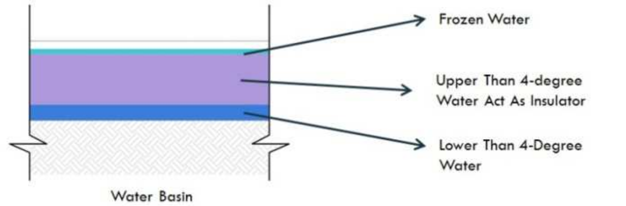
Ice Principle Producing

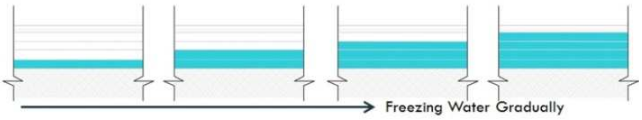
The principle governing the function of ice-houses is to make use of below-zero winter temperatures by constructing tall wall casting shadow on ground and thus preparing freezing condition. at night especially when the sky is clear, the ground temperature drops quickly due to radiation. In points where the earth is cooler due to having been in shadow, the temperature drops more quickly and reaches zero point.



Ice Principle Producing

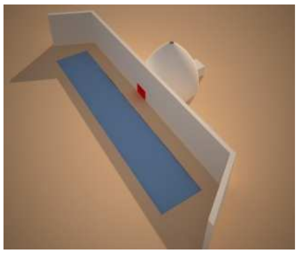
In order to produce ice, shallow basins were constructed. Since water density is highest at 4 degree Celsius and drops above or below that point, so only a thin layer on the surface of the basin freezes and a comparatively warmer layer of water acts as a thermal barrier between that layer and much of 4-degree water sinking to solve this they used shovels to pour water on the thin frozen water make it thicker, so the act was continued until dawn.



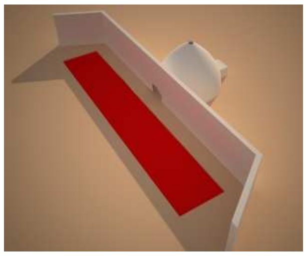


Ice-house components

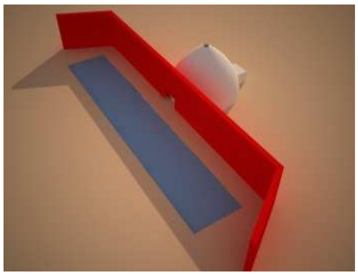
1-Water basin: ice was produced here the needed water was determined from brooks near water sources like qanat , pond or river 2- Ice transfer closure :They moved ice from basin through this windowto store it 3-tall wall:The height of this wall was at last 12 meter , usually it was stretched from east to west preventing south sun light and two shorter wall was beside main wall these two wall had 2 role first to thwart west and east sun light and the a second as structural role because the height of main wall was too tall so there was danger of collapse. 4-Yakh-chal Dome: To prevent hot air penetrate, and push warm air out 5-Yakh-chal Store: for ice storage, a large container with 6 meters of depth was required. As a result of earth’s seasonal heath delay effect the depth would help contribute to keeping temperature low. (the earth doesn’t play the role of a thermal barrier only) the standard dimensions of ice house (8-14 width and 6 meters of depth) are among its inseparable idiosyncrasies. 6-Yakh-chal stair:There are two kind of Yakh-chal stair one straight an the other spiral around the store. 7-Yakh-chal sewage :There is a small hole at the bottom of the store which its work is to vacate the melted ice.



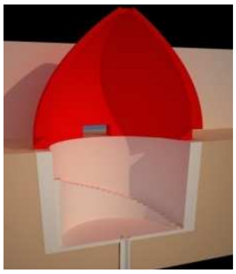
a) Yakh-chal Basin



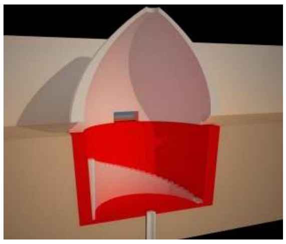
b) Ice Transfer Closure



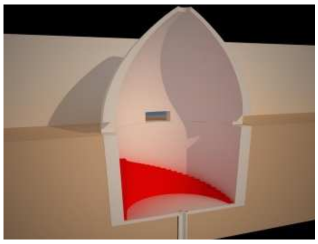
c) Tall Wall



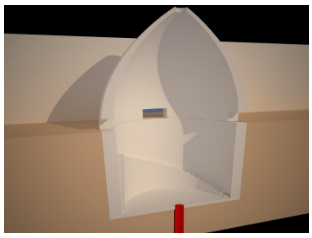
d) Yakh-chal Dome



e) Yakh-chal Store



f) Yakh-chal Stair



e) Yakh-chal Sewage

Ice-houseTemperature:

To prevent the solar heath from entering the ice-house a substantial dome is required. On top of the dome a large hole would let the warm air out. Allow the cool air to penetrate the storage area from below. Such shape is the ideal from for an ice-house.

Temperature during the Day

1) The high walls throw a shadow on the pond. So the earth of the bottom of the pond does not absorb much heat.2) Cold and fresh air goes down. So warm air goes up and exit from a hole on the top of the dome. 3) “Large thickness of container's dome”, “using masonry (with low coefficient of heat transfer) “, and” its external thatched coverage “have the role of thermal insulation to prevent thermal conductivity.4) As a result of “Earth’s Seasonal Heat Delay Effect”, the container keeps it's winter's condition during hot seasons.

Temperature during the Night

1- Water in the pond loses heat.2- Cold air goes down the ice-house and covers the upper layer of the stored ice.3-A staircase connect the door of the ice-house to the lower level of it, to store the ice pieces in a deeper level of the earth.

Yakh-chal Types

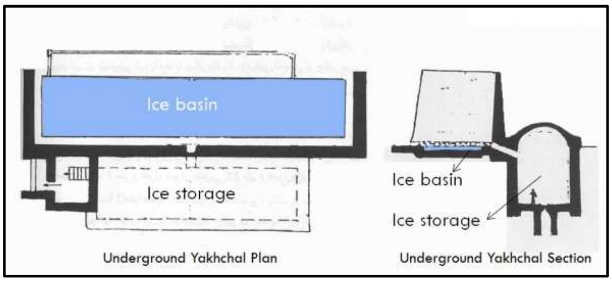
There are 3 common kinds of Yakh-chals in Iran

1-Domical Yakh-chal:These kind of Yakh-chal have domes on storage part, they are more usual in periphery of central Kavir and districts on west north of Iran. 2-Underground Yakh-chal :Another type of Yakh-chal was common in central-north districts of Iran like Tehran, Zanjan, Saveh and … its function was like domical Yakh-chals but its body-shape is different the main part of it was underground.3-

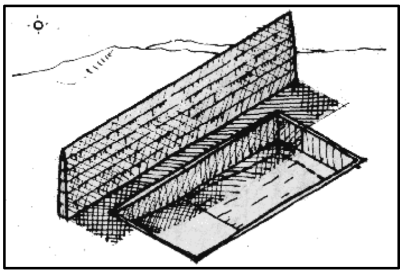
Vaultless Yakh-chal: The third type of Yakh-chal which is without vault was current in Isfahan and like other Yakh-chals was used since 40-50 years ago this Yakh-chal has tall-wall with 4-5 meters height and 12 meters length . In north side of wall there was a pool with 5-6 meters deep and 12 meters length and width.

Domical Yakh-chal:

Underground Yakh-chal:



Vault-less Yakh-chal:



CONCLUSION

The great Iranian tradition is as yet little known in the West and there is much to be learnt both from it and the building techniques which are integral with it. It is the fate of vernacular buildings throughout the world to be neglected until they are nearly extinct. The Folk Museum and the Museum of Buildings are relatively new ideas in Europe, where they are thought of primarily in terms of conservation and education in history and the arts. In Iran their value could be even greater since these functions could be combined with those of an institute of intermediate technology. Not only is the building tradition itself still alive, but there is much to be gained from a knowledge of a highly developed technology which makes such ingenious use of natural resources without the consumption of additional power. The Persian ice-house with its great shade wall could hardly be described as small, but the technology it represents is certainly beautiful in its simplicity. However, unless positive action is taken, most Iranian cultural heritage buildings will have crumbled.

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