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Monitoring the Thermal Performance of an Insulated Earth-sheltered Structure: A Hot-arid Zone Case Study

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An earth-sheltered structure built in the arid Negev Highlands of southern Israel was monitored during several seasonal periods in order to analyse its thermal behaviour and to determine the appropriateness of this type of building for the Negev and climatically similar regions. Temperatures were measured at various points within the building, which consists of two connected concrete shell domes totalling 58m² in floor area. A comparison of thermal conditions was made between various operating patterns, which included the introduction of shading and night ventilation for cooling and direct solar gain for heating. Mechanical heating was used in winter for the evaluation of energy input required to maintain comfort conditions. The paper analyses various thermal effects of the earth cover and of the particular envelope design, based on temperature measurements taken both in the interior space and within the soil, and evaluates the particular design approach taken in terms of its appropriateness for the given climatic conditions.

Background

Earth-integrated structures have been commonly observed to provide favourable thermal comfort conditions with an economy of energy input, particularly in regions characterized climatically by extreme stresses of heat or cold [1]. The potential benefits attributed to earth-sheltering stem from a number of mechanisms at work in this type of construction:

(1) In comparison to a conventional structure, whose envelope is exposed to the wide daily temperature fluctuations of the ambient air, an earth-sheltered envelope is surrounded by a thermal environment whose temperature is relatively stable, becoming more and more so as the depth of the earth cover increases. This may be attributed to both the thermal resistance and heat storage capacity of the earth layer, which together may be expressed as its Thermal Time Constant (TTC), in hours: [2]

$$TTC = 1/2\, RC \qquad (1)$$

where R is the total thermal resistance [m$^{2\circ}$C/watt] and C is the heat capacity [watt*hrs/m$^{2\circ}$C] for a layer of given thickness.

While the relative values of R and C are related to specific soil characteristics such as density and moisture content, both the overall resistance and total heat storage capacity of a given earth layer increase with thickness, resulting in a higher time constant. The high TTC resulting from a sufficiently thick earth layer has the inter-related effects of increasing the time lag and reducing the amplitude of thermal variations at the surface of the building envelope in relation to those at the exterior air interface.

In the study of boundary layer climates, this familiar phenomenon is known as heat flux convergence: since the air-ground interface is the site of the greatest energy absorption by day and depletion by night, it is also where the greatest thermal response is found, with both temperature gradient and heat flux diminishing as the distance from the interface grows. Thus with increasing depth, the amplitude of the temperature wave is dampened and the time required for the wave to penetrate is prolonged. Both the decrement and phase change in the temperature wave may be calculated with reference to the soil's diffusivity (α), a property similar to TTC defined as the ratio between its thermal conductivity and volumetric heat capacity, in units of m²/hr. The wave amplitude at any depth (ΔT_α) is given by: [3]

$$\Delta T_d = \Delta T_o\, e^{-d\,(\pi a P)^{1/2}} \qquad (2)$$

where ΔT_o is the surface temperature wave amplitude [°C], *e* is the base of Napierian logarithms, and *P* is the wave period.

Thus it can be seen that the temperature range for a given wave period decreases exponentially with depth: over the *daily* cycle, temperature fluctuation is virtually eliminated in most soils below a depth of about 75cm. Beyond this point, temperature change follows *seasonal* variations on a yearly cycle, whose wave amplitude is gradually reduced to zero at a depth of 10-15m[4]

The time lag (t) in hours for propagation of the wave crest through a soil layer of depth (d) is given by:[3]

$$t = \frac{d}{2}\left(\frac{P}{\pi a}\right)^{1/2}$$

Within the depth affected by daily temperature fluctuations, the direction of this propagation will in general be downward during the daytime and upward at night, while at lower depths the shift in time delay for propagation of the daily temperature wave through a 60cm layer of dry loess soil (with a diffusivity α of 7.20×10^{-4}m²/hr) may be calculated at 31 hours, while at a depth of 1m the annual temperature wave will be out of phase with the ambient by approximately 41 days. The result of such a time lag is to offset the maximum thermal loads on the structure in summer and winter, displacing them into slightly milder temperature periods [5].

(2) Typically, underground structures make use of this stable environment by thermally "coupling" the interior space with the surrounding mass of the earth cover [6]. In this way, a large addition of heat storage capacity is available not only for internal absorption and delayed reradiation of solar energy, [7] but for temperature stabilization in the event of negative thermal stresses caused by air infiltration or a sudden loss of heating or cooling supply [8].

Such a coupling naturally requires a highly conductive building envelope which will allow an efficient transfer of heat between the space and the mass of the earth cover, since the effect of thermal mass in producing a time-lag and decrement in a building's daily temperature swing [9] is dependent not only on the envelope's overall transmittance and heat capacity, but on the proximity of the mass to the interior space, and hence on the order in which layers of different materials are arranged [10]. For this reason, earth-integrated envelopes are often designed without the addition of thermal insulation between the structure and the earth.

It is in this latter respect which the building under consideration differs from "conventional" underground structures: while its envelope is surrounded by a considerable thickness of ground cover, it is in fact insulated from the surrounding earth and therefore not efficiently coupled with it. An important aim of this study is to investigate the effects of such a thermal barrier on the performance of an underground structure in a hot-arid climate.

Project Description

Building Design

The monitored structure was erected several years ago on the campus of the Institute for Desert Research at Sede-Boqer as part of another experiment, and was slightly modified for the

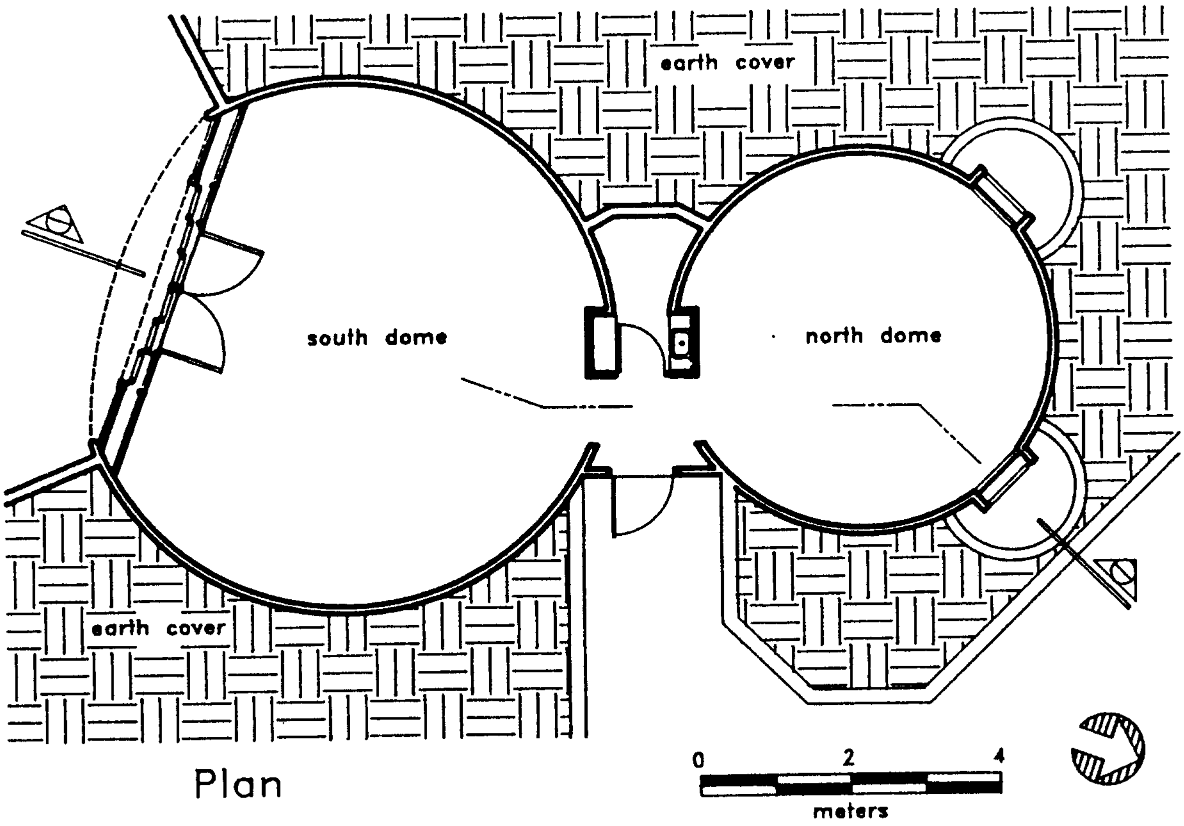

Figure 1. Ground plan of the earth-sheltered structure.

purposes of the present project. It consists of two distinct rooms, separated by a small transition space (Figs.1&2). Each of the two rooms is formed by a thin-shell concrete dome, cast on a pneumatic form. The larger of the two domes, with a floor area of 38m², is entirely covered with earth aside from its southern wall, which contains a 5.5m² glazed opening fitted with operable insulated louvre shutters. The smaller dome to the north, with an area of 20m², is also entirely earth-sheltered except for two north-facing windows of approximately 0.65m² each, also with operable louvre shutters.

under 4°C, and strong winds of variable direction. Rainfall is sporadic, with an annual average of less than 100mm and a wide variance from year to year [11,12].

The yearly pattern of ground temperature with relation to the ambient is discussed in Section 6 (see Fig. 7). In general, temperatures at a depth of one meter are higher than the mean daily ambient air temperature throughout the year, with the difference ranging from 6-7°C in the winter months to less than 1°C in the spring and summer.

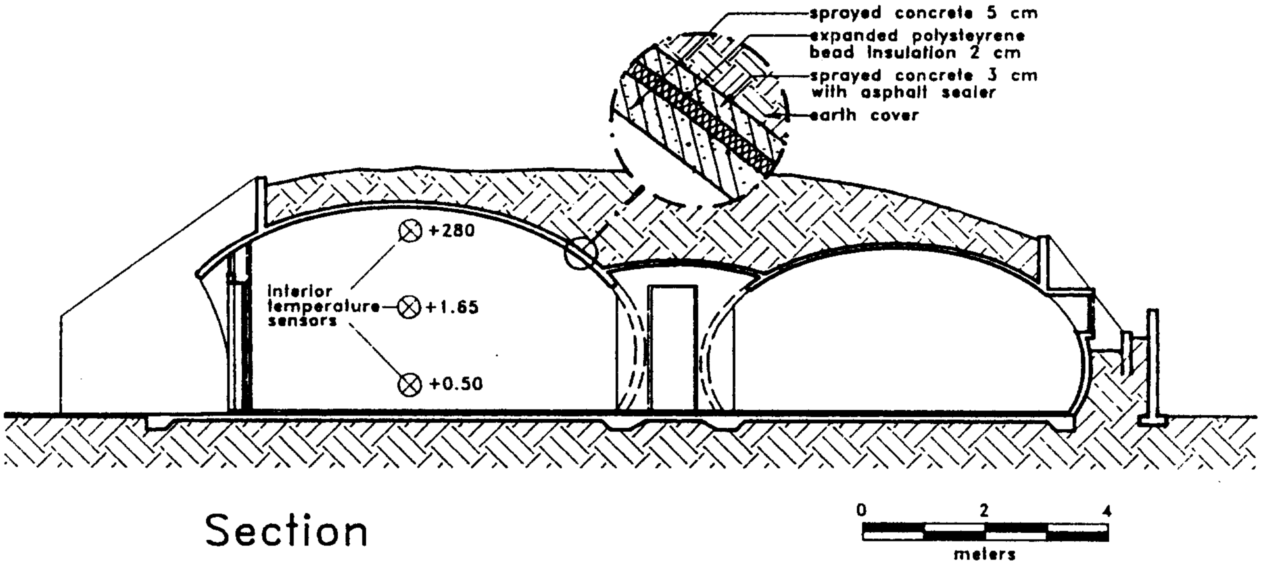

Figure 2. Section view, showing building shell cross-section and location of sensors.

In section, the domed shell is composed of a 5cm interior layer of sprayed concrete, over which is applied a continuous 2cm layer of expanded polystyrene bead insulation and an exterior coating of 3cm sprayed concrete with an asphalt sealer (Fig.2). Local loess soil covering the structure varies in thickness from approximately 40cm directly above each dome to between 2.5 and 3m at the periphery. The building's floor consists of a 10cm thick slab on grade, topped by ceramic tiling on a 10cm bed of sand and mortar.

Unlike the spherical shells which were insulated from the surrounding earth mass, the floor surface, comprising approximately 35% of the total envelope area, had no thermal insulation. Thus while a portion of the envelope is in fact characterized by contact with the earth, the majority (about 60%) is thermally isolated from it.

Local Conditions

The climate at Sede-Boqer in the Negev highlands is characterized by wide temperature fluctuations over the course of both its daily and annual cycles. Average maximum daytime temperatures in July-August of 32°C are accompanied by relative humidity as low as 25%, and by night time minima of 18°C. The summer months are virtually free of precipitation, with consistently clear skies and daily global insolation of nearly 8kWh/m². Prevailing winds are consistently north-northwesterly, and the area is frequently exposed to the effects of airborne sand and dust. In January, maximum temperatures of 15°C and daily insolation averaging approximately 3kWh/m² contrast with nightly minimum temperatures of

Monitoring Methods

Monitoring was conducted during the summer and winter seasons, with comparative measurements taken in the transition (spring) season as well. The building's performance in each season was monitored under a number of patterns of operation, which included the introduction of nocturnal ventilation cooling in summer and of direct solar gain in winter. Each mode of operation was monitored for a period of 5-7 days, with a minimum interlude of 3-5 days between monitoring in each mode in order for the building to "acclimate" to present conditions and overcome the effects of the previous pattern. In a follow-up experiment designed to aid in analysis of the observed thermal behaviour, temperatures were monitored at a series of depths within the earth cover during the winter season. (Unfortunately, it was not possible to insert temperature sensors beneath the concrete floor as well, since the experiments were conducted in an existing building.)

Acquisition of climatic data was carried out with an automatic monitoring system, using a Z.L. Electronic Industries Data Trapper 1806 for data storage. For measurement of interior air temperatures, PT-100 sensors with aluminium foil radiation shields were placed in the southern dome at heights of 50cm from the floor, 50cm from the ceiling's apex and midway between, with interior temperatures reported reflecting the average of these three measurements. Ambient dry bulb temperature was measured at a height of two meters above the ground, using a PT-100 sensor inside a Lambrecht 814 protective screen, and the incidence of global insolation on a south-facing surface was measured with a Kipp & Zonnen CM-5 solarimeter. In winter, interior temperature was maintained by thermostat-controlled 1.5 kilowatt electric space heaters, whose daily power consumption was monitored with standard household metres.

Thermal Performance

Summer Performance

Conditions during the summer season were of special interest in evaluation of the structure's performance in a hot-arid zone: while daytime ambient conditions during this season are typically overheated, the average daily temperature typically falls within the comfort zone.

Summer monitoring, conducted in August, 1990, included two modes, in which the effects of nocturnal ventilation were compared with the thermal performance of the building when all openings were closed and shaded.

Closed mode

In the initial mode, with all windows and insulated shutters continuously closed, the building's thermal behaviour showed the stability expected in an underground structure: interior temperatures in both north and south domes fluctuated by less than 1°C over the daily cycle, while at the same time the exterior range averaged nearly 14°C (Fig.3a). Thus the combined effect of earth sheltering and insulating measures used in this mode was to nearly neutralize the effect of external fluctuations. However, interior air was stabilized at a temperature of 27-28°C, substantially higher than the ambient average of 25°C. These elevated room temperatures correlate closely with soil temperatures measured at the average depth of the earth cover during this season, (as described in Section 5) suggesting that the inner earth layer plays a dominant role in dictating the building's thermal performance in this mode.

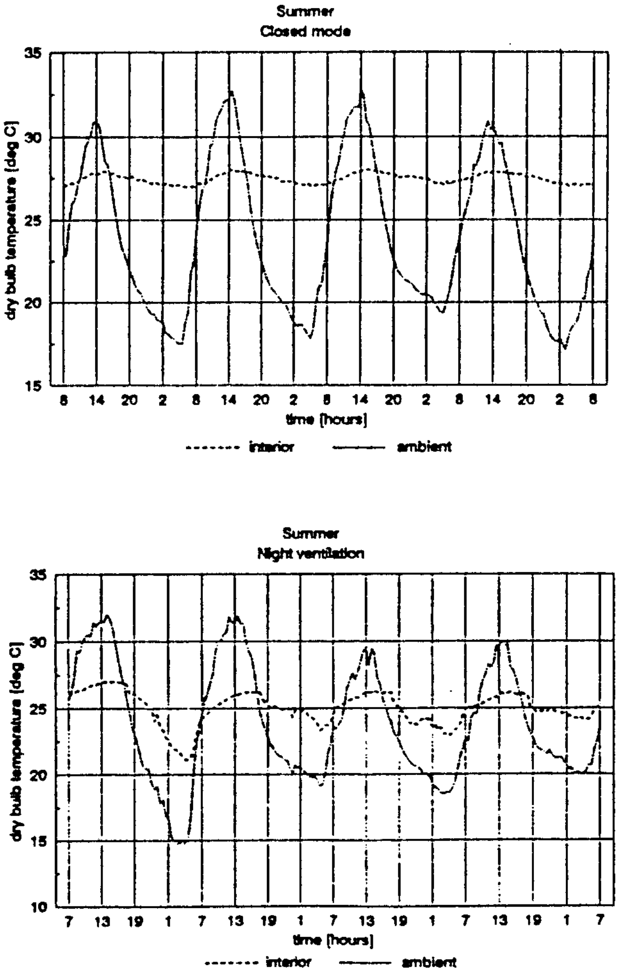

Figure 3. Summer season thermal performance in (top) closed mode, August 15-19, and (bottom) night ventilation mode, August 24-28.

Night Ventilation

The introduction of cool ventilation air by opening all windows and louvres of operable shutters between 18:00 and 8:00 was investigated in this mode as a passive means for lowering internal temperatures. As can be seen in Fig.3b, the effect of this ventilation was to immediately lower evening temperatures following the opening of windows at 18:00, such that the average nightly minimum was reduced to 23°C, or approximately 4°C below that of the previous mode under similar ambient conditions.

The extent to which this cooling effect carried over to daytime hours was less pronounced than what might be expected from a massive underground structure, with peak temperatures only 1-2°C below those of the closed mode, and the daily fluctuation increased to over 3°C.

The rapid night cooling and negligible damping of daytime peaks attest to a relatively *low* thermal inertia, atypical for an earth-sheltered structure. This effect may be attributed to the insulating layer in the shell's construction, which effectively isolates the space from its surrounding earth cover in the *short-term*. Thus with the passage of the ambient curve's nightly minimum, interior temperatures rose sharply with only a minimal time lag. Once windows were closed to ventilation air, the space was slowly but steadily heated by heat transfer through the opening and by the uncooled earth surrounding it. When windows were opened "prematurely," that is, before the ambient temperature had dropped below that of the interior, room temperatures immediately jumped by as much as 3°C in response to the infusion of warmer air, highlighting the sensitivity of the building to "correct" operation.

The observed temperature pattern over the course of several days shows only a marginal downward trend which could be attributed to the accumulated effect of nocturnal convective cooling. From results in both summer modes, it is apparent that while the earth cover is an effective means of minimizing conductive heat gain through the envelope, the building is sensitive to the short-term effects of heat transfer through its openings.

While the building suffered from moderate overheating in the closed mode, the introduction of nocturnal ventilation improved thermal comfort to a certain extent. Given the low relative humidity, it was possible to maintain interior conditions within the comfort zone (albeit close to the upper limit) at all hours, with the employment of exclusively passive means for climate control.

Transitional Period

Monitoring conditions during the spring season (May-June) were relatively mild, with ambient temperatures ranging only several degrees above and below the comfort zone. Under such circumstances, a stabilization of interior temperatures around the average ambient is sufficient to ensure continuous comfort in the building.

In the closed mode, results show a temperature pattern typical of an earth-sheltered structure, with extremely stable conditions and little apparent influence of the outside climate. With an average temperature of approximately 20°C and a daily fluctuation of under 1°C (Fig.4a), no need for temperature modification is necessary. While the introduction of ventilation air increased the amplitude of the daily swing to 3.5°C, temperatures remained comfortable at all hours in this mode as well (Fig.4b).

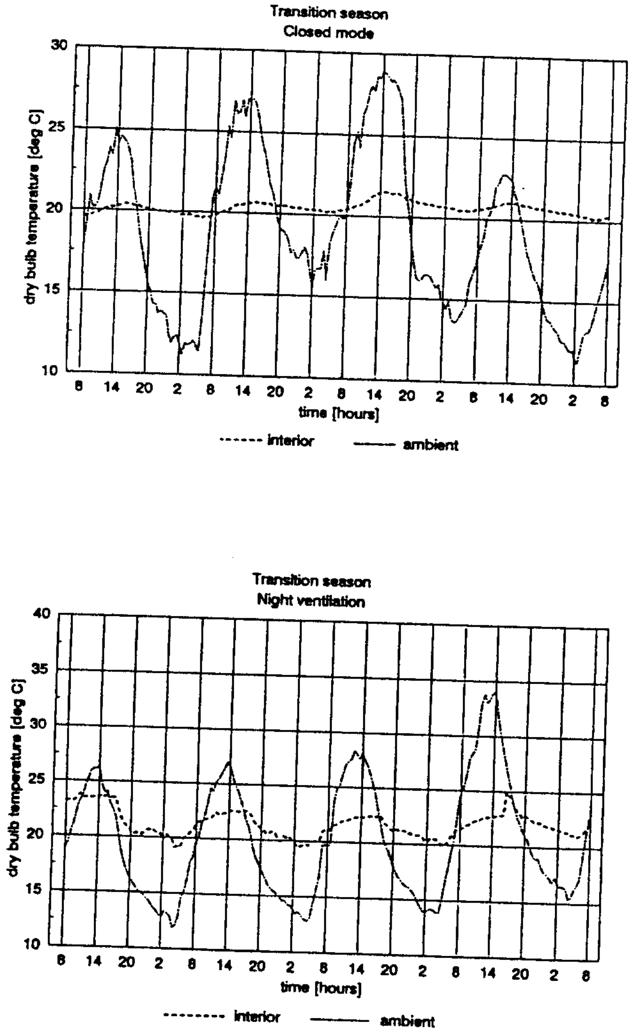

Figure 4. Transition season thermal performance in (top) closed mode, May 7-11 and (bottom) night ventilation mode, June 4-8.

What these results illustrate is that measures taken in the building design to respond to extreme conditions in summer and winter do not disturb the potential for "normal" performance in the mild transition season.

Winter Performance

Monitoring in winter was divided into periods in which backup heating was supplied, in order to evaluate the structure's energy requirement for maintaining comfort conditions, and periods without backup heating for analysis of thermal behaviour patterns. Further measurements were taken the following winter to obtain a detailed temperature profile within the earth cover of the building.

Closed Mode

In this mode, where all windows and insulated shutters were closed, room temperatures were considerably higher than the

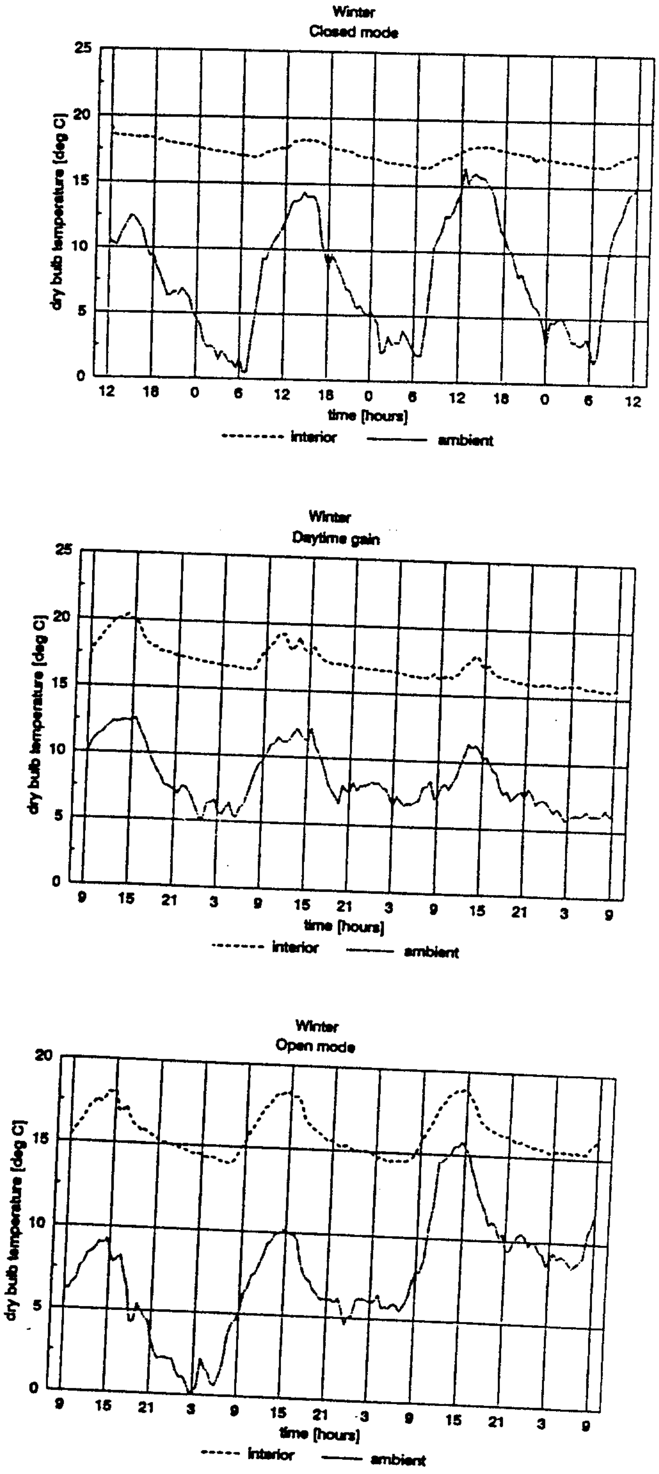

Figure 5. Winter season thermal performance in (top) closed mode, January 13-36, (middle) daytime gain mode, January 22-24, and (bottom) open mode, January 27-30.

ambient, despite the lack of direct solar contribution. An internal average of 17°C was observed under exterior conditions averaging under 8°C. (Fig.5a). Though the interior temperature curve followed ambient fluctuations on a daily cycle with only a minimal time lag, its amplitude was less than 2°C, in comparison to an exterior range of nearly 13°C. As in the summer, when the building's openings remained closed the interior space was relatively unaffected by ambient conditions, and its behaviour was largely dictated by the thermal state of the earth cover which surrounds it.

Daytime Gain

In this mode, south-facing shutters were opened during daytime hours in order to examine the building's efficiency in collection and storage of solar energy, but closed again each night. The quantity of solar absorption was determined from measurements of global solar intensity on the south facing surface. Hourly shading calculations, based on sun angles for the winter solstice and the geometry of the glazed opening, showed that, of the total window area (5.5m^2), the proportion exposed to direct radiation ranged from 85% in the early morning and late afternoon to 64% at solar noon. Assuming that direct radiation comprises 75% of the total insolation on a south-facing surface, as measured for the winter solstice at Sede-Boqer [13] and using a glazing transmissivity factor of 0.86, the total gain could then be calculated: on a clear day during this period, for which the measured daily insolation on the southern surface was 3.5kWh/m^2, the total solar contribution through the opening was estimated at 12.5kWh.

With the addition of direct solar gain, daytime temperatures in the south-facing dome were brought well into the comfort zone, with peaks reaching over 20°C and a daily average of 17.5°C, nearly 9°C higher than the average ambient (Fig.5b). This was despite relatively low insolation levels averaging 1.1 kWh/m^2 per day on the south surface, or about one-third of that measured on a clear day in the same period. In contrast to the stable temperature curve observed in the closed mode, however, the daily fluctuation in this case was between 3-4°C; thus nightly minima were left at a relatively unchanged level of 16-17°C, slightly below optimum comfort conditions.

Open Mode

In this mode the large southern opening was exposed day and night by opening the insulated shutters. Daytime heat gains were therefore accompanied by increased conductive losses at night. Although internal temperatures show an amplitude of 3-4°C, similar to that of the previous mode, the average is approximately 2°C lower (Fig. 5c). Despite an average solar input of 1.9kWh per day, which resulted in daily temperature peaks of over 18°C, the nightly minimum was lowered to an underheated level of 14-15°C. Still, the average internal temperature was well above the ambient average of 7.5°C, and relatively resilient to changes from day to day. This is illustrated by the very minor increase in interior temperatures between the first and third days of monitoring, while the mean daily temperature of the ambient air rose by nearly 7°C.

In both modes utilizing solar gain, the implications of the building's lack of internal mass are once again demonstrated. While sufficient energy is absorbed to raise daytime temperatures above a minimum comfort level, the building's short-term storage capacity is insufficient to prolong comfort conditions throughout the daily cycle. On the other hand, the pattern of thermal behaviour seen *over the course of several days* is one of great stability, in open modes as well as closed. This longer-term thermal inertia is a result of the massive earth cover, which provides in this case a degree of independence from ambient fluctuations despite its lack of full thermal contact with the space.

Backup Heating

During separate monitoring periods in each mode of operation, the electrical consumption required to maintain a minimum temperature of 20°C at all hours was measured with the use of a metered, thermostat-controlled space heater. The results of heating requirements in the various modes, along with ambient conditions during the same periods, are presented in Table 1:

Table 1

Electric Power Consumption for Backup Heating in Various Modes

Mode	Daily heating to maintain required 20°C [kWh/day]	Mean daily ambient temperature [°C]			Mean daily insolation on vertical south-facing surface [kWh/m^2]
		max	min	avg.	
Closed	4.28	16.8	4.8	10.2	-
Daytime gain	0.88	18.0	8.1	12.3	1.7
Open	1.71	16.7	6.2	11.0	2.0

The energy requirement under characteristically cold January conditions was relatively minor, regardless of mode of operation. Even without the contribution of solar gain, the daily consumption was just over 4kWh, while with shutters open 24 hours, this requirement was reduced to under 2kWh. With south glazing exposed in the daytime only, heating was nearly eliminated, totalling to under 1kWh per day.

This minimal heating requirement is a reflection of the vast overall thermal resistance imparted to the building by its insulated earth-covered envelope, as well as the small initial temperature differential between the heated space and the inner earth layer. However, even this minor amount of heating may be seen as unnecessary: in both modes which allowed solar gain, interior daytime temperatures rose to peaks of 24-25°C, well above the requirement for comfort under winter conditions. The failure to absorb and store this excess energy for further reduction of the nightly heating load is another illustration of the building's lack of internal mass.

Influence of Earth Cover

In order to gain a better understanding of thermal processes within the earth layer and their influence on the building's observed behaviour, a follow-up period of winter monitoring was undertaken, which included the measurement of temperatures at various depths within the ground covering the south dome. Sensors were located at 40cm intervals in a line perpen-

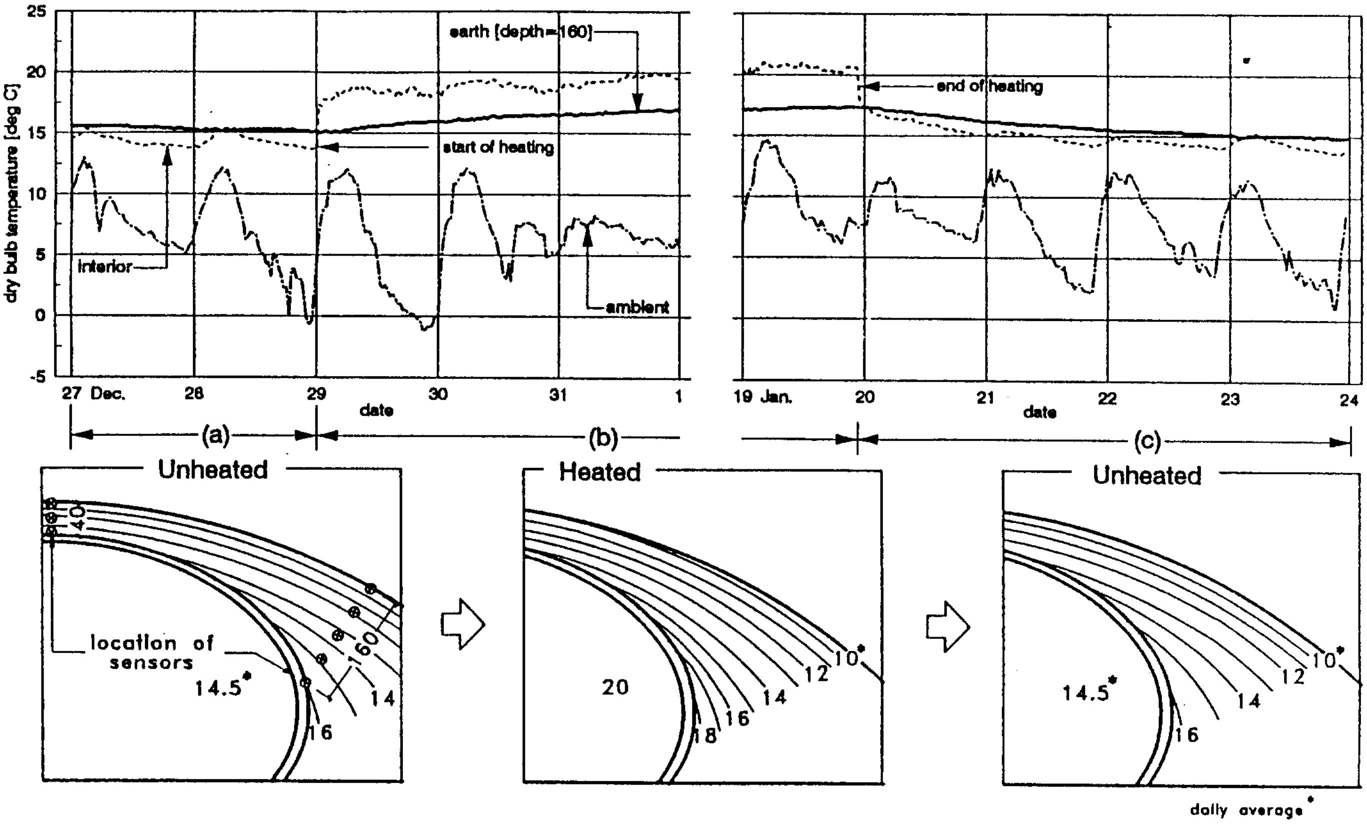

Figure 6. Graph (above) and sectional profile (below) of temperatures measured within the earth cover during successive periods: (a) before the start of heating (sensor location shown), (b) during heating, and (c) following cessation of heating.

dicular to the side of the dome, and at 20cm intervals above the dome (Fig. 6a). Monitoring was conducted in the closed mode for several days, after which backup heating was initiated as earlier with a cut-off temperature of 20°C. The structure was heated for several weeks, after which heating was terminated and temperatures were observed in the days following.

Prior to Heating

Measurement of earth temperatures before the start of heating illustrates the extent to which climatic effects are mediated with increasing depth below the surface. At a depth of 40 cm, the effect of daily ambient temperature swings was seen to already be negligible, with only a gradual downward trend between 12°C and 11°C noted over the course of several days parallel to a reduction in the average ambient (Fig. 6a).

Beyond this point, any signs of thermal connection with the outside were imperceptible, with temperatures remaining virtually constant at approximately 13°C (80cm) and 14°C (120cm).

Temperatures adjacent to the building shell (160cm deep), though still extremely stable at about 15°C, once again showed a slight response to the downward trend in ambient average over the course of several days. The source of this thermal connection is presumably the conduction of heat through the building shell to the interior space, which in turn loses heat to the surroundings through its large glazed opening. *The lack of thermal variation in the middle layers points to the fact that any correlation in short-term temperature patterns between the room and ambient conditions is a result of heat transfer through the glazed opening, rather than through the earth cover.*

Heating

The nature of heat transfer through the building envelope and into the various layers of earth cover is illustrated by thermal response at various depths to mechanical heating from within. While the interior air was heated within minutes from under 14°C to 18°C, (and then gradually, with fine adjustment of the thermostat, to 20°C) temperatures within the earth responded at increasingly slower rates as their distance from the heat source increased. (Fig. 6b) In the soil adjacent to the building shell, a rise in temperature was observed after approximately five hours from the commencement of heating; afterward this layer steadily rose in temperature, gaining about 3°C over a four-day period and then levelling off at 18°C. At a depth of 120cm, or 40cm away from the shell, response was perceivable only after about 16 hours, and the increase thereafter was damped to a total of about 1°C over three days, at which point temperatures stabilized at 15°C. Above 80cm no thermal response to heating was seen, with changes responding increasingly to ambient trends as depth decreases.

Post-heating

The clearest indication of the earth's thermal influence on interior performance is seen in the period immediately following the conclusion of mechanical heating. While interior air temperature dropped by nearly 3°C within the first hour, even the slightest response in the inner earth layer was seen only after a time lag of approximately five hours. Once the interior temperature had descended below that of the adjacent earth, its rate of decrease abruptly levelled off, with both the air and earth cooling gradually at a parallel rate of about 0.5°C per day (Fig. 6c).

The sharp initial temperature drop and subsequent levelling off of the interior temperature are directly linked to the thermal state of the earth layer adjacent to the building envelope. With relatively little internal mass for heat storage, the space was cooled rapidly by heat loss through the glazed opening, until its temperature dropped just below that of the inner earth layer. Having stored up heat during the previous weeks, the earth then acted as a thermal "magnet," holding the air close to its own temperature by transmitting enough heat to nearly balance further loss through the glazed opening.

During this period, interior air temperatures still followed a pattern of shallow daily fluctuations with only a minimal time lag of 1-2 hours from ambient swings, indicating that the pattern of *short-term* response to ambient changes within the insulated space was dictated not by the stable inner earth layers, but by heat transfer through the glazed opening. However, the generally stable temperature pattern was due to the *long-term* effect of the earth cover. Inner earth temperatures naturally showed no variation on a daily cycle; in fact beyond a distance of 40cm from the building shell (depth of 120cm), response to the loss of heating was barely perceptible.

Discussion

The structure's general patterns of behaviour are dictated by a dichotomy of thermal effects:

(1) The combined thermal resistance and heat capacity of the massive earth cover effectively eliminate the transmission of ambient fluctuations *through* the majority of the envelope, and lend the structure a long-term thermal inertia which tends to dampen interior temperature variation over the course of several days. Interior temperatures are therefore stabilized around a longer-term average rather than fluctuating with ambient variations. The extent to which the mass of the earth controls internal conditions was illustrated by the comparison of earth and air temperatures upon the removal of an interior heat source, and was observed in each season, most prominently when the building was operated in the "closed" mode.

(2) The insertion of an insulating layer between the space and this stabilizing mass produces a high short-term sensitivity, unusual for an earth-sheltered structure, to thermal stimuli which are transmitted through the building's glazed openings. This sensitivity was demonstrated by the introduction of both direct solar gain in winter and night ventilation in summer, both of which had a rapid but short-lived impact since they were allowed to exchange heat directly with the room air rather penetrating to the surrounding mass. Because of the envelope's insulation, the observed effect on the earth cover is in fact a time-lagged stabilization, or a thermal "memory" which keeps the space temperature within a certain range of its own temperature, but allows it to fluctuate in the short-term.

The immediate sensitivity of the insulated envelope was shown to amplify the importance of building operation in each season, which causes it to be either a potential liability or a potential advantage. On winter nights, for example, this sensitivity led to uncomfortably low temperatures due to a lack of solar heat storage and immediate effects of infiltration, but allowed quick and efficient correction by backup heating without over-absorption by the earth mass. During the summer, convective cooling at night produced immediate reduction in interior temperatures but was relatively inefficient in terms of mass storage for the following day.

Still, the question arises as to the benefit of this insulation for overall thermal comfort, given its tendency to reduce thermal coupling of the space with the earth cover on a short-term basis, and the resulting dependency on correct building operation. To the extent that earth temperatures at the given depth fall within the human comfort zone, it may be assumed that the insulation is extraneous, since thermal coupling would tend to improve interior conditions by stabilizing the daily swing at an acceptable level. When earth temperatures are not within the range of comfort, however, small-scale correction is indeed required, in which case the thermal separation of the insulating layer can increase the efficiency of such corrective measures.

Fig. 7 shows the yearly distribution of soil temperatures in Sede-Boqer at a depth of one meter, the average depth of cover in the earth-sheltered structure. This distribution is compared with the ambient annual range, both representing long-term averages based on five-year periods of monitoring [14,15]. It can be seen that at a depth of one meter, the yearly earth temperature range has an amplitude of approximately 12°C, and either borders or goes beyond the limits of thermal comfort for nearly half the year. In addition, the time lag of peak values at this depth is about one month; therefore the earth cover provides stabilization at a temperature which is representative of the current season. It is also seen that earth temperatures are up to several degrees higher than the average ambient throughout the year, a fact that correlates with measurements in various other studies, and which has been attributed to solar absorption at the surface [16].

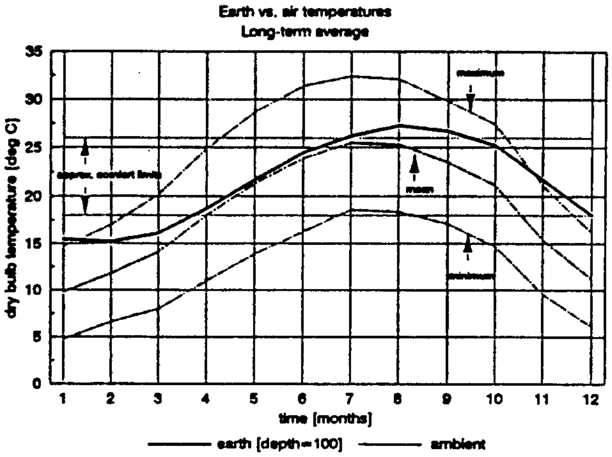

Figure 7. Annual pattern of ambient and earth temperatures, based on long-term averages at Sede-Boqer. [Zangwill, et al, Offer, et al]

Although earth temperatures are comfortable during the mild transitional seasons, the burden of extreme ambient temperatures in summer and winter is not entirely eliminated under the ground. In the cold season, earth temperatures are 6-7°C higher than the average ambient, but below the comfort level: thus additional heating is required beyond that provided by even maximal contact with the earth. During the summer months, contact with the soil actually creates an extraneous heat load, since soil temperatures rise above the comfort level while the average ambient does not (as seen in long-term monitoring results, Fig. 7). It is clear that in this season small-scale temperature modification is warranted as well, as was observed in the summer monitoring.

In these cases, then, some degree of insulation from the vast battery of thermal mass in the earth cover may be seen to have value, both for efficient daytime heating in winter and night cooling in summer, whether by passive or active means. However the greater need for climate modification is in fact in the alternate periods, at night in winter and during the heat of day in summer. With little mass inside the domed shell's insulation, the given design was shown to be relatively inefficient in storing energy over the daily cycle - despite the presence of an uninsulated floor coupled with the mass of the ground. Thus a suggested improvement would be an addition of internal heat storage capacity, whether by structural means (interior partitions, thicker inner roof) or by a change in placement of the insulation (within the earth cover). While results in this case suggest that an overall earth cover thickness of about one metre is necessary to provide a sufficient thermal isolation from ambient fluctuations, the proportion of thickness which is needed for internal mass can only be determined by further study.

Conclusions

While much of the existing research on underground structures has focused on the use of this building type in cold northern climates, the present study shows that a correctly designed earth-sheltered building can provide excellent comfort conditions in a hot-arid climate as well. In the monitored building, at least one mode of operation in each season allowed comfort conditions to prevail at all hours with only passive means of climate control, and when active temperature modification was provided, its efficiency was high.

However, it was seen that the optimal configuration of an earth-covered structure in a desert environment requires more than a sufficient layer of soil surrounding the envelope. While results showed the thermal state of the inner earth layer to largely dictate interior conditions, this thermal state is not necessarily a comfortable one. In a cold climate, where the predominant thermal issue is winter heating, maximum thermal coupling with the soil may be desirable since temperatures deep within the earth are consistently higher than the seasonal average at the surface. With the addition of an opposite thermal extreme in summer, whereby full contact with the earth may actually cause overheating, a particular need for thermal insulation arises which may not exist in a cold climate.

Monitoring in each of the seasons illustrated the benefits of such insulation, as well as the potential drawbacks due to a lack of interior mass. The design objective which arises, then, is to optimize the placement of insulation with respect to both the soil and building mass, and in this way maximize the daily stability and thermal comfort which earth-sheltering can provide.

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