AN ECONOMIC COMPARISON OF
PASSIVELY CONDITIONED
UNDERGROUND HOUSES

By

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PREFACE

This study is concerned with the analysis of underground housing alternatives that strive for minimum expenditure of energy for space conditioning. The two alternatives that are compared to the conventional "base" underground house introduce the theoretical principles of soil mixing and introduce a new method of predicting underground house cooling costs. This study also introduces a method of maximizing the flow of heat collected during the summer into the soil for winter space conditioning and conversely the rejection of heat during the winter for low soil temperatures during the summer. The end product is radiant conditioning of the underground alternative through lower than steady state soil temperatures in the summer and higher soil temperatures in the winter.

The author wishes to thank his adviser, Dr. Lester L. Boyer, for his assistance, guidance and instruction throughout the degree program. Special thanks is also expressed to Professor Walter Grondzik who through many courses, provided the technical background, interest, and motivation for pursuance of ideas generated in an earlier underground design competition. Much appreciation is given to Professor George Chamberlain who provided valuable design guidance and priceless insight into my architectural history avocation. In addition, appreciation is extended to Mr. Robert Roush for his criticism, especially in the underground housing competition. Finally, I would like to thank Mr. James Netherton for his valuable instruction and criticism and the

suggestion to incorporate heat pump conditioning as a standard for economic comparison.

I owe the largest thanks to my parents, Randy, Lisa, and Darlene for their continued sacrifice, patience, and love. Without them, I could not have completed this thesis.

Finally, special gratitude must be given to Major Samuel Brown and the Air Force Institute of Technology for giving me the time, opportunity, and breathing room to complete this degree program.

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NOMENCLATURE

A	Area in square feet
A_s	Soil temperature variation at a two inch depth below bottom of soil topping
AU	Total area heat loss
Btuh	British thermal units per hour
c	Thermal diffusivity in square feet per day
^oC	Degrees Centigrade
cfm	Cubic feet per minute
e	Natural logarithm
EER	Energy Efficiency Ratio. The ratio of net cooling capacity in Btuh to total rate of electric input in watts.
f	Dimensionless temperature rise
F	Dimensionless time function
^oF	Degrees Fahrenheit
fpm	Feet per minute
ft	Foot, feet
ft^2	Square feet
$\bar{k}$	Ratio between outgoing radiation on clear vs. cloudy nights
k	Thermal conductivity
K	Adjustment factor based upon ratio of outlet to inlet (Table VI)
$\vec{k}$	$(w/2c)^{\frac{1}{2}}$
km	Kilometer
kw	Kilowatt
kwh	Kilowatt hour

lgy	Langley unit of solar radiation
lb	Pounds
MBtuh	Thousand British thermal units per hour
mm	Millimeters
pcf	Pounds per cubic foot
q	Number of days from 31 December to the time when bare ground surface temperature first equals T_m .
q'	Human heat load
Q	Air flow in cubic feet per minute
R	Resistance to heat flow
Re	Effective resistance to heat flow through soil
RH	Relative humidity
Rw	Outgoing radiation on clear nights
R	Outgoing radiation on cloudy nights
S	Specific heat
S	Reradiation intensity in calories per square centimeter per minute
sf	Square feet
T_m	Average steady state soil temperature.
t	Number of days from 31 December
T	Undisturbed soil temperature at depth x and day t
U	Thermal transmittance value
V	Velocity in feet per minute
w	Radian conversion factor ($2\pi/365$ radians per day)
x	Material thickness or depth
Ø	Phase angle = $2q\pi/365$
Δt	Temperature differential in degrees Fahrenheit
ρ	Density in pounds per cubic foot

CHAPTER I

PROBLEM STATEMENT

Introduction

The availability of cheap energy sources and the perfection of inexpensive, convenient heating and cooling systems has made the "climate controlled" environment an integral and irreversible part of American life. However, the current shortage and high cost of fuel is threatening the quality and perhaps the availability of the climate-controlled environment. To prolong the life of the climate controlled environment, the national policy has been one of promoting conservation of the fuels that are available and promoting alternative energy systems that are often of high technology or of energy intensive materials. Fortunately, a grass roots response to the lack of energy has been an increase in the interest and construction of underground or earth-sheltered housing. The underground house, featuring a covering of earth on walls and roof, offers a high degree of energy conservation through low technology construction and the use of low energy intensive materials.

However, the typical underground house presently is simply energy conservative and is not approaching energy self-sufficiency. Although when compared to above grade structures, large savings in the quantities of energy required for space heating and cooling have been made, the loads in an underground house can be reduced to eliminate the need for heating and cooling.

The Problem

Although underground housing is seen as a means of maintaining a climate-controlled environment without a massive energy requirement, there are few underground projects under construction. In order to gain public acceptance, the underground house must be comfortable, both psychologically and thermally, affordable, and energy conservative. There are conventional types of underground houses and at least two types of underground houses that attempt to maximize energy conservation. Therefore, if the underground house can be a practical solution, what type of underground house is most cost effective?

The basis for any comparison and evaluation requires common criteria from which to rate the alternatives. The common criterion for evaluating the types of underground houses is the degree of human thermal comfort that each house can provide. The range of human thermal comfort that is statistically considered to be a "comfort" condition must be the standard of acceptability and the common basis of evaluation for each type of underground house.

The best method of evaluation for the underground houses with acceptable levels of comfort is a cost comparison that evaluates the life-cycle costs of the building. The life-cycle cost method yields quantifiable results for comparison of relative and actual costs. Therefore, the problem statement is: "Using equivalent human thermal comfort as a basis for reference, which underground alternative is most cost effective during a life cycle".

Procedures for Comparison

Prior to any evaluation, the mechanisms and principles that condition the three types of underground houses must be explained. Specifically, the first step in the comparison for this thesis is to describe the features of climate, heat transfer, and soils that combine to define the human thermal comfort found in any underground house. Secondly, for purposes of comparison, a "base" underground house is presented that is representative of conventional Oklahoma underground house construction. The "base" underground house emphasis is upon typical trends and is not meant to be an example of energy conservation maximization techniques. The "base" house is an underground house design based upon a composite of the typical construction features and a site in Stillwater, Oklahoma. Energy consumption for space conditioning is calculated based upon heat pump operation.

The first underground alternative to be compared to the "base" is the passive solar-conditioned underground house. The passive solar underground house is intended to be self-sufficient for space conditioning. Principal features are moveable insulative panels for seasonal and daily alteration of temperature, a heat storage and distribution system, and modified soil used for earth cover. The major design emphasis includes the solar and soil principles involved in conditioning the house, the operation and application of the moveable insulation and the design and operation of the natural ventilation system. After the determination of comfort levels through passive conditioning and any make-up requirement, estimates of energy consumption and capital construction expenditures required to allow passive conditioning are calculated. No human energy costs to operate the passive equipment are included in the costing.

For the second underground alternative; soil, structural, heat transfer and design problems must be solved to place a house deep enough in the earth that the house responds only to relatively stable soil temperature that varies inversely with seasonal temperature fluctuations. The major design objective with this "deep earth" house is to raise soil temperature and lag seasonal temperature variation to provide the warmest soil temperatures during the winter and the coolest soil temperatures during the summer.

The final step in the cost comparison is to determine the cost of the alternatives in underground construction and to apply life cycle costing procedures and select the best alternative.

Summary

Of the underground alternatives that are compared to the "base" house, there are few representative examples and little performance data. In fact. neither of the proposed underground alternatives are based upon existing or designed prototypes.

Although this study is not based upon existing or even constructed underground alternatives, the underground design principles have been based upon four areas of background research. The first area of research is in standard building components with proven capabilities and performance, such as the operation of heat pumps. The second area of research is in the theoretical laws and relationships that describe physical properties and phenomena, such as heat transmission calculation procedures. Experimental and statistical laws based upon readily observable and reproducible phenomena, such as soil thermal properties comprise the third area of background research. The fourth area of research is in the unknown quantities, especially site conditions, that must be addressed by recommendation.

The synthesis of the theoretical principles must provide underground solutions that approach energy self-sufficiency and human thermal comfort.

CHAPTER II

UNDERGROUND MECHANISMS

Introduction

The process of receiving energy from the surface of the earth and transferring that energy to the depth of the underground house is a relationship of climate, soils, and heat transfer principles, all contributing to human thermal comfort. The process is basically the same for all types of underground structures; however, the degree of importance of any component varies with each type of underground house.

Climate

There are three types of climate that affect the underground house. Important in the decision to build an underground house is the regional or "macro" climate that explains average conditions of air temperature, humidity, precipitation and solar radiation. The "micro" climate or climate unique to a specific site, is necessary in the selection of building orientation and location. The third type of climate is the surface climate that controls how and how much energy is transmitted to and from the soil.

Macroclimate

To a degree, macroclimate determines the popularity of the underground house. Macroclimate with extremes in amplitude or extremes in temperature appear to be most basic in the underground house selection process. The macroclimate is best characterized by the factors of average air temperature, precipitation and radiation. Macroclimatic data can be used to predict the annual freeze dates, the depth to place insulation below grade, and the required capacities for mechanical equipment. The base underground house is most dependent upon macroclimate because the design is based upon the averaging effects of a depth of soil, the average temperature, the statistical quantities of radiation, and the average temperature effects for the calculation of heat gain and loss. For a given soil, the greater the depth of earth cover, the greater the dependence of the underground house upon the macroclimate.

The macroclimate for the sites in Stillwater, Oklahoma, may be described by the same climatological data that is required to design an above grade house. Specific climatic design conditions are listed in Table I and plotted in Figure 1.

Microclimate

The microclimate is especially important in determining the success of the passively conditioned underground house. The effect of microclimate is significant because of the low factor of safety of heating and cooling systems and the length of thermal lag in the space conditioning process. For an underground house in particular, microclimate is determined generally by the microclimatic factors of average temperature and incident solar radiation and specifically by the microclimatic features of topography (especially slope, altitude, and land form) and vegetation (plant and ground cover).

TABLE I

CLIMATIC DESIGN CONDITIONS FOR STILLWATER, OKLAHOMA

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temperature (34)	37.9	42.2	49.6	60.6	68.5	77.9	82.5	82.3	74.2	63.5	49.1	40.8
Heating Degree Days	893	683	539	213	47	0	0	0	18	158	522	787
Daily maximum temperature (34)	45.9	51.6	60.0	70.5	77.9	87.2	92.9	93.1	85.6	75.0	58.6	49.0
Average daily temperature range (8, p. 319)	19.4	21.1	22.9	22.3	20.2	20.0	21.6	22.1	22.7	22.5	21.1	19.0
Average Precipitation	1.16	1.35	1.86	2.86	4.62	4.24	3.53	3.21	3.38	2.78	1.85	1.34
Depth of snow	4.0	2.4	1.6	0	0	0	0	0	0	trace	.5	1.6
Relative Humidity (noon)	58%	53%	51%	52%	58%	60%	55%	55%	59%	49%	55%	60%
Relative humidity (midnight)	71%	69%	66%	70%	78%	79%	73%	75%	81%	73%	74%	73%
Wind speed mph	13.8	13.9	15.4	15.3	13.7	13.2	11.5	11.2	11.6	12.6	12.7	13.0

TABLE I (Continued)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind direction	N	N	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	S	S
Average daily solar radiation (Langleys)	241	310	402	478	524	584	580	550	444	361	265	221

First one inch snow occurs 1 January. Last one-inch snow occurs 15 February.
First killing frost occurs 15 October. Last killing frost occurs 15 April.
Average maximum depth of frost penetration into the soil is six inches (estimated).
Extreme depth of frost penetration is twenty inches (estimated).
Calculated cooling degree days for the "base" house are tabulated in Appendix B.

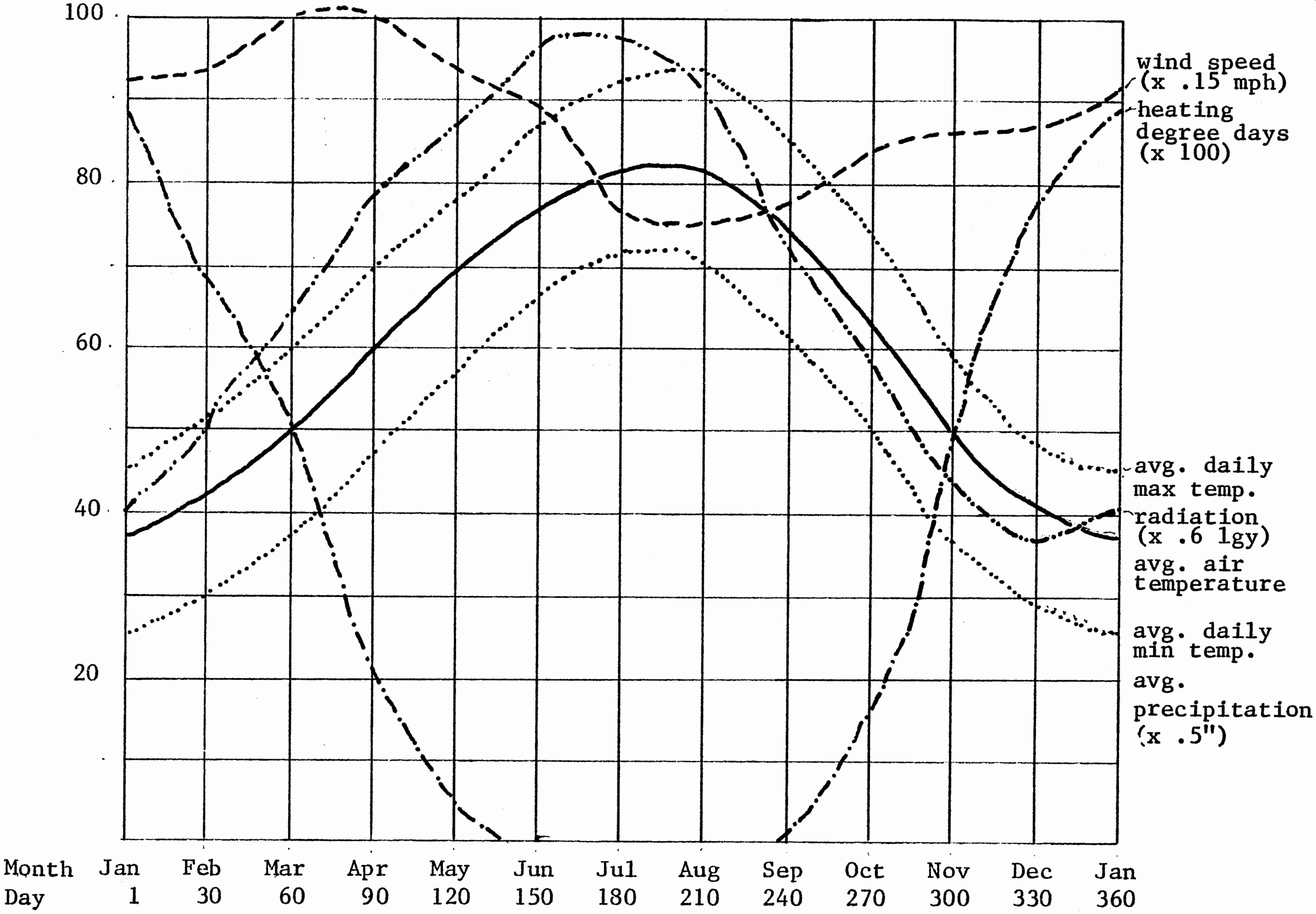


Figure 1. Climatic Design Plot for Stillwater, Oklahoma

Topographical Effects Upon Micro Climate

The optimum slope and orientation for solar radiation maximization for underground structures differs from the slope and orientation required for optimum solar reception for a solar panel. According to Geiger (11)

> . . . the coldest direction of slope, as might be expected, is the northern. The warmest direction varies; however, in the course of the year. From January till spring the temperature maximum lies in the southwest; then it moves quickly toward the southeast where it is found in June. During summer and autumn it completes the cycle back to the southwest (p. 225).

For an underground house with minimal earth cover and where annual heat cycles are only slightly delayed

> . . . the ground temperature depends not only on the intensity of insolation, but also on the condition of the ground, particularly on its highly variable moisture content. The morning sun finds a moist ground. A great part of the solar energy radiated during the forenoon is therefore used up in evaporation with a drying out effect on the soil. But when in the afternoon the sun does its greatest work on the southwestern slopes...the ground is already comparatively dry, the heat used in evaporation is scanty and most of the absorbed heat energy is applied toward raising the temperature (p. 225).

But for a deep earth underground house placed at a depth where annual heat cycles lag by as much as six months and in a climate similar to Stillwater's where thermal comfort during winter conditions may be most crucial, it is important and fortunate that the maximum temperature occurs not at the south but rather toward the southwest. Taking the west-northwest as the neutral temperature, the western exposure is warmer and the eastern exposure is colder than the neutral exposure. For sloping ground, a 30° east oriented slope receives more radiation, but a west slope maximizes ground temperature because the shielding effects of early morning moisture are absent when the sun reaches the west slope (11, p. 225).

The final selection of a sloping site should recognize that the effects of all sides may be felt in the subgrade. For example, for a house where walls are covered with sloped, bermed earth with one northern exposure, the area of northern exposure may cancel the benefits of more favorable slopes. It follows therefore, that to maximize energy savings, the north slope must be minimized or eliminated. This can best be accomplished by a non-north slope orientation.

The slope and orientation of earth cover also is important in determining the type of plant cover and rate of plant growth. For mid-May (a time important for plant growth), the following percentages of radiation were observed for varying slopes (11, p. 224).

TABLE II

PERCENTAGE OF TOTAL RADIATION

Slope	Percentage of Total Radiation
South slope, inclined 23°	65
South slope, inclined 30°	65
Horizontal surface	60
East or West slope, inclined 30°	55
South Slope, inclined 60°	53
North Slope, inclined 30°	39
East or West wall	30
South wall	29
North wall	04
Continuously perpendicular to sun's rays	100

The greater the percentage of total radiation, the greater the potential for shielding the surface with plant growth and reducing soil temperatures.

Topographical Effects Upon Microclimate-Altitude. Since significant altitude is not encountered in the Stillwater area, microclimatic influences will strictly determine plant growth and general temperature. The differences in average temperature from sea level for varying altitudes are shown in Table III (11, p. 253). The increase of wind frequency and velocity at higher altitudes has an averaging effect upon the microclimate.

TABLE III

EFFECTS OF ALTITUDE UPON TEMPERATURE

Altitude in meters	650-850	850-1050	1050-1250	1250-1450
Clear nights	2.2°F	1.2°F	1.6°F	0.6°F
All nights	1.2°F	0.8°F	0.8°F	0.4°F

Topographical Effects Upon Microclimate-Land Forms. Land forms are prime determinants of the microclimate. Not only the topographical effect of slope is critical for underground houses, but the shape of the land affects the microclimate.

First, although underground houses are usually of tighter construction than their above-grade counterparts, modification of wind patterns by an underground structure may increase infiltration effects and promote drying of the soil. However, the consideration of wind effects upon an underground house may be far less important than the role of the land forms in capturing cooler, more humid air and concentrating the coldest air in low level entrances to the underground house.

The land forms concentrate cold air in two different ways. First of all, concave land forms physically contain the cold air. The cold air is created as a result of outgoing radiation and any structure (topography, vegetation, or other physical barriers) that hampers the flow of air required to balance nocturnal or low temperature periods alters the micro climate. Temperature differences of more than nine degrees have been noted at vertical differences of a yard on extremely clear "frost" nights (29). It has also been noted that for areas that serve as "frost holes" and have sides of the concave surfaces of 1% or greater slope, the cold air enters the concave surface in short, sudden bursts that lift the warm air from the ground. After passage of the cold air, the warm air is allowed to return to the surface.

Secondly, the concave land form receives less radiation, (both direct and diffuse) because of the elevation and azimuth of the sun. For azimuths up to 60°, the incident solar radiation flux is less than half of that for an azimuth of 0° (29) and consists typically of diffuse radiation (29). The diffuse radiation ranges from a minimum of 16% to a maximum of 100% of the total radiation (29). Besides, the lower quantities of solar radiation, and the general horizontality of the concave form allows excessive nighttime heat losses due to "black body" radiation (6).

Surface Climate

The surface climate is described by the ground surface cover rather than by the ambient above-grade conditions. The surface climate extends from the ground surface to just above the vegetation and is most significantly influenced by site orientation, surrounding terrain, plant growth and other micro climatic effects. Surface climate provides the potential for altering average soil temperature within a range of $10^{o}F$ (26).

The principal benefit of the surface climate is the control of heat transfer throught the boundary layer of trapped air usually held within the first four inches of the ground surface. Since the surface cover is usually of vegetation, the wind movement is often reduced to zero and moisture content remains stable around 100% relative humidity.

Soils

The depth and type of backfill soil is one of the most important economic decisions concerning the base house. The soil cover for an underground house is responsible for the thermal, structural and maintenance performance of the underground house and requires detailed analysis. The objective in soil selection is to maximize the thermal performance of the soil while minimizing depth of cover and structural load. The modification of the soil to obtain low thermal conductivity with low weight is the answer to one underground housing soils problem.

Technical Aspects

The soil properties that most affect the underground house are the thermal, structural and fertility properties. Of these properties, the thermal properties are of greatest importance.

Soil Thermal Properties

The thermal properties of the soil influence the time lag between the average air temperature and the soil temperature at a given soil depth. Since the soil generally transfers heat on a capacitance basis, rather than upon a resistance basis, the diurnal fluctuations of temperature are eliminated in inverse proportion to the thermal conductivity of the soil.

The most important thermal property of the soil is thermal conductivity. Within the soil, the property of thermal conductivity "k", or the quantity of heat flow in a unit time through a given area, accounts for thermal lag between soil temperatures and average air temperature. When other soil properties are held constant, the smaller the value of thermal conductivity, the greater the depth to reach stable earth temperatures. Generally for a given soil, the lower the moisture content, the greater the thermal lag and the lower the thermal conductivity. However, for non-homogeneous soil materials, or areas of discontinuity, the variation of temperature is in actuality very complex. For the range of soils encountered in Oklahoma, the following is a summary of the thermal conductivity variation for typical backfill soils (17)

1. Above freezing, thermal conductivity increases with an increase in mean temperature. At 170°F, the thermal conductivity is 4% higher than the value at 40°F.

2. Below freezing, for soils at low moisture contents, it shows very little change; for greater moisture contents, it shows an increase for a decrease in temperature.

3. For a change from unfrozen to frozen soil, it changes variably according to the moisture content. For dry soils, it does not change; for soils of low moisture content,

it decreases; and for soils of high moisture content, it increases.

4. At a constant moisture content, it increases with an increase in dry density. The rate of increase is fairly constant and is independent of the moisture content. Generally, for each pound per cubic foot increase in density, thermal conductivity increases 2.8% for unfrozen soil and 3.0% for frozen soil.

5. At a constant dry density, it increases with an increase in moisture content.

6. At a given density and moisture content, it varies in general with the texture of the soil, being higher for gravels and sands, lower for the sandy loams, and lowest for the silt and clay soils.

7. For saturated, unfrozen soils, the conductivity decreases for a decrease in density. For saturated, frozen soils, the data indicates no well-defined relationship between density and conductivity. Sand soils in such a condition and at densities normally obtainable gave higher conductivities than soils with relatively high silt and clay contents.

8. The thermal conductivity of a soil is dependent upon its mineral composition. Sands with a high quartz content have greater conductivities than sands with high contents of such minerals as plagioclase feldspar and pyroxene, which are constituents of basic rocks. Soils with a relatively high content of kaolinite and other clay minerals have relatively low conductivities. This may be due to the fine texture and is not necessarily the result of the presence of these minerals.

9. For purposes of prediction of thermal conductivity, soils should be divided into two groups, sands or sandy soils and silt and clay soils. The line of division, in general is based upon the silt and clay content: soils with 50 per cent or more of silt and clay are in the fine textured group. The thermal conductivity also differs according to whether the soil is frozen or not. The four equations for these conditions are:

a. Silt and Clay soils, unfrozen

$$k = ((0.9 \log \text{Moisture content}) - 0.2)(10^{0.01}) \qquad (1)$$

b. Silt and Clay soils, frozen

$$k = 0.01\ (10^{0.0227}) + 0.085\ (10^{.010087})^{\text{Moisture content}} \qquad (2)$$

c. Sandy soils, unfrozen

$$k = (0.7 \log \text{Moisture Content}) + (0.4)(10^{0.018}) \qquad (3)$$

d. Sandy soils, frozen

$$k = 0.076\ (10^{0.0227}) - 0.032\ (10^{0.0087\rho})\ \text{Moisture content.} \qquad (4)$$

> Where the thermal conductivity, "k" is in British thermal units per square foot per inch per hour per degree Fahrenheit, the moisture content is a percentage of the dry soil weight, and ρ is the dry density in pounds per cubic foot. The equations for the silt and clay soils apply for moisture contents of 7 per cent or more; those for the sandy soils, of one per cent or more.

Average soil temperature plots are shown in Figures 8 through 11 for typical values of thermal conductivity with variation in soil properties.

Of specific interest in the computation of the average soil temperature is the determination of thermal diffusivity of the soil. The thermal diffusivity is the ability of a material to undergo temperature change (17, p. 10). The smaller the diffusivity, the more the resistance to temperature change. Thermal diffusivity "c" in square feet per day, is calculated by the relation

$$c = \frac{k}{24\rho S} \qquad (5)$$

Where "k" represents thermal conductivity in British thermal units per hour per square foot; ρ is the density of the soil in pounds per cubic foot; and "S" is the specific heat of the soil in British thermal units per pound per degree Fahrenheit.

Changes in the homogeneity of the soil can quickly and drastically alter the thermal diffusivity. Therefore, the addition of rock, increased moisture content, and frozen ground increase the thermal diffusivity and allow ambient air temperature to penetrate into the soil

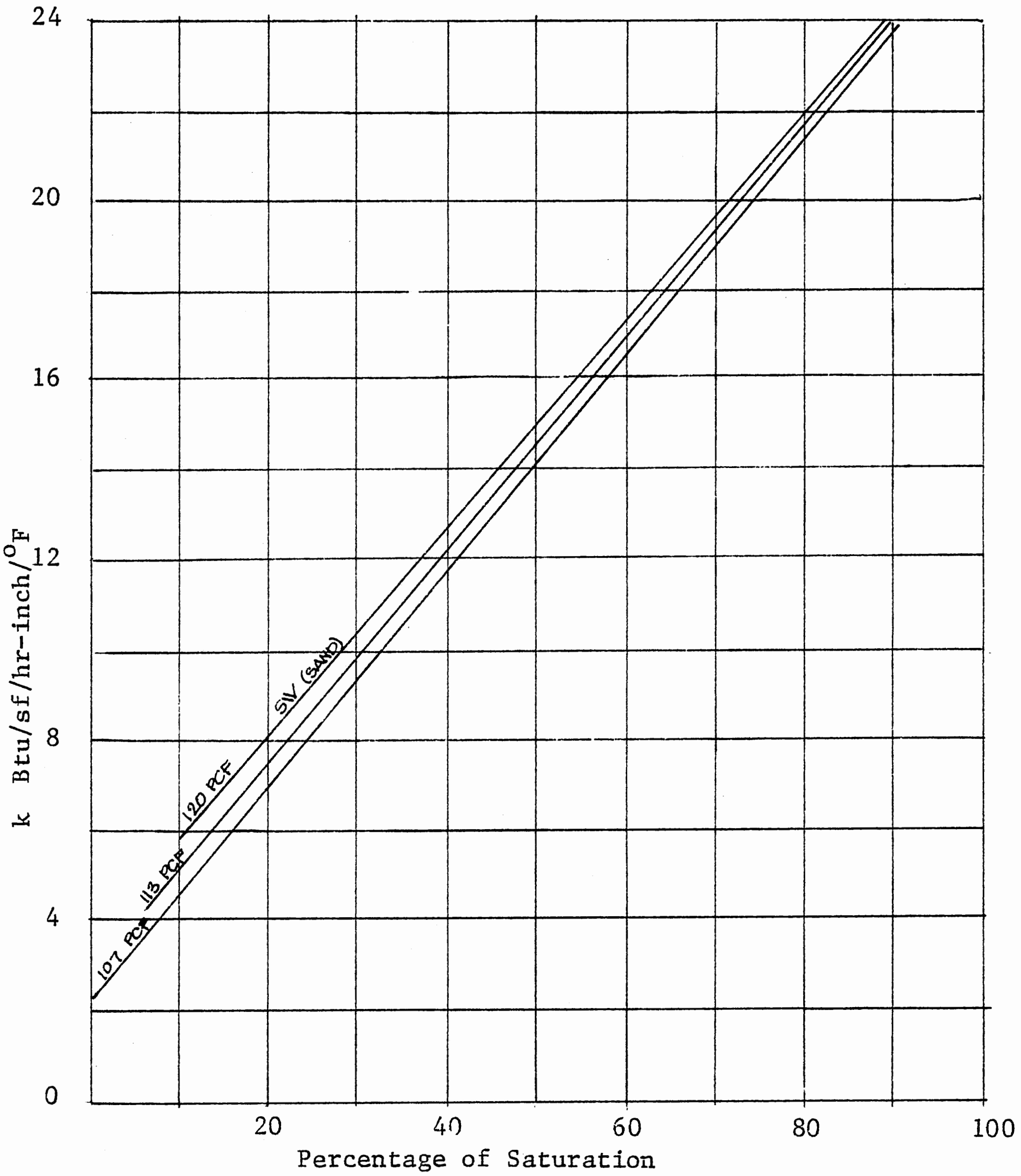


Figure 2. Thermal Conductivity versus Percentage of Saturation (17, p. 55-56).

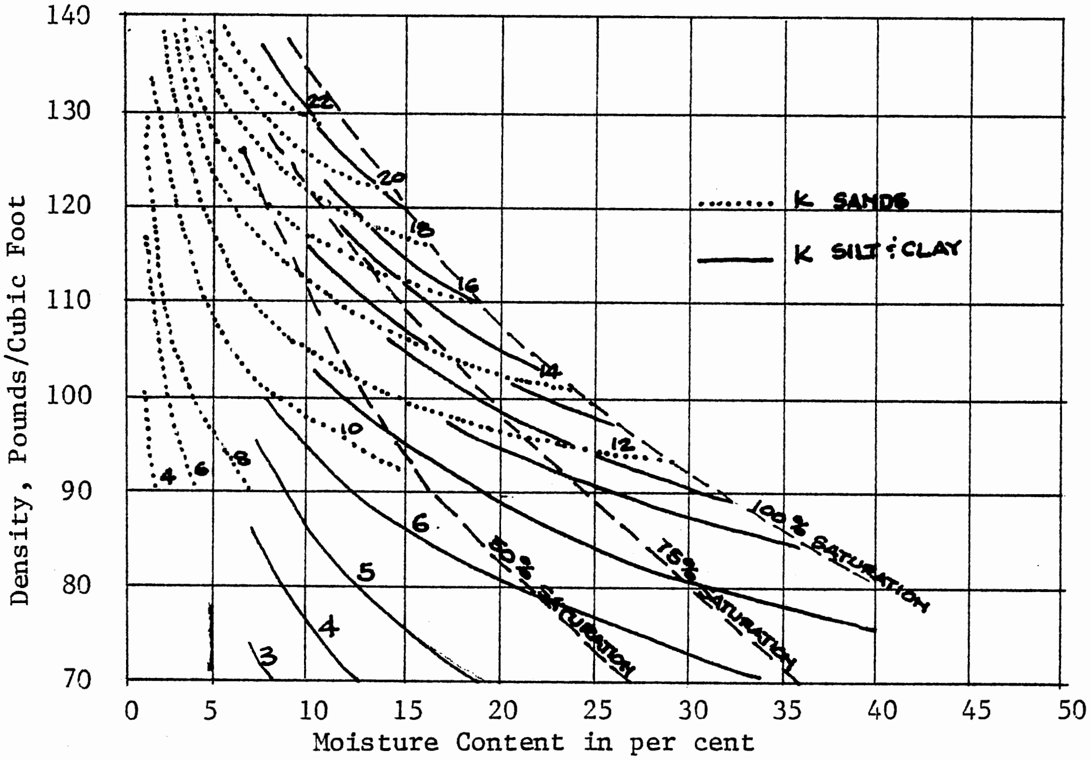


Figure 3. Variation of Thermal Conductivity and Density with Percentage of Saturation (17, p. 36-38).

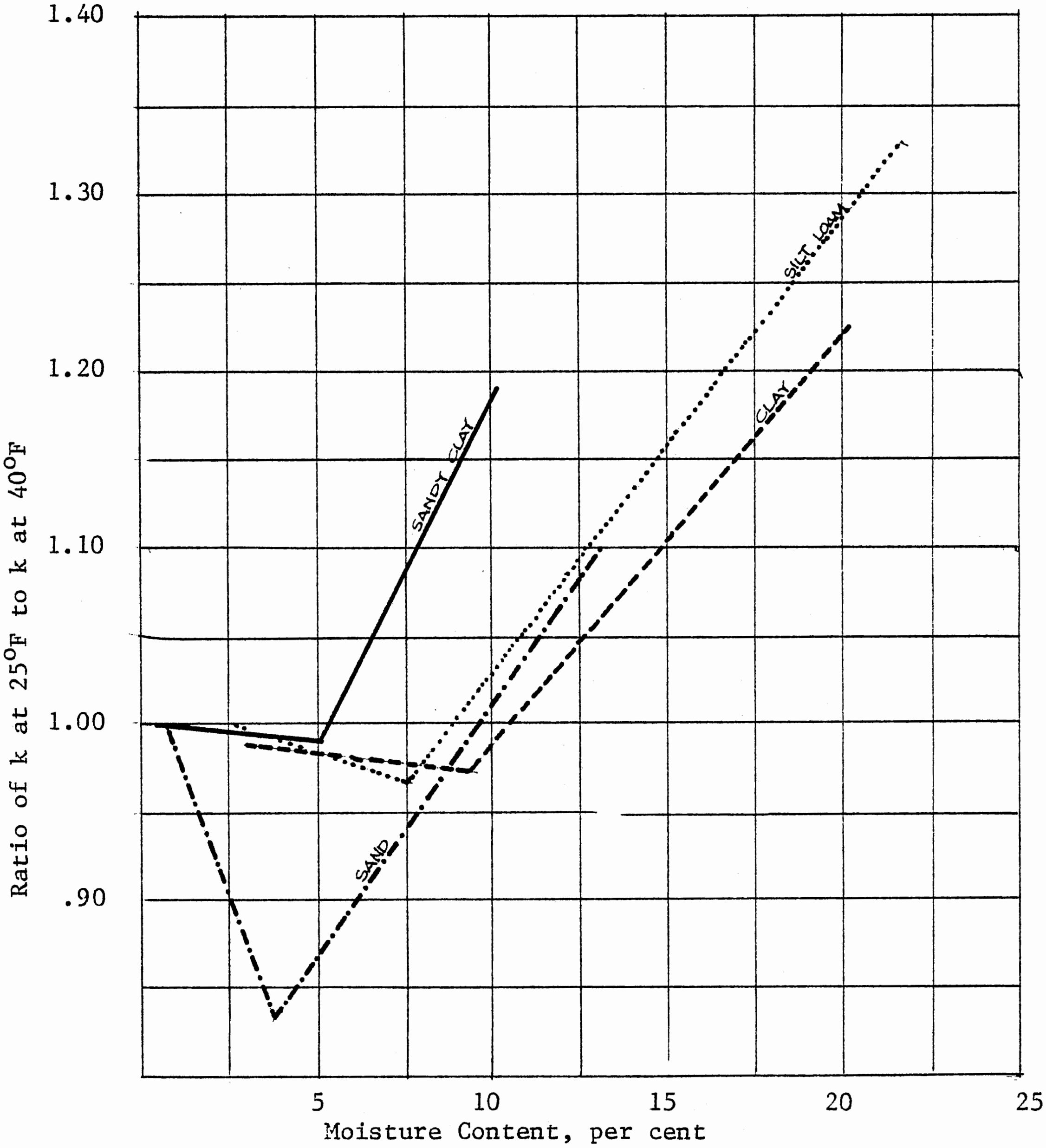


Figure 4. Conductivity Above and Below Freezing Temperatures (17, p. 44).

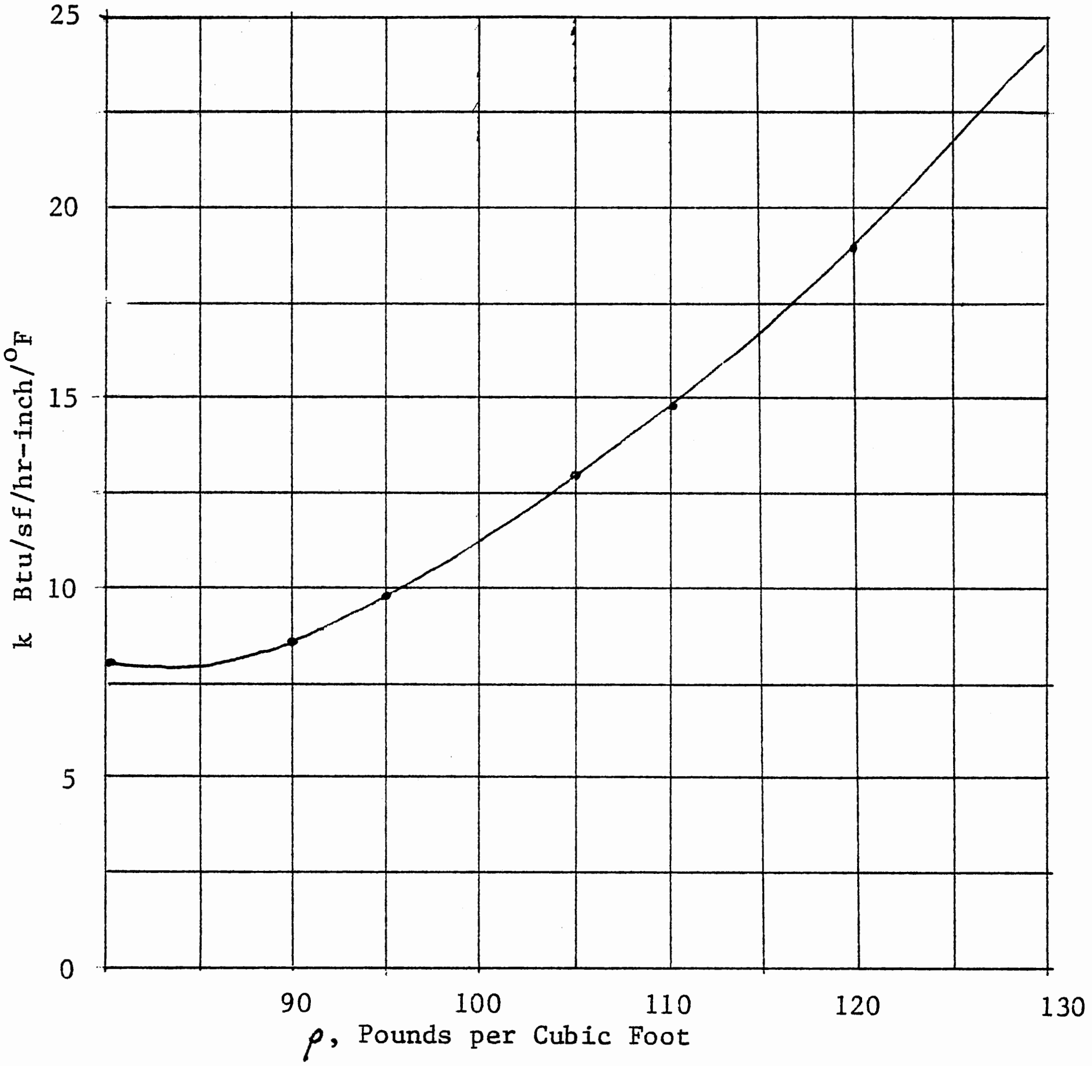


Figure 5. Conductivity versus Density (17, p. 44-57)

at a much more rapid rate. During extreme conditions of cold, each class of soil responds to freezing differently (31, p. 65). For the fine clayey soils common to the Stillwater area, shrinkage of the clay and the formation of lenses of ice are common when the soil is freezing. The opening of cracks in the soil due to migration of water to the freezing front could allow saturation of the soil, which would drastically reduce the thermal performance of the entire underground structure. For sands, water is squeezed away from the freezing front, resulting in drier soils.

The higher the cohesive (clay) content of the soil, the higher the thermal conductivity. The flake-like shape of the clay particles allows more rapid heat transfer than the rounded shape of the cohesionless (sand) particles. Thus, for a given moisture content, the thermal conductivity of a soil is inversely proportional to the liquid and plastic limits (9, p. 34). (The liquid limit is a measure of the soil's ability to deform under its own weight. The plastic limit is a measure of the workability of the soil and is a function of grain shape and organic content.) The flake-like shape of the clay particles tends to lower the plastic limit, while organic material found especially in the topsoil raises the plastic limit at a rate that results in a low plasticity index (the difference between liquid limit and plastic limit). Effects of the lower plasticity index are shown in Figures 6 and 7 (9, p. 36).

A method used to reduce the plasticity index of the soil, might be used to improve the thermal diffusivity of the soil. One method is lime stabilization of the soil, but its potential to limit plasticity is limited. An untested method with potential is the mixing of insulative materials such as perlite or vermiculite into lime modified soils.
A mix of insulative materials with a soil treated to reduce retention of

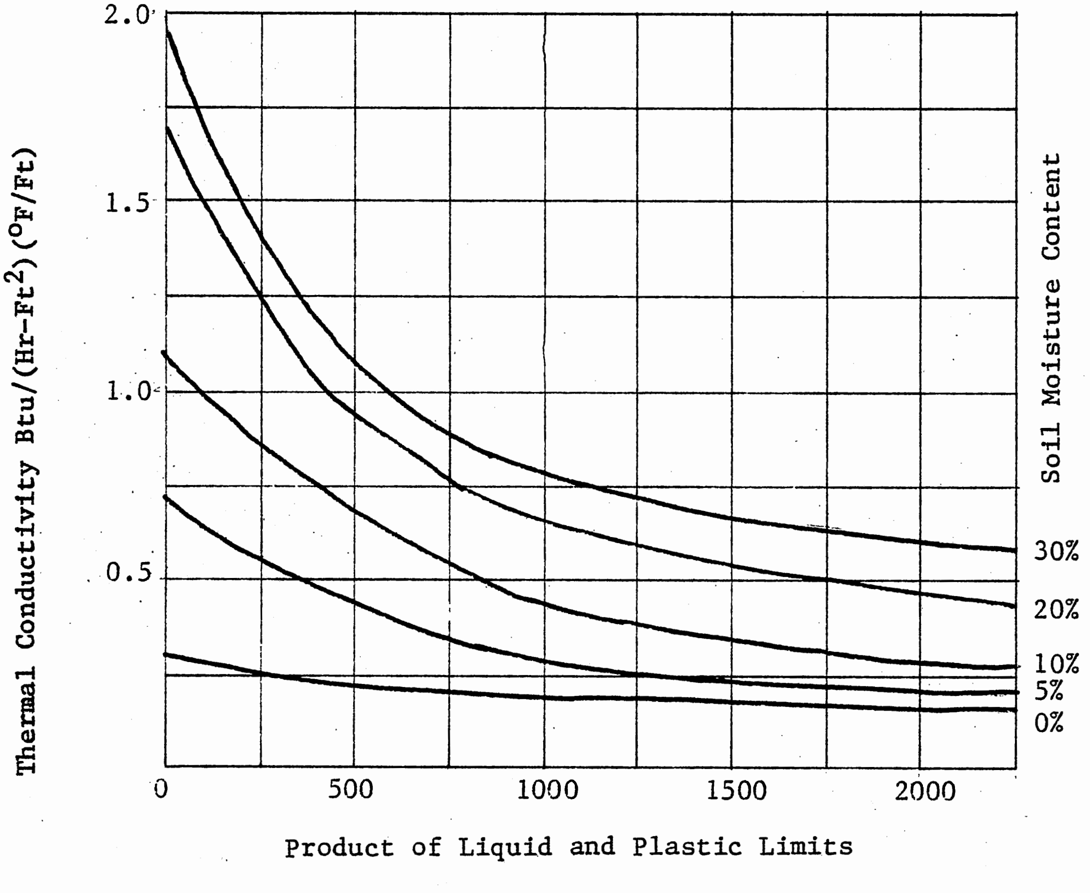


Figure 6. Product of Liquid and Plastic Limit versus Thermal Conductivity

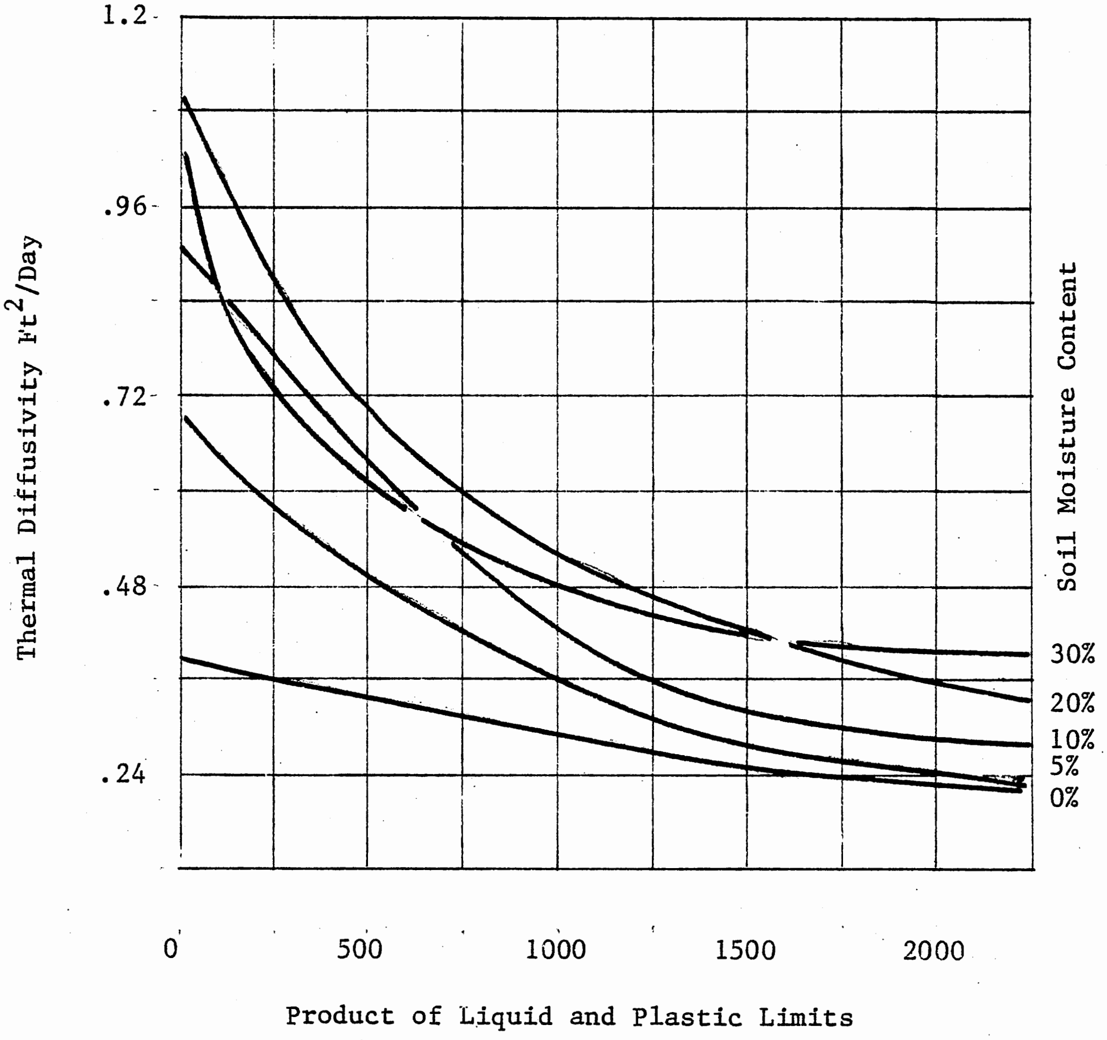


Figure 7. Product of Liquid and Plastic Limits versus Thermal Diffusivity

water could increase thermal lag by reducing the thermal diffusivity.

Fertility of the Topsoil

The fertility of the topsoil is closely related to the temperature of the soil. To a slight degree, the type of surface climate affects the soil temperature and thermal lag. Fertility is responsible in part for the heat valve effect. The heat valve effect is the selective admittance of above-ground heat into the soil through the variation of seasonal ground cover (12). The ground covers vary in length, lushness, transpiration of moisture and indirectly, will vary the depth of snow that is held in place by the retained vegetation. The effect is most pronounced when mean temperatures are at the freezing point and the variations in the thermal characteristics of the surface cover are occuring in phase with variation in the temperature across the ground cover. The heat valve effect can account for a variance in average steady state soil temperature from average air temperature from 2°F to 8°F depending upon the latitude. The higher the latitude, the greater the difference between the soil and average air temperature (21).

In soil temperature tests performed by Kusuda, surfaces of short grass, long grass, and bare earth were compared to black and white asphalt surfaces applied over bare earth. Compared to the bare earth, the effect of the long grass was to reduce average soil temperatures at all levels of the soil regime, and to reduce temperature during the summer, without effect upon the winter soil temperatures (18). The vegetation covered areas experienced annual temperature extremes significantly smaller (75°F to 30°F) than the black asphalt areas (91°F to 28°F). The effect of the asphalt covering was to raise soil temperatures at all depths during summer and at the lower depths during winter. The overall average temperature of the asphalt at steady state conditions was at least one degree Fahrenheit higher than for the short grass (26). The alteration of the soil temperature due to the effects of the asphalt is due to the control of soil moisture content and evaporation, the higher surface temperatures, and the extreme radiation from the "black body" surface of the asphalt.

Of particular importance for an underground house and especially for a deep earth underground house is that the average soil temperature and the extremes of soil temperature can be controlled by a soil covering. The ability of the asphalt surface to control moisture content, evaporative heat losses and outgoing radiation during non-sunny periods means that soil temperatures may be altered to benefit the underground house both in temperature and in thermal lag.

Structural Considerations

Economically, the structural costs usually produce the least visible benefit with the most expense. It is therefore important that the forces acting upon an underground house be reduced by using the minimum required soil cover and the soils that give the least lateral loading.

A great reduction in the overburden forces from the soil cover, and the lateral loads can be obtained by removing the ground water from the soil surrounding the underground house. This is best accomplished by the use of free-flowing soils, good drainage around the perimeter of the building, and site selection that allows for quick removal of surface water.

Fortunately, the use of cohesionless materials ensures that the hydrostatic forces are quickly eliminated. Additionally, the cohesionless materials do not have the shrink and swell capabilities that the highly plastic cohesive clays have when in the process of becoming wet. Sands, followed by silty-mud loams, heave and expand less upon freezing than do fine clays (31, p. 76). Although the depth of freeze will rarely exceed the twenty inch depth in Stillwater, (discounting the possible effects of an uninsulated opening through the soil) the use of cohesionless materials for backfill will reduce the moisture content of the soil and reduce the possibility or the effects of the freezing.

Kusuda (19) noted that single-dimension heat flow occurs when the soil area is significantly greater than depth. This implies that when different materials are to be used to backfill walls and to provide earth cover, the earth cover should extend beyond the walls by a length equal to the depth of the structure.

When using a mixture of vermiculite and concrete, Kersten noted that the concrete absorbed more moisture than standard mix concrete and the thermal conductivity was greater. Therefore, some means must be devised to control the moisture content and to protect the vermiculite soil mix from saturation. An impervious barrier (either artificial or impervious clay) could stabilize moisture content for a soil mix; however, the use of an impervious clay barrier would require adjustment in structural loads and depth of earth cover required for thermal performance.

Previous Research

Little research has been accomplished in the area of underground housing. Work in the area of prediction of soil temperature forms the most applicable research for the underground house. Collins determined that the soil at "deep earth" depth is stable and within two or three degrees Fahrenheit of the temperature of well water for much of the United States (20). This average steady-state soil temperature is the basis for establishing "deep earth" temperatures and is also useful in predicting soil temperatures at all depths.

Other early work in soil temperature prediction by Fluker established the basic harmonic equation describing the variation of soil temperature with depth, thermal diffusivity and time (10). However, the equation is limited in its assumption that the earth is a homogeneous material with uniform diffusivity and that ambient average air temperature varies with time. Additionally, the harmonic equation does not directly account for temperature level, micro climate, soil topping, and disturbed earth. Therefore, the general harmonic equation for predicting soil temperatures cannot be used for the estimation of a soil temperature on a specific date or location, but it can be used to predict average temperatures for a specific depth and period of time and to estimate average annual temperatures to which an underground house is exposed.

Plots for Stillwater, Oklahoma, based upon the harmonic equation for temperature variation with respect to depth, thermal diffusivity, time, and average temperature are shown in Figures 8 through 11. Calculation procedures are given in Appendix A.

Conclusions

The selection of backfill materials for the underground house is a significant economic decision. The optimum solution will be the selection of the cohesionless soil with the smallest coefficient of thermal dif-

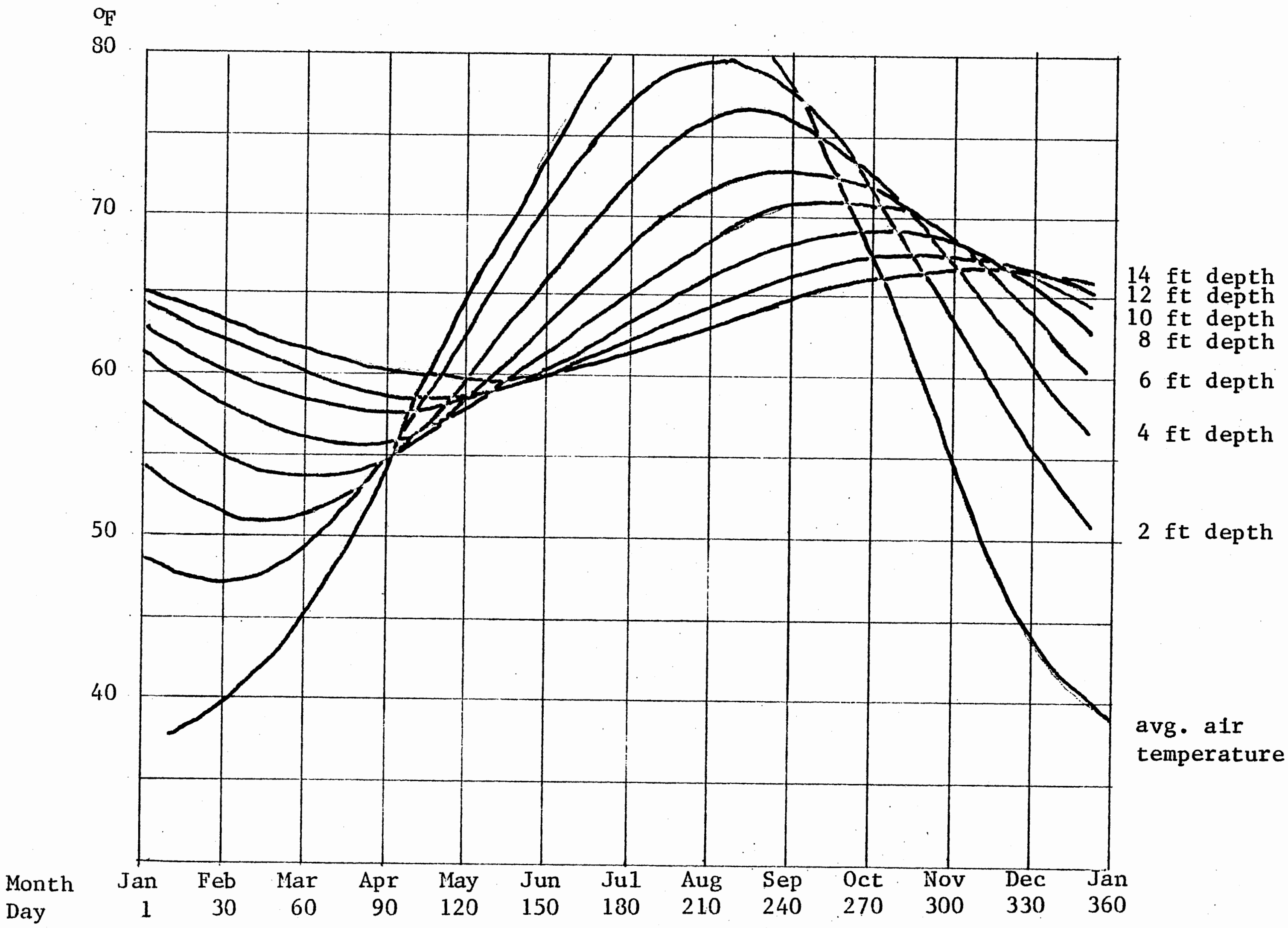


Figure 8. Undisturbed Soil Temperature for c = .50 ft^2/day

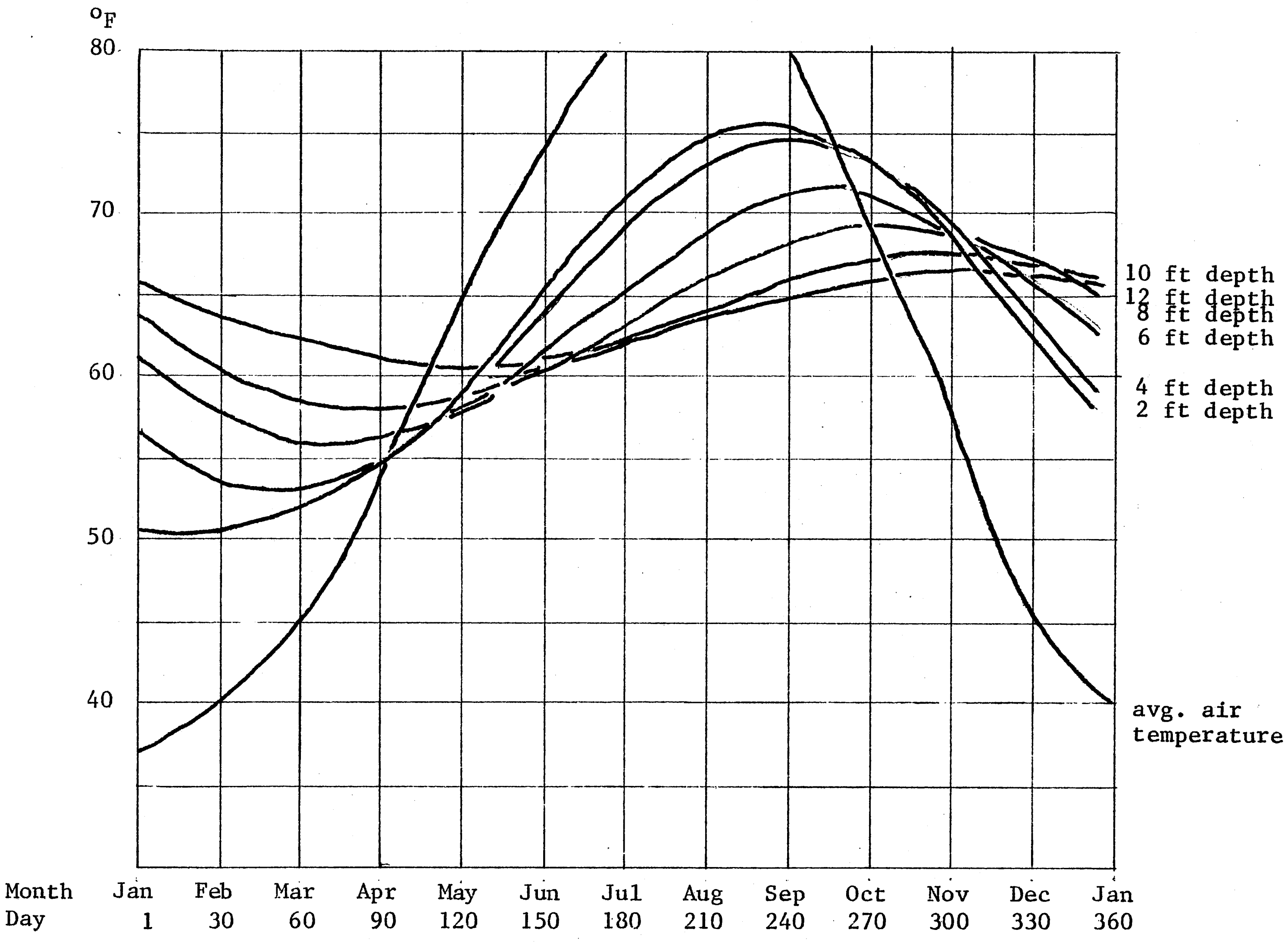


Figure 9. Undisturbed Soil Temperature for c = .30 ft^2/day

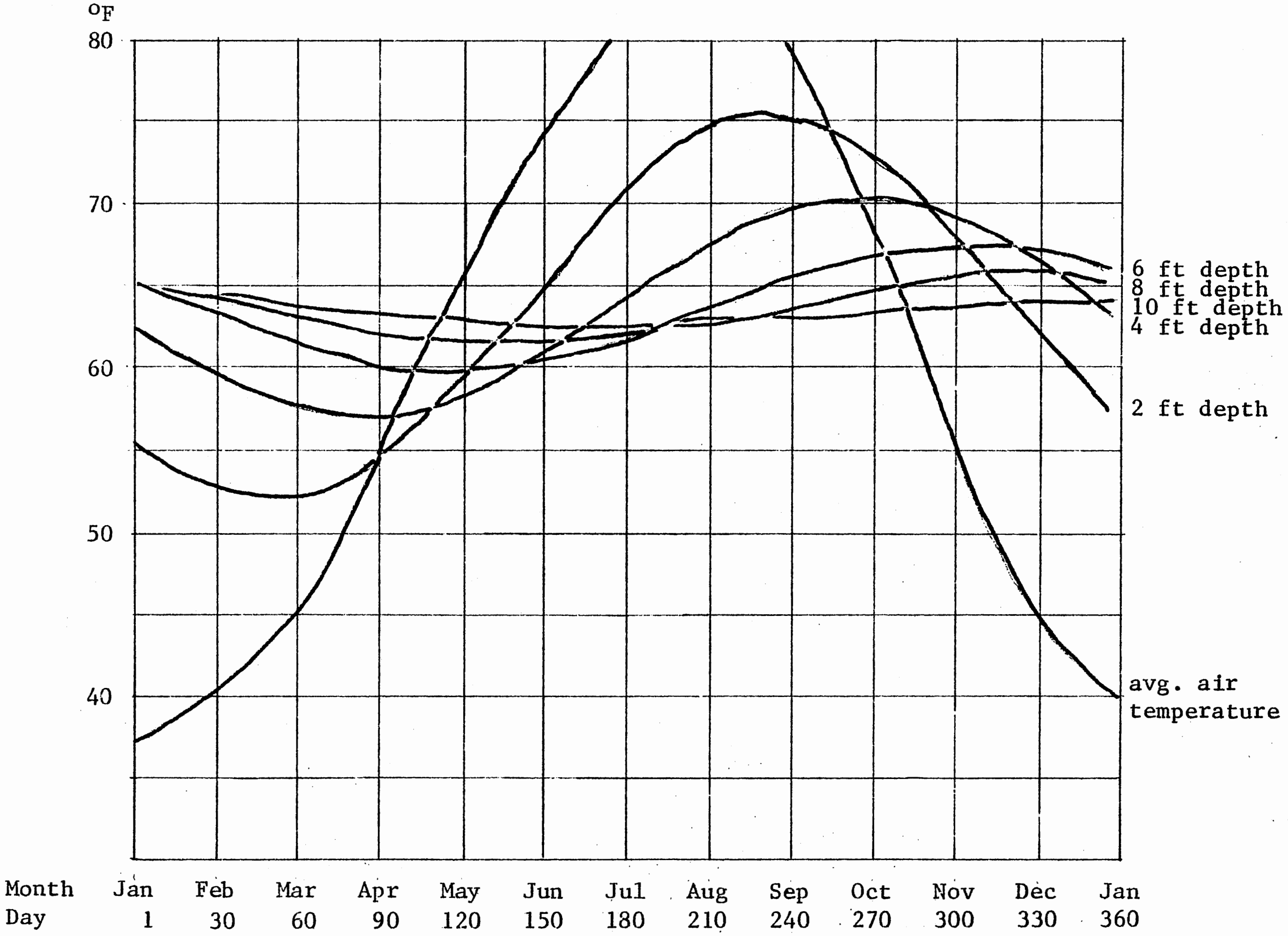


Figure 10. Undisturbed Soil Temperature for c = .10 ft^2/day

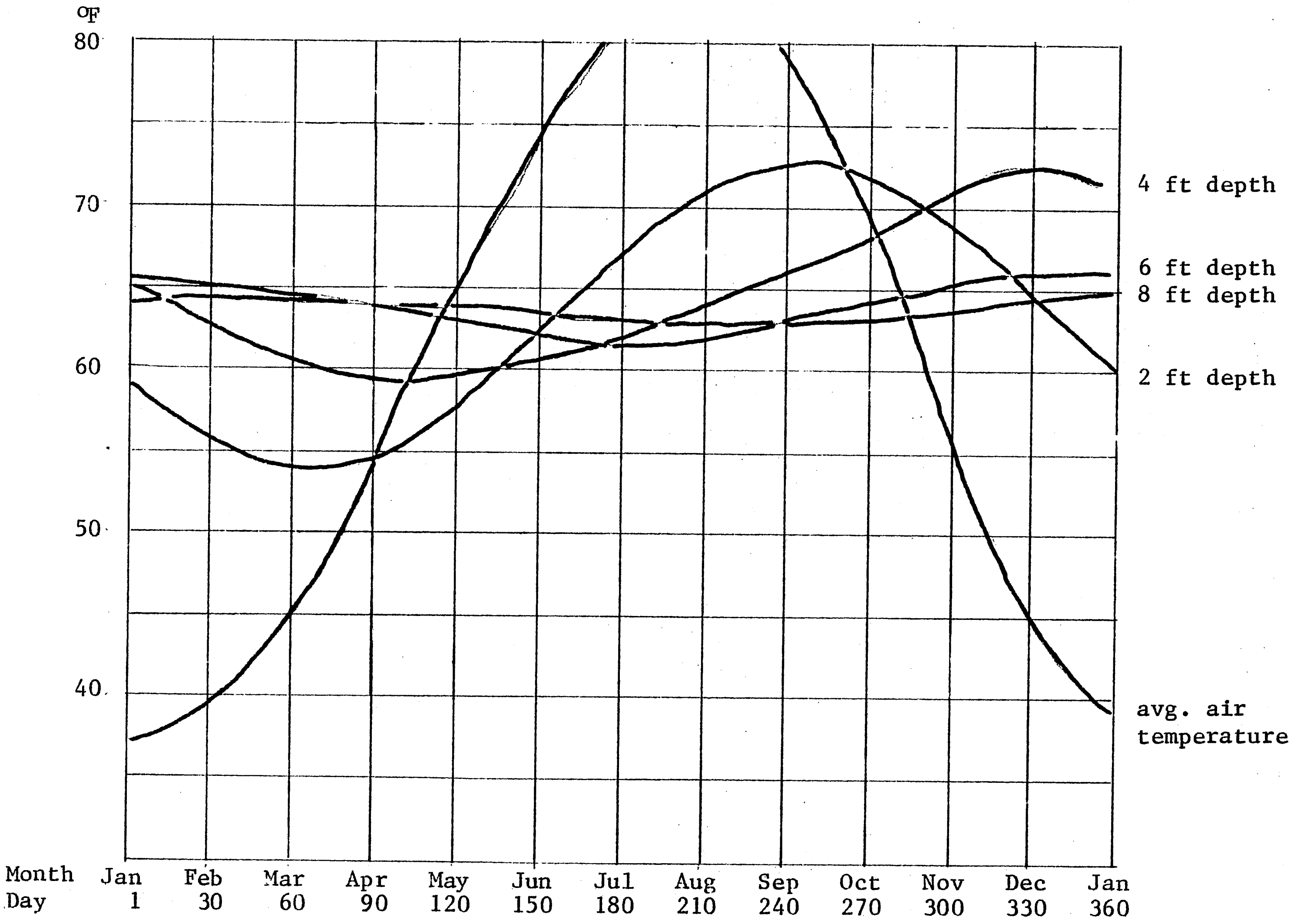


Figure 11. Undisturbed Soil Temperature for c = .05 ft^2/day

fusivity. Normal light, dry sand provides the best performance with the lowest total weight; however, the most typical solution will be to backfill walls with sand to reduce wall loads and use the maximum amount of vermiculite mixed into a low plasticity clay. The amount of vermiculite will be limited only by the amount of topsoil required to promote plant growth.

Heat Transfer

The placement of a structure below the earth attempts to use the soil either as insulation, as a means of heat storage, or as a heat source, through thermal lag effects. In any of the three modes, the underground structure is exposed to different cycles of heat transfer than a conventional above-grade structure.

Basic Heat Transfer Processes to the Underground House

The three heat transfer modes of conduction, convection and radiation are responsible for conditioning the underground house. The proportion of each heat transfer mode is dependent upon the ground cover, depth of soil and other site factors, and varies with seasons and with climate.

The majority of the underground heat transfer occurs by conduction. Conduction is the exchange of heat through a material. Conduction occurs between ground surface and the air, between the soil particles (for dry soils) and between the soil and the wall. Especially for dry soils, heat transfer by conduction is extremely slow and is responsible in part for the lag between surface temperature and the temperature at greater depth (26, p. 36).

Convection is heat transfer accomplished by the motion of a fluid from a location where heat is received to a location where the heat is given up. Convection occurs primarily at the ground surface in the process of heat transfer from or to the air. Convection also occurs in soils containing water and allows heat transfer at a much faster rate than would be expected of typical dry soil conduction.

At the surface, convection is responsible for thermal lag in the heat transfer through the surface topping. A change in air speed at the ground surface; either air speed reduction by grass or rough surface toppings, or by air speed increase by paving or mowing to an extremely short height, will alter the rate at which heat is transferred to or from the soil. The convective lag is additive to the conductive thermal lag of the soil.

Surface heat transmission

At the surface, there are four types of heat transmission; radiation, transmission via changes in water states, convection and conduction. In the heating and cooling process that the surface undergoes daily, the following is a typical cycle. Some time before sunset, radiation begins to flow outward to the much cooler sky, cooling the surface and the air adjacent to the surface. At night, the condensation of dew (change in the state of the water) transmits heat to the surface. Conduction causes the midday ambient air temperature and solar radiation to move downwards into the earth layers, and heat from the ground is transferred to the adjacent air molecules, creating a boundary layer.

Radiation

It is estimated that of the extraterrestial radiation, only 58% reached the ground surface (11, p. 2). The air and soil layers at the surface attain high temperatures and create a discontinuity between the ambient air temperature four inches above the surface and the soil temperature four inches below the surface.

The radiation exchange and its effect upon soil temperature is also influenced by the loss of radiation due to nighttime reradiation. By the Stefan-Boltzmann law of radiation, the nighttime radiation loss intensity is proportional to the fourth power of the absolute tmperature of the earth's surface. Since by the Wien displacement law, the product of the absolute temperature of the earth's surface and the wavelength of the most intense radiation is a constant, the higher the earth surface temperature, the shorter the wavelength of radiation (and the higher the energy) that is reradiated. The maximum intensity of night radiation from the earth is in the long wavelength (10 microns) or infrared portion of the spectrum and can be calculated as follows (11, p. 13)

$$S' = 8.26 \times 10^{-11}(t^{\circ}C + 273)^{4} \qquad (6)$$

The reradiation intensity "S′" in calories per square centimeter per minute is modified by the noctornal temperature drop (decreased by seven per cent) and by the counter-radiation of the atmosphere. From work by Angstrom and others, the outgoing radiation "R′" on clear nights is described by the equation (11, p. 32)

$$R' = 8.26 \times 10^{-11}(t^{\circ}C + 273)^{4}(0.23 + 0.28 \times 10^{-0.074p}) \qquad (7)$$

Here, "p" represents the vapor pressure in millimeters of mercury at the ground surface and for cloudy nights, the outgoing radiation "R'_w" is calculated by:

$$R'_w = R\,(1-\bar{k}) \tag{8}$$

where "$\bar{k}$" is the ratio between outgoing radiation on clear and cloudy nights. Since "$\bar{k}$" is proportional to cloud cover height, values of "$\bar{k}$" are given in Table IV.

TABLE IV

OUTGOING RADIATION COEFFICIENTS

Cloud cover ceiling height	1.1mi	1.5mi	2.2mi	3.8mi	6mi
value of $\bar{k}$=	.87	.83	.74	.62	.45

The outgoing nocturnal radiation accounts for the nighttime freezing of the surface when ambient air temperatures are above 32°F and there is little air movement. However, the surface climate created by outgoing radiation is greatly affected by shading. Trees and shrubs, as well as artificial shading devices, provide protection from freezing when nocturnal outgoing radiation is the prime determinant of temperature. The protection from nocturnal outgoing radiation results because the heat from the soil radiates to the underside of the shading device and the slight difference in tree temperature and soil surface temperature allows little reradiation.

Heat Transmission via Water States

Heat is transmitted into the soil by precipitation and from the soil by evaporation. Although the energy transfer is readily estimated for precipitation based upon the quantity and temperature of the precipitation, heat exchange due to evaporation is not as easily determined.

Evaporation during the daytime is governed by the temperature of the surface, while at night, the evaporation rate is controlled by the vapor pressure of the air; however, the vapor pressure at the surface is a function of the soil topping and the soil (11, p. 178). Bartles found that when sod covered soil is compared to a sand covered surface, the sod covered soil evaporates 28% more water yearly. Table V shows the rates of evaporation when compared to open water.

TABLE V

DAILY SURFACE EVAPORATION

Condition	Sand Surface	Sod Surface	Water Surface
Following Rain	2.38 mm	2.80 mm	2.24 mm
On clear days	.47 mm	2.15 mm	3.61 mm
On dry days	.26 mm	1.14 mm	3.80 mm

The rapid evaporation from the sod surface will allow the moisture content of the soil below to be less than for a sand surface, all other factors equal. This increased evaporation is due partially to the growth of ground cover. The sod covered surface is consequently lower in temperature than a sand surface, because of the shading from the ground cover and because of an evaporation rate that is 39% higher than a sand surface (11, p. 188).

The importance of evaporation is emphasized by the fact that one gram of evaporated water removes 600 gram calories of heat from the soil (depending upon water temperature). The heat loss due to evaporation only becomes negligible when snow entirely covers the area.

Convection

Heat transmitted by convection is transferred through the movement of the air above grade and through the movement of free water in the soil. Unless there is strong movement of the wind and a thin soil topping, the surface climate is affected little by the convective losses from the soil and the soil is hardly influenced by the convective effects from the surface. However, when a thick soil topping slows air movement, the result is a reduction of solar insolation and a reinforcement of the cyclical effects of conduction within the earth.

Conduction

Conduction is the prime method of heat transmission within the earth. For layers of uniform material, which soil may be assumed to be, the general equation describing the undisturbed soil temperature "T" at depth "x" and time "t" is as follows (21)

$$T_{(x,t)} = T_m + A_s e^{-k'x} \sin(wt - k'x - \phi) \qquad (9)$$

Heat Transfer to the Underground House

The heat transfer from the soil to the interior of the underground house comprises the majority of the load for space conditioning. However, there is heat exchange that is carried by ambient air temperature difference and includes infiltration, ventilation for both cooking and exhaust and cooling ventilation.

Infiltration Heat Gain

Infiltration heat gain is assumed equal to extremely tight construction values of .2 air changes per hour which in the base house results in 33.54 cubic feet per minute for an hourly design heat loss or gain of 35 Btuh/^{O}F, which is negligible compared to the other building heat gains and losses.

Exhaust and Minimum Ventilation Gains

The minimum ventilation rate for four adult occupants is 1.68 cubic feet per minute, therefore, the 33.54 cubic feet per minute infiltration load is more than sufficient for basic ventilation requirements (32, p. 80). An additional two air changes per day are required to remove kitchen odors, and exhause fans above cooking areas and in the baths are required for humidity removal. Assuming a 16 minute cooking time and a 150 cubic feet per minute exhaust hood rate, the cooking exhaust will provide more ventilation than the minimum (15, p. 22). Therefore, it is beneficial to use activated charcoal filters for odor control in the kitchen.

Cooling by Ventilation

Ventilation winds occur as a result of pressure differences resulting from wind movement and suction, inertia, and differences in temperature. Alteration of structure temperature is accomplished by maximum air flow and is described by the equation for air flow "Q" in cubic feet per minute (25, p. 104)

$$Q = KAV \tag{10}$$

Area "A" of inlet and outlet is measured in square feet, while wind velocity "V" is measured in feet per minute. "K" is an adjustment factor based upon the ratio of outlet and inlet.

The heat flow transfer resulting from the air flow is then eight per cent greater than the product of "Q" and the inside and outside temperature differential.

Since structural cooling or heating is seldom a problem with an underground house, of prime importance to the underground house is human thermal comfort. Extending the limits of human thermal comfort by ventilating is achieved by winds of up to 700 feet per minute that enter the living space at low levels and pass across the individual. The upper limit of cooling ventilative effects is to raise the limit of summer dry bulb temperature from a maximum 81°F to 90°F dry bulb for relative humidities below 50%.

Energy Balance and Human Thermal Comfort

Providing equivalent human thermal comfort is the common denominator and minimum standard for comparing the types of underground houses. Although there are numerous indices that model and predict human thermal comfort, the Bio-Climatic Chart shall be used to describe the interacting forces of human heat gain, radiation effect, air movement, vapor pressure, evaporation and dry bulb temperature that influence human comfort conditions (22, p. 2). Figure 12 shows the effect of various influences upon the Bio-Climatic Chart comfort zone (25, p. 22).

Heat Gain Produced by Human Activity

In the home, minimum activity (basal metabolism and simple processes such as digestion) is the major source of body heat released to the space. For minimum levels of activity, approximately 290 Btuh sensible heat and 250 Btuh latent heat is produced per individual.

Absorptive Gain of Radiant Energy

Primary sources of radiant energy will be from the surfaces heated by passive solar radiation. The amount of radiant energy is dependent upon the particular passive application. The principal source of non-solar radiation is the lighting load.

Heat Conduction Toward the Body

Primarily, conductive heat gain occurs during those periods in summer when cooling ventilation using outside air at ambient temperatures is required. Conductive heat losses from the body occur when the body comes in contact with the perimeter.

Condensation of Atmospheric Moisture

Condensation is a potential problem because the cooler walls of the underground house may be at a temperature below the dew point of the air

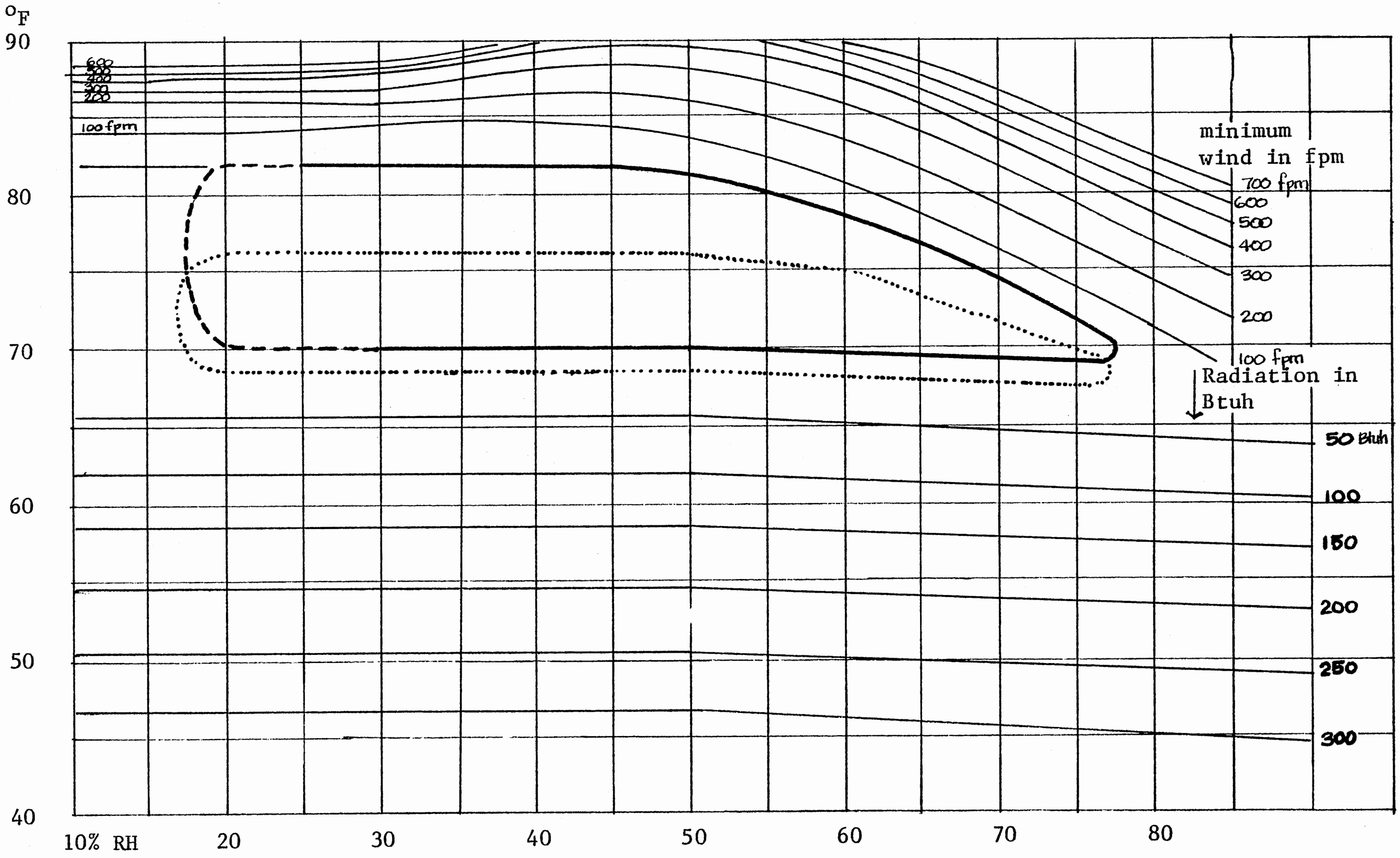


Figure 12. Bio-Climatic Chart

introduced for ventilation.

Outward Radiative Losses

The exchange of heat between the human body and the cooler walls is influenced by Mean Radiant Temperature (MRT). In practice, a maximum temperature difference of five degrees Fahrenheit can exist between ambient air temperature and the walls. Outward radiative losses also occur from the underground house through glazed areas to the low temperature sky.

Heat Conduction Away from the Body

Cooling and ventilating winds and contact with exterior perimeter surfaces are the principal sources of conductive heat loss from the body.

Evaporative Losses

Respiration and sweating losses from the skin are the primary evaporative heat losses. The balance of heat gains and losses is dependent upon the interrelationship of the body and the climatic elements (thermal factors) of radiant and air temperature, relative humidity and air velocity. The balance of these thermal factors achieve the condition of thermal comfort.

Conclusion

Any underground house can have much more of a response to its environment than a comparable above-grade house. The underground mechanism of climate in the forms of macro climate, micro climate, and surface climate all play a more important role in the amount of energy that is saved, the performance of the house and the overall quality of the environment that the underground house experiences.

The soil obviously serves more functions for the underground house than it does for an above-grade house, but the soil is more important as a surrounding medium than the surrounding air medium is for an above-grade structure. The soil as a medium is important not only for its moderating influence on heat transfer, but also for its ability to alter the delivery of heat to the underground house. As a result of interaction of climate and soil, the heat transfer process is just as important to the underground house, although the effects of heat transfer are not realized as quickly as in the above-grade house.

Probably because the underground house is unproved, because it is new and different from the norm, it is not enough that potential owners take financial risks beyond those of an above-grade house in the hopes of substantial energy savings. The underground house must meet levels of comfort comparable with above-grade houses.

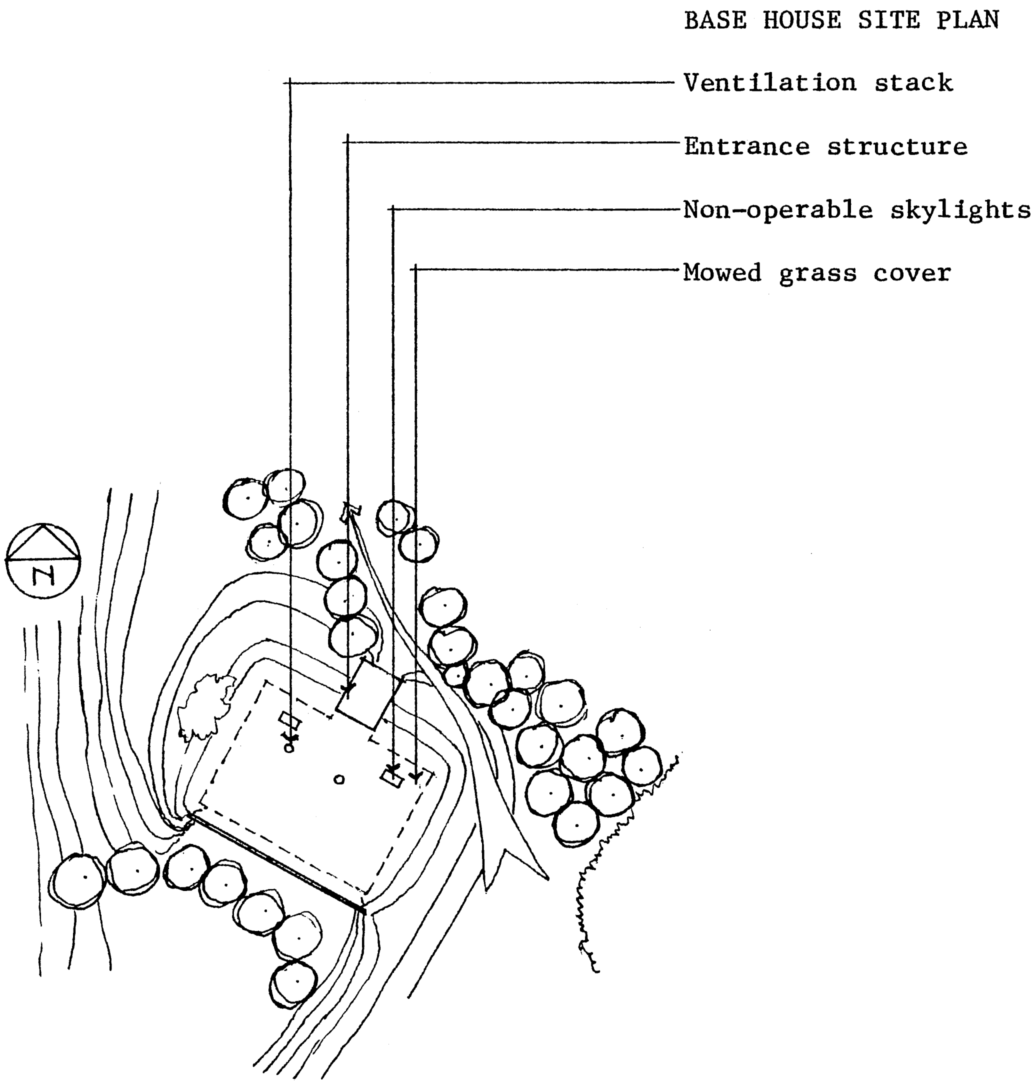
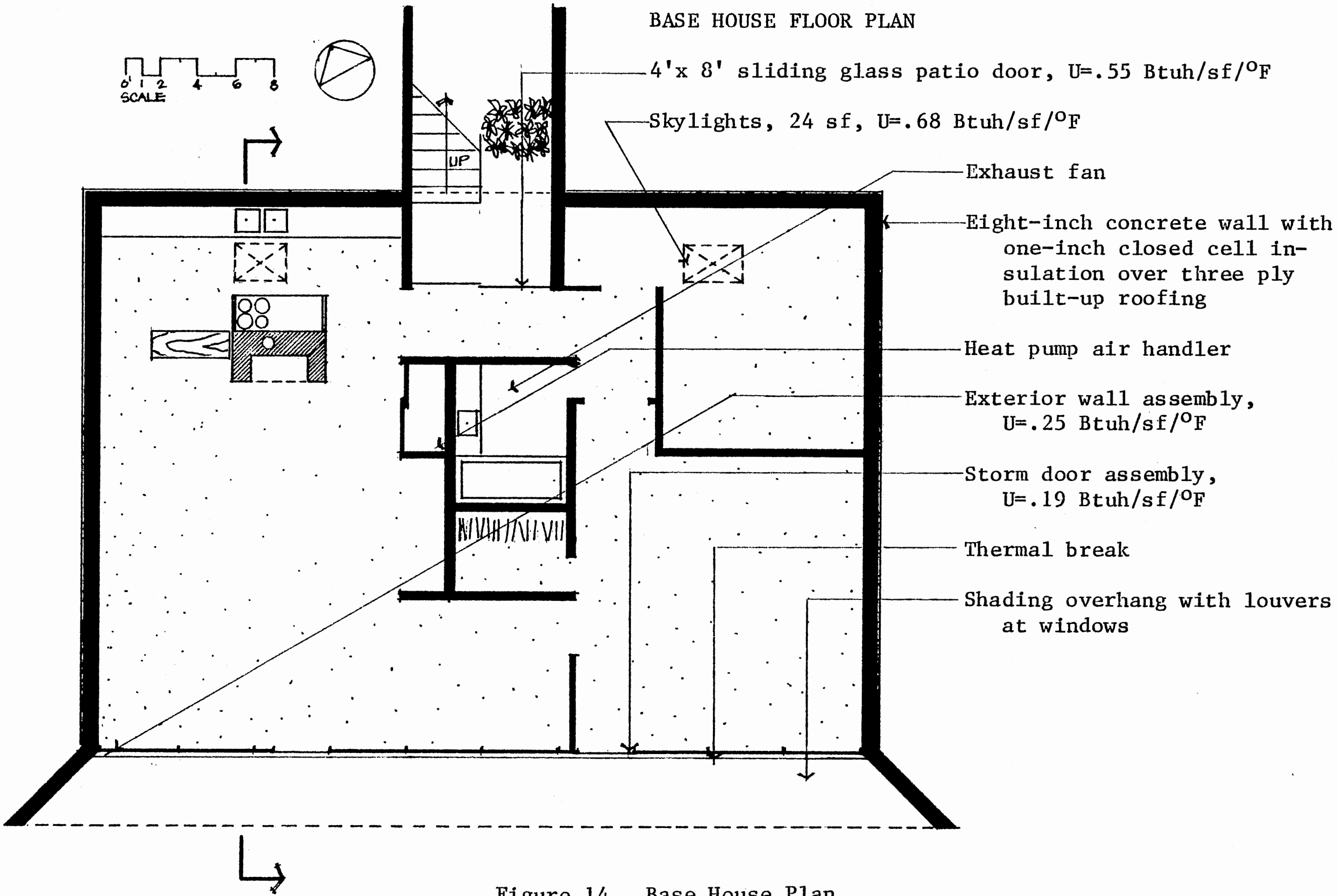


Figure 13. Base House Site Plan



BASE HOUSE FLOOR PLAN

4'x 8' sliding glass patio door, U=.55 Btuh/sf/^{O}F

Skylights, 24 sf, U=.68 Btuh/sf/^{O}F

Exhaust fan

Eight-inch concrete wall with one-inch closed cell insulation over three ply built-up roofing

Heat pump air handler

Exterior wall assembly, U=.25 Btuh/sf/^{O}F

Storm door assembly, U=.19 Btuh/sf/^{O}F

Thermal break

Shading overhang with louvers at windows

Figure 14. Base House Plan

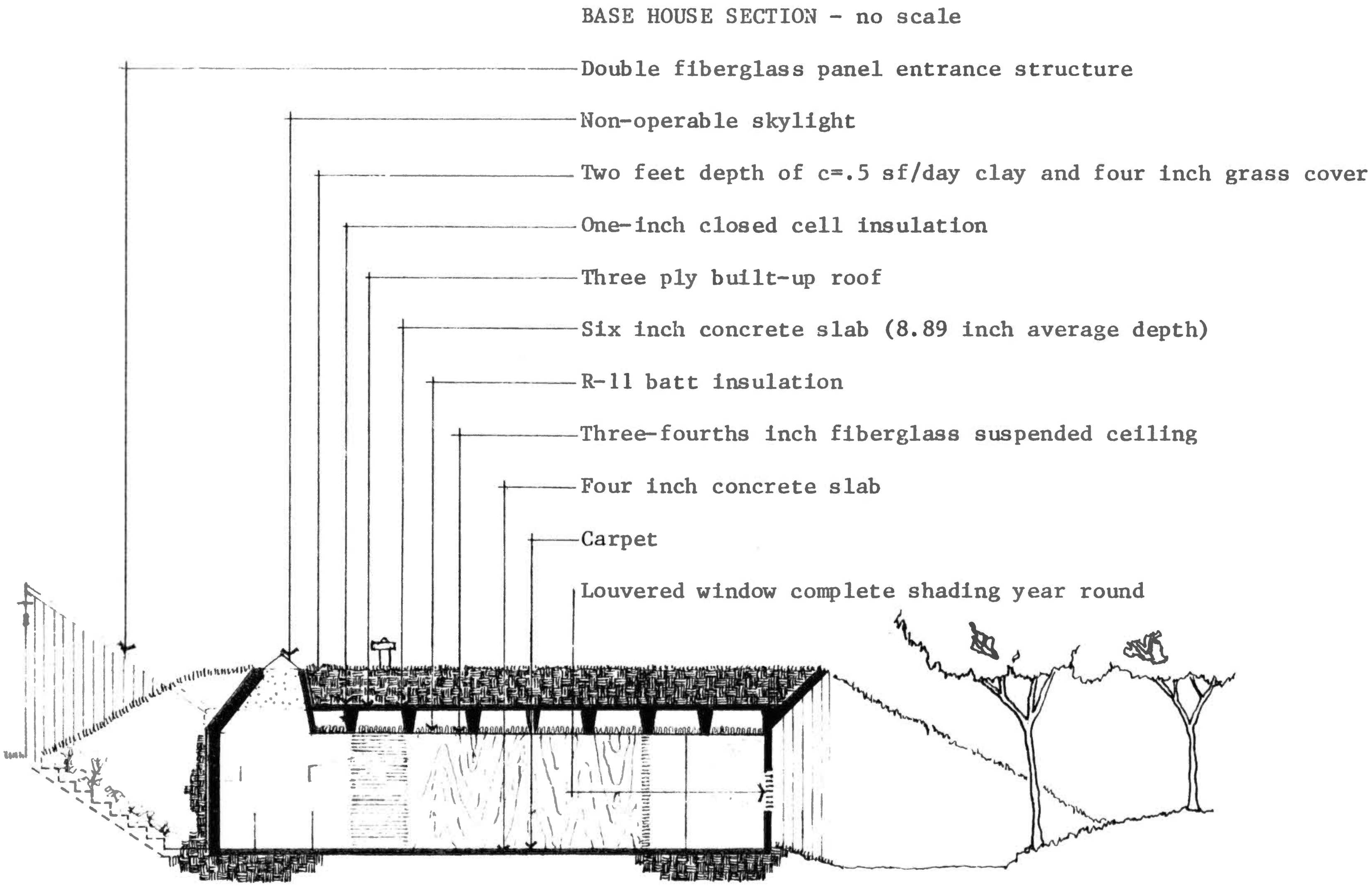


Figure 15. Base House Section

CHAPTER III

THE "BASE" HOUSE

Introduction

The "Base" house is the composite of the most typical features of underground houses currently being constructed in Oklahoma. By identifying and applying typical underground housing features and then calculating heating and cooling loads based upon equivalent human comfort requirements, the "base" house serves as a reference for economic comparison with passive underground housing alternatives.

The typicality of the "base" house components was determined from preliminary data gathered by Oklahoma State University Architectural Extension and represents recently completed and under construction (up to 1979) underground housing systems and components (27). The "base" house components were usually selected without benefit of architectural or engineering advice and in most cases are not optimum systems for energy savings.

General Statement of the "Base" House

The "base" house is not patterned after a single house but is a composite based upon typical underground construction features applied to a specific climate and orientation. Based upon preliminary data, the following features are typical in underground houses constructed in

Oklahoma.

Location

Underground locations are widely distributed across the state. Most underground houses are constructed on small acreages and farm sites. Adequate room therefore for any underground structure is available and any passive solar devices would not typically be shielded. The acreage site also implies that the sanitary sewer is probably a septic tank and drain field system, which might alter soil water content and soil thermal properties. Since soil types range from clayey silts and clays to mixes of clays and sands, the alteration of soil water content also means that soil thermal and structural properties must be considered.

Depth of Earth Cover

Depth of earth cover is typically, and on the average, 24 inches, although depths range from zero to 44 inches, with depths of 12, 24, and 36 inches being most common. Depth of earth cover determines the amplitude of variation in soil temperatures and the types of ground cover that can grow in the earth cover.

Construction

The typical construction system is reinforced, poured concrete walls and roof structure. Presumably, the poured concrete systems were chosen for waterproofing reasons.

Plan and Section

The plan of the "typical" Oklahoma underground house is only more compact than the plan of an above-grade structure primarily because of the structural costs. Plan considerations include economy of construction and excavation but functions are arranged without regard to the use of soil temperature for heating or cooling (i.e. living areas are not arranged around the perimeter of the underground structure).

The typical plan size of 2000 square feet with minimum external wall area lends itself well to the reduction of heat losses during the winter. But the compact plan does not benefit from heat loss to the surrounding soil during the summer.

The typical section is well suited for space conditioning by radiant effects. The typical section is eight to nine feet floor-to-ceiling height with relatively short spans between walls. The typical design is of a conventional above-grade type. Plans are usually identical to above-grade structures with skylights used in the underground house in lieu of windows when perimeter walls are covered with soil. Seldom is regard given to utilization of earth-covered walls for natural heating and cooling from earth temperatures. As a result, planning is for compactness and emphasis is upon insulation rather than upon the use of conductive materials for the exterior surfaces.

Insulation

Typically, the insulation of the underground structure varies from nominal to above-grade housing strandards, with interior and exterior applications. Insulation is used to reduce the heat transfer through the ceiling and the walls, therefore insulated suspended ceilings and furred walls are common. The design of the "base" house emphasizes reducing heating costs (despite the fact that air conditioning costs often are higher than the heating costs).

Mechanical Systems

The heating, ventilating and air conditioning system is typically a conventional system consisting of a package air conditioner and a gas-fired furnace. Heat pump installation is increasing with publicity and is popular in underground housing because of the safety, compactness and high efficiency of the package system.

Background and Specific Objectives

The specific economic objectives behind the construction of an underground house in Oklahoma were primarily low maintenance, protection from storms, security, and energy savings.

The underground house provides lower maintenance costs than conventional above-grade houses because of the relatively stable earth conditions and the absence of much of the extremes of temperature, humidity, solar radiation and winds. Also, the exterior coatings (waterproofing and insulation) are rarely, if ever disturbed and therefore seldom require replacement or servicing.

The primary reason for constructing an underground house however, remains the objective of reducing heating and cooling costs by using the thermal lag of the earth cover to smooth above-grade temperature peaks. Heating and cooling costs in houses with relatively shallow earth covers are reduced by providing a temperature differential in both winter and summer that is less than for above-grade conditions. Since heating and cooling equipment size and energy costs are dependent in part upon the maximum (or design) temperature differential, the lower temperature differentials found in an underground house reduce energy costs, reduce the need for large design safety factors and often reduce equipment size for a given area and insulative value.

The method of saving space conditioning energy costs by using the thermal lag of the two feet (shallow depth) of clay cover is not a maximizing technique from an energy standpoint or often from an overall economic standpoint. Calculated soil temperatures based upon shallow depth of earth cover are shown for undisturbed soil temperatures in Figures 8 through 11.

Technical Aspects

There are technical aspects to underground housing that must be solved, such as waterproofing, structure, sewage, insulation, and other aspects not encountered in above-grade housing. However, for the purpose of comparing only the thermal performance of underground building types on an economic basis, technical aspects that do not affect energy consumption are assumed to be solved in the most economical way that is consistent with the design. Of the technical aspects that deal with energy consumption, the most important energy calculations are the determination of heat loss and gain with the earth and the computation of cooling and heating costs. Both energy calculations are detailed in Appendix B.

Conclusion

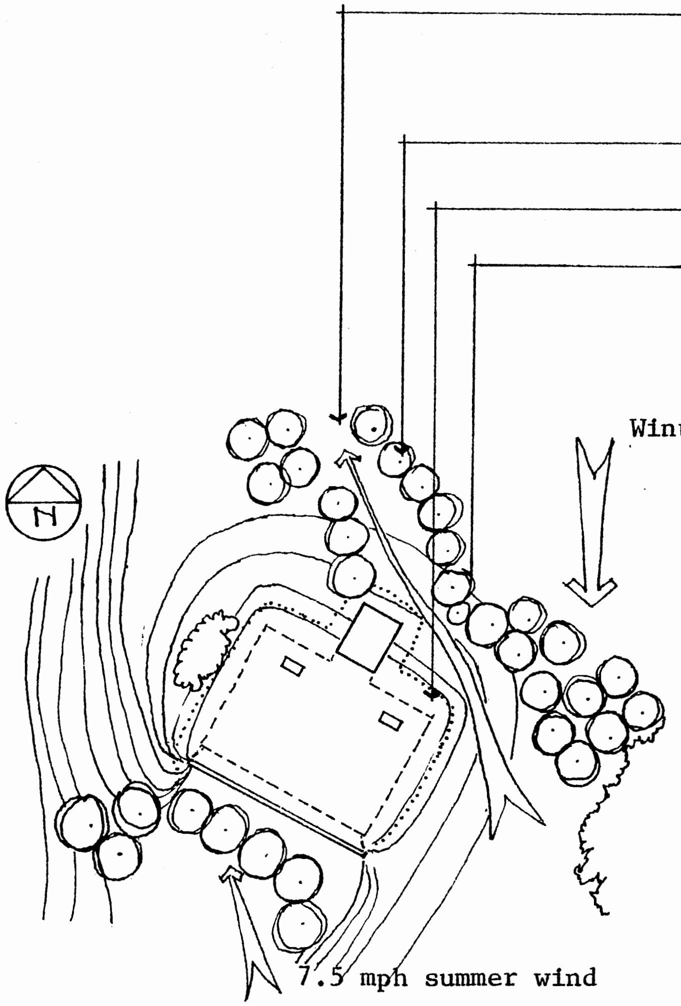
Actually, few technical aspects of underground houses have been specifically researched. There are many aspects that have no available performance data. For example, the effect of structure within the soil upon undisturbed soil temperatures and the ability of the soil to recharge its heat transmission ability are both critical information, the lack of which limits the design of underground housing to the use of soil as a moderating and low temperature differential medium rather than as a source of free heating and cooling.

Additionally, no research has been done to determine when heating and cooling is required in the underground house. Appendix B shows a method of computing heating and cooling costs based upon a "degree day" system of describing soil conditions.

The cooling costs are based upon an undisturbed soil temperature boundary and upon a predicted number of hours where cooling will be required. The prediction of the number of cooling hours is the converse of a heating degree day; however, actual testing is required to determine the base temperature.

An area where assumptions were made that could prove to be a source of error is in the selection of typical features rather than an actual house. Also, to provide a basis for reference, assumptions were made that may not represent the typical practice. For instance, insulative standards meeting ASHRAE 90-75 are probably not typical of most underground houses, and many do not have heat pump space conditioning. Finally, the selection of the underground house perhaps should be based on other than energy considerations. The features of safety from wind, vandalism, and probably the novelty of the underground house may be overriding selection criteria.

PASSIVE HOUSE SITE PLAN



Negative pressure area due to summer winds, convection due to heated translucent fiberglass panels and difference in height between intake and exhaust openings.

Plantings to create high pressure area during summer months

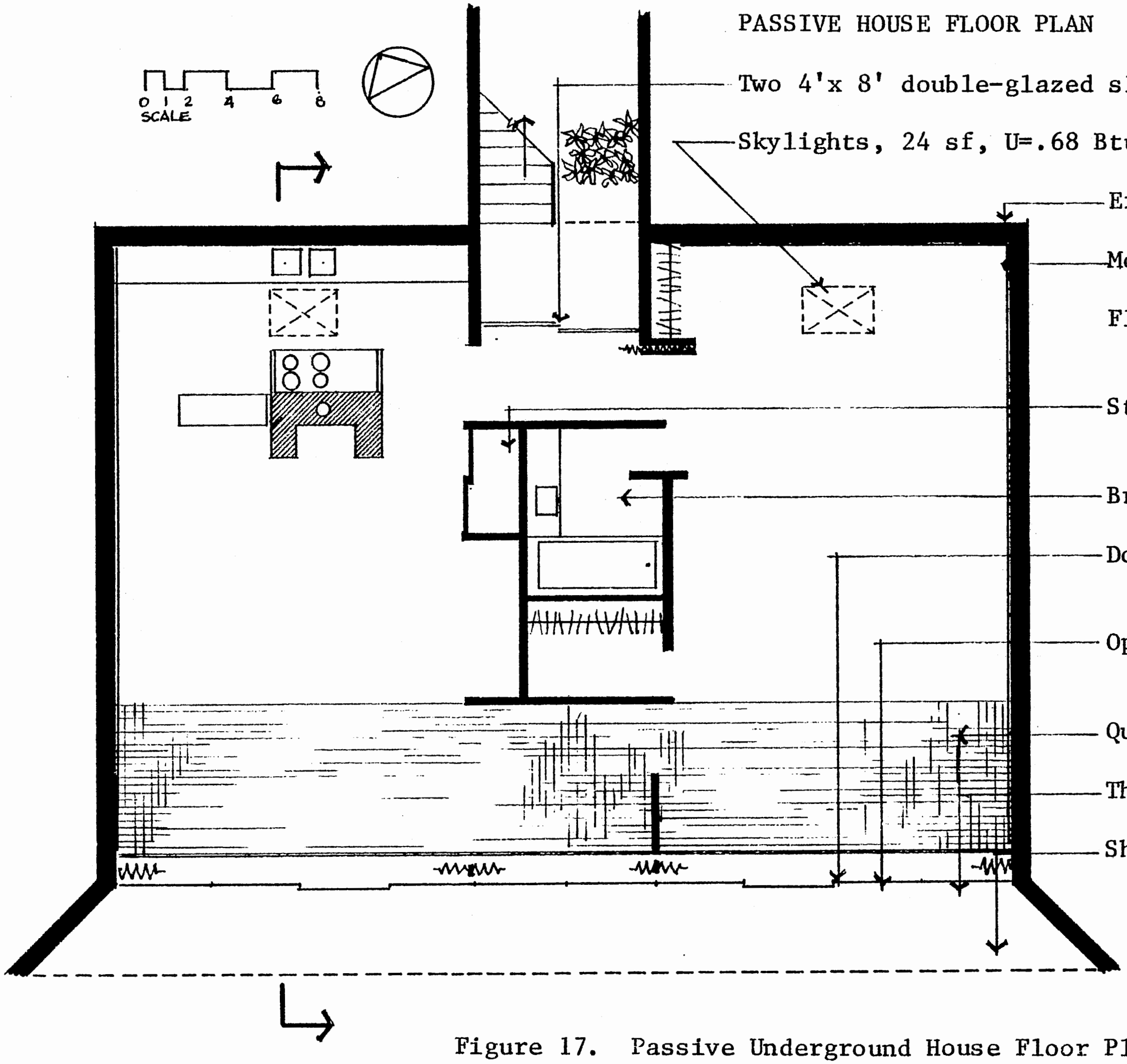
Minimum six foot width of c=.3 sf/day fill

Upper and lower canopy trees to funnel summer winds

Winter winds pass above windbreak

7.5 mph summer wind

Figure 16. Passive Underground House Site Plan



PASSIVE HOUSE FLOOR PLAN

Two 4'x 8' double-glazed sliding doors

Skylights, 24 sf, U=.68 Btuh/sf/^{o}F

Eight inch concrete wall

Moveable insulative panels

Floor return air duct sloped
one-eighth inch per foot

Storage for moveable insulative
wall panels

Brick wall heat storage

Double glazed windows and sliding
patio-type doors, U=.55

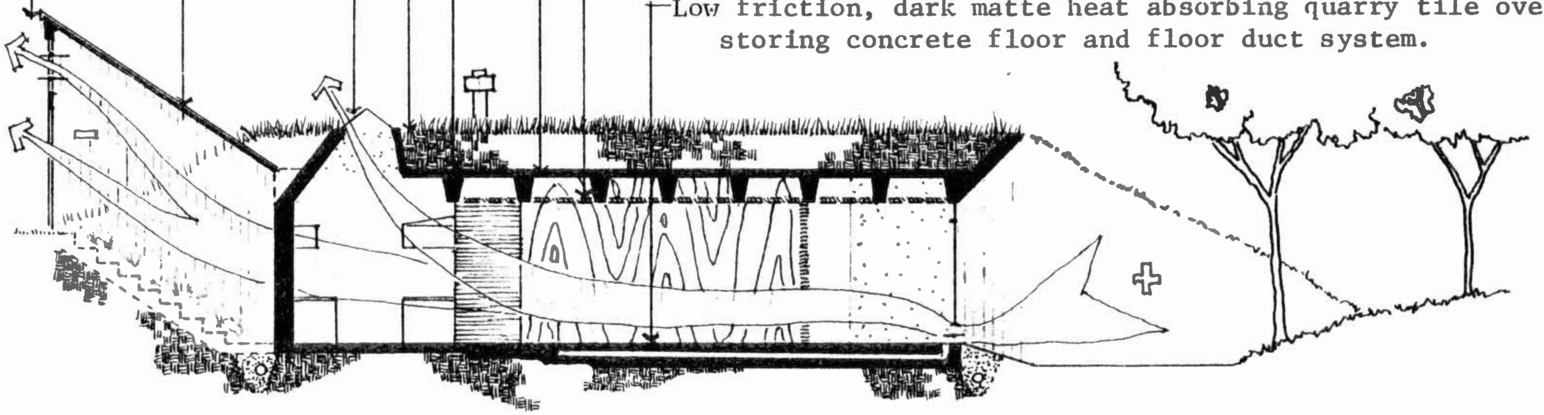
Operable bottom windows,
area = 33 sf.

Quarry tile floor

Thermal break

Shading overhang, selective
from 21 May to 21 November

Figure 17. Passive Underground House Floor Plan



PASSIVE HOUSE SECTION - no scale

Operable screened ventilation windows with screened sliding glass door. Area ratio of opening is 2.2 and height differential is 16 ft.

Double fiberglass panel entrance structure

Operable skylight for ventilation and passive solar heat gain with removeable insulative panel

Two feet depth of c=.3 sf/day sand and uncut sod cover. Sod alters soil temperature by minimum of 2°F and maximum of 8°F

Three ply built up roof

Six inch concrete slab (8.89 inch average concrete depth)

Removeable insulative wall and ceiling panels in mounting track

Low friction, dark matte heat absorbing quarry tile over heat storing concrete floor and floor duct system.

Figure 18. Passive Underground House Section

CHAPTER IV

THE PASSIVE SOLAR UNDERGROUND HOUSE

Introduction

A variation on the "Base" house that requires little additional cost is the incorporation of passive solar heating and natural ventilation for summer cooling. The thermal comfort within this passive house is dependent upon the design of the glazed areas to selectively admit and distribute solar radiation in winter and to reject solar radiation in the summer. Moveable insulation is used to vary and seasonally exclude solar heat from the interior of the underground house. The moveable insulative panels are used to maintain the desired winter design temperature by reducing the building heat loss. To provide an even distribution of heat within the space, heat must be stored and distributed throughout the building mass. In summer, the interior is cooled by the radiant effects of body heat loss to the walls and by natural ventilation.

General Statement of the Passive House

The passive house has the same location as the "base" house, the same depth of cover, and the same mechanical system (now used only as back up or considerably reduced). However, several basic changes to the construction, plan and section are necessary for passive solar conditioning.

The construction is altered by the addition of a considerably thickened concrete slab with a darkened matte floor covering at areas exposed to the solar radiation. The thickened slab is used to absorb solar radiation during the peak solar radiation periods for storage and redistribution during low solar periods. The matte finish improves visual comfort by eliminating glare and improves solar absorption. Within the thickened slab, a floor duct system moves heated air through the slab by convection or by a small ventilation fan and back to the areas where solar radiation does not penetrate. The duct system serves to smooth the temperature fluctuations inherent in most passive solar designs and to allow radiant heating from the floor slab.

The construction also differs from the "Base" by the incorporation of moveable insulative panels and the removal of fixed insulation used on the wall and ceiling areas of the "Base" house. The moveable insulative panels are installed and removed on a seasonal basis when wall and ceiling temperatures reach a level determined by interior heat loss and outside air temperatures. For example, for soils with a thermal diffusivity "c" of .3 square feet per day, the ceiling insulative panels are installed when soil temperatures drop from the comfort zone (approximately 1 November) and are removed when air temperatures enter the comfort zone (approximately 15 May). For the insulative wall panels, for a "c" of .3 square feet per day soil, the panels should be installed approximately 15 October and removed approximately 15 May. On a daily basis, insulative curtains are adjusted to allow sunlight into the interior during sunny, cold days and are closed on cold nights and cloudy days to minimize conductive and radiative heat losses to the exterior.

The problem of conditioning with natural ventilation is twofold; first to create a flow of air that is of a satisfactory temperature and humidity and secondly, to introduce the air at a low level and high velocity such that it passes across the occupant without draft. The alteration required in section is to introduce low-level air through relatively small openings and withdraw the air through a large opening that provides and reinforces a "stack" exhaust effect.

Ramifications of the Passive House

The acceptability of a passive solar system depends somewhat upon the lifestyle change that is acceptable for the occupants. In order to optimize savings in energy consumption to the point of complete energy self-sufficiency, the occupants must be conscious of weather changes not only seasonally, but also on a daily and almost hourly basis to insure that solar radiation utilization is maximized or eliminated and that heat loss through windows and walls is minimized.

A similar limitation of the passive solar heating system is that the economical storage of the solar heat is limited and cannot bridge large periods without solar input. However, for sudden temperature drops, soil temperatures would be unaffected and the closed curtains could reduce heat losses and prolong the heat stored in the slab throughout cold periods to provide levels of acceptable thermal comfort. Additionally, the daily ambient temperature fluctuation and the propensity of the passive solar system to concentrate heat in one area of the house may entice the occupant to draw the curtains to reduce the supply of solar radiation. The use of a small circulation fan to circulate air and reduce overheating will help ensure uniform distribution of heat throughout the storage slab.

The use of ventilation may be in two modes, the use of mechanical ventilation, and the use of natural ventilation. The desire for minimal energy output to achieve maximum thermal comfort necessitates that the passive solar underground alternative utilizes and facilitates natural ventilation, or at least requires minimal mechanical assistance in promoting natural ventilation. However, the major drawback of natural ventilation is the inability to ensure a temperature and humidity controlled air volume or velocity. The use of natural ventilation also introduces more dust into the space than would air conditioning. The use of natural ventilation involves alteration of lifestyle for savings in space conditioning energy.

Design for Natural Ventilation

From site weather data, the prevalent summer breezes are from the South South East at an average of 15 miles per hour. Velocity rarely falls below one half of the average velocity, therefore, calculations are based upon a seven-and-one-half mile per hour wind (2, p. 153). Natural ventilation and cooling design shall be based upon the ventilating forces of pressure differentials due to wind and temperature.

Required comfort ventilating air quantities are based upon the requirement to move wind at the highest velocities short of a draft condition. Design for comfort winds is determined by the velocity of the winds passing over a human and is the quotient of the quantity of air divided by the area of the inlet admitting the air. The quantity of air is described by equation (10), except that the adjustment factor K is modified by the ratio of the area of the outlet divided by the area of the inlet. Table VI lists values of "K" for differing values of the ratio of the area of outlet to area of inlet (25, p. 105).

TABLE VI

VENTILATION RATE ADJUSTMENT VALUES

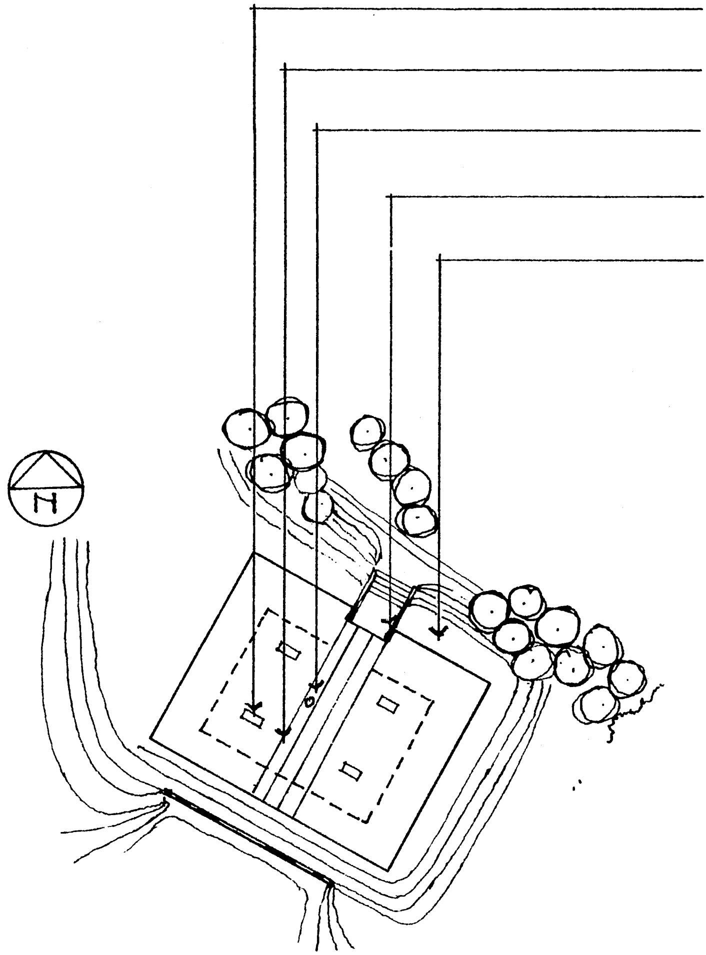
K value	Ratio of Area of Outlet / Area of Inlet
4000	2:1
4250	3:1
4350	4:1
4400	5:1
2700	3:4
1100	1:4
3150	1:1

Conclusion

The advantage of natural ventilation as compared to the use of mechanical air conditioning is the savings in energy for thermal comfort conditioning. Although the air conditioning design load is small, the non-availability of energy to run an air conditioning system (or mechanical ventilation) may be a very real situation. The design and use of natural ventilation to achieve comfort conditions are realistic from a minimum energy standpoint.

The prime advantage of a passive solar space-conditioning system is the freedom from external energy sources for survival or thermal comfort. Additionally, the use of passive solar energy is a free, non-polluting source that is collected by a low maintenance system.

To provide a minimum or subsistence level of space conditioning, the passive solar system in an underground house is self-regulating.



DEEP EARTH HOUSE SITE PLAN

Skylights (below collector cover plate)

Panel storage

Utility Openings

Southwest orientation

Disposal of insitu material in berms

Figure 19. Deep Earth Underground House Site Plan

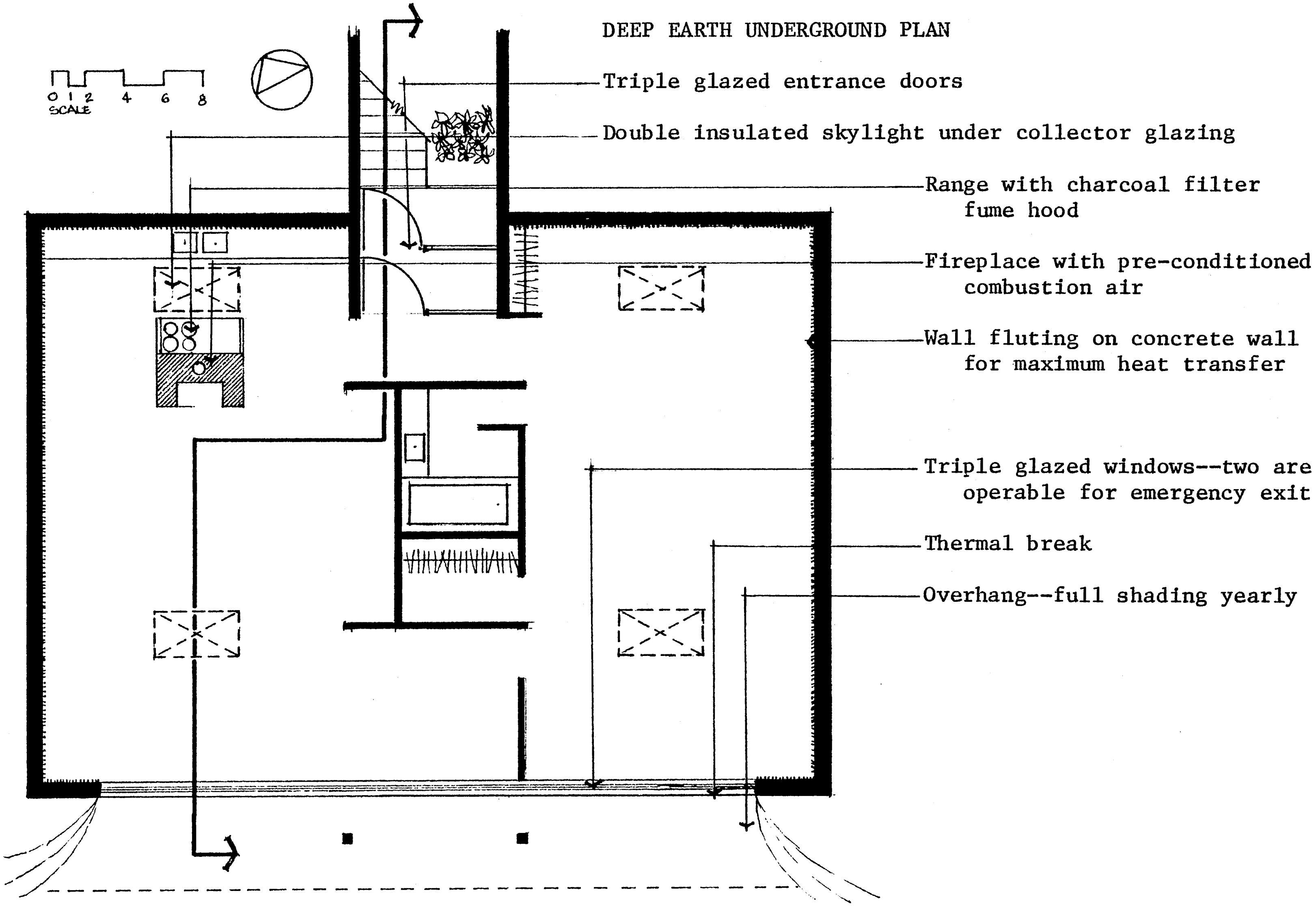


Figure 20. Deep Earth Underground House Plan

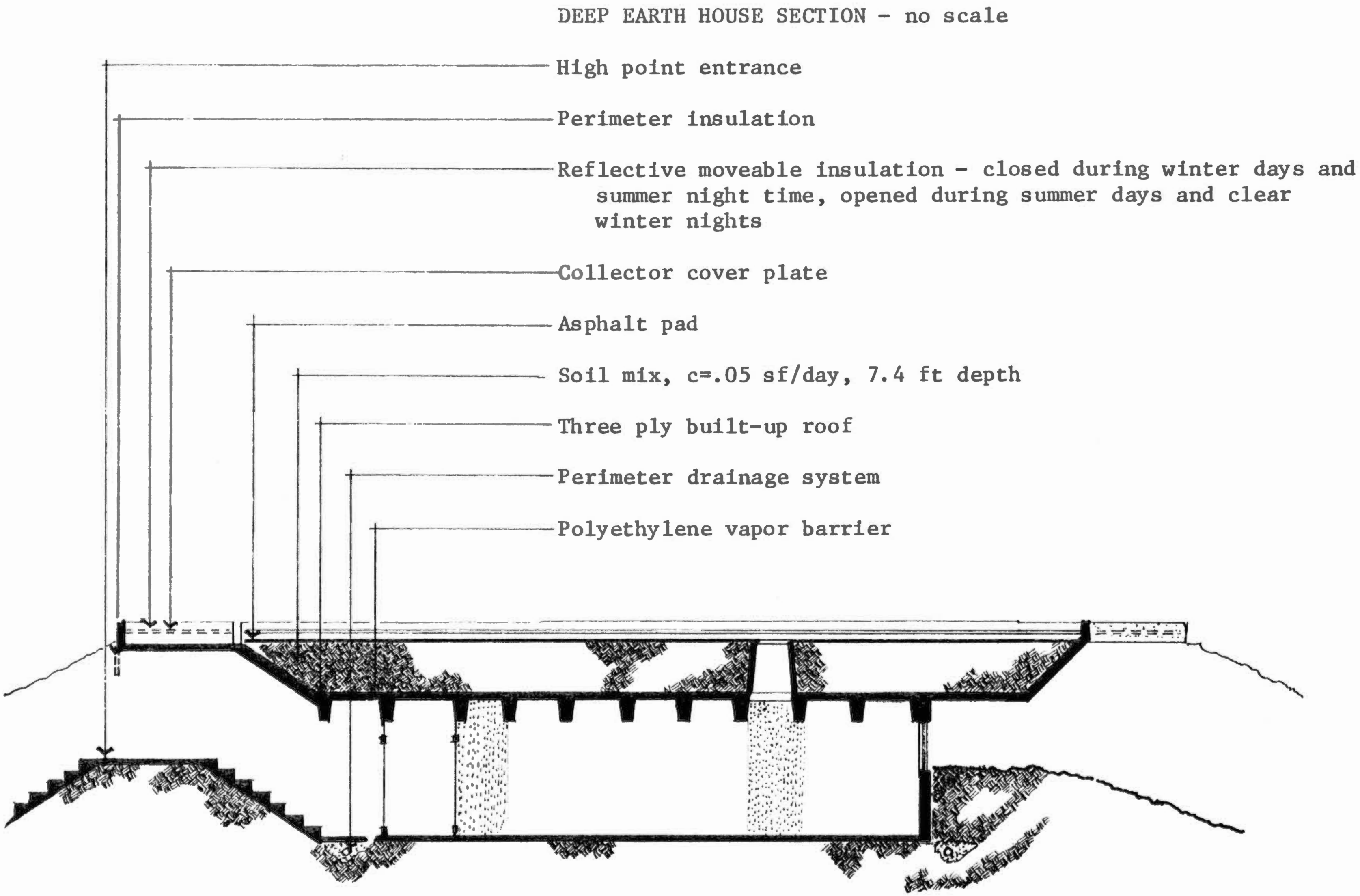


Figure 21. Deep Earth Underground House Section

CHAPTER V

DEEP EARTH PASSIVE HOUSE

Introduction

The ultimate perhaps in passive systems for earth sheltered housing is the placement of the structure at deep earth; the minimum depth at which there is little soil temperature fluctuation. The deep earth temperature is characterized by constancy (within an amplitude range of three degrees Fahrenheit) that roughly approximates the average yearly air temperature and follows a lagging cyclical pattern that varies with geographic, site and earth characteristics (20). Geographic characteristics include latitude, altitude and climatic conditions; however, for Stillwater, Oklahoma, the major influence is the 60.3 degree Fahrenheit average air temperature. Site characteristics include surface toppings, landscaping, orientation, shading, neighboring construction, bodies of water, prevailing winds and water table. The site characteristics vary but are of equal or greater importance than the geographical characteristics. Earth characteristics include the thermal and physical properties of the earth (including moisture content and density).

Because the soil temperature is dependent upon statistically regular climatic phenomenon, deep earth is the ultimate in passive design; however, the undisturbed steady state soil temperature in most continental United States regions is a few degrees away from the thermal comfort zone. To achieve the thermal comfort zone, the alternative of a deep earth passive underground house modifies the soil temperature by altering the quantities of climatic input conducted into the soil.

The benefit of deep earth installations is total space conditioning with elimination of heating and cooling equipment and without energy input for space conditioning. The soil temperature modification concept may be implemented wholly, or in part, and may be applied to the passive underground also. Even without temperature maintenance of any sort, the deep earth house would always be within survival temperatures. For example, if no attention is paid to the deep earth soil temperature conditioning system for long periods of time, the moderating effects of the soil may tend to overheat in winter or overcool in summer or simply return to an average temperature that is several degrees above the mean annual air temperature.

General Problem Statement

The objective of the deep earth conditioning process is to achieve human thermal comfort while eliminating primary heating and cooling systems. This is done by alteration of soil temperatures through selective reception of solar radiation and reduction in nocturnal outward radiation losses. When factors tend to increase the amount of shortwave radiation received during the day or tend to minimize the outgoing longwave radiation that leaves the ground during the night or cloudy periods are altered, the average soil temperature is raised.

Since the highest ambient temperatures occur in summer and snow covers in winter reduce the solar radiation received at the surface;

a lag of six months in order to shift comfort conditions would be desirable. For clays typically found in the Stillwater area, to provide a six month lag in the amount of time required to transmit surface temperatures to the deep earth house would require at least 23 feet of earth cover before steady state soil temperatures could be reached; therefore creating excessive overburden pressures. Once conduction through the soil has reached the deep earth house, the method of heat transmission into the space is by radiation.

Three ramifications of deep earth space conditioning differ from the other underground alternatives. First, usually massive structure resulting from the excessive overburden pressures of the deep earth depth is required. The structure required to support loads of greater than one ton per square foot means greater structural costs. One effect of the increased structure is to provide increased insulation and a somewhat greater resistance to heat flow. The second ramification of deep space conditioning is that since the heat transmission is by radiation, the soil temperature must necessarily be at or above a "comfort condition" temperature. The third and most important factor in determining high consistency in comfort throughout the house is that the perimeter walls of the important living areas must have maximum contact with the soil. In order to transfer as much radiant heat as possible, maximum surface area per volume must be exposed. The radiant surfaces must be near the occupants (in the form of low ceilings and narrow rooms) and most importantly, the plan form should enclose a minimum volume for a maximum surface area, and strive for the largest area per person. This principle was used in defense shelters to reduce per capita ventilation. Space allowances for shelters on a per square foot of floor area basis was a minimum of 50 square feet of floor area per person (24, p. 5-14). More important than with any other type of house, the goal of the deep earth house is to "live on the perimeter".

Deep Earth Considerations

Site Selection

The general problem in site selection is the optimization of the site for an underground structure. The optimization process is important because a bad site may make the difference between the requirement and expense of a heating and cooling system (albeit small capacity). Additionally, the selection of an optimum site is critical because of the low safety factor and the long response time involved in obtaining comfort conditions without expenditure of energy. The maximizing of solar radiation upon the site, the minimization of low areas for the trapping of cold air especially at the entrance, and the control of soil moisture content are primary qualitative considerations in site selection.

Soil Temperature Modification

The general objective of soil temperature modification is to bring soil temperature into the thermal comfort range and then to adjust the soil temperatures with the use of variable insulation, adjustment of lighting load, and ventilation. Prior to any calculation, the decision must be made to use the steady state soil temperature or the cyclical temperatures and apply a thermal lag that varies cyclically with the seasons. The selection of the steady state temperature involves raising the average temperature of the soil to within year round comfort levels; however, the steady state temperature has little capacity to respond to emergencies and may require supplemental conditioning to raise or lower the comfort level. The cyclical temperature of the soil on the other hand, has the benefit of high temperature peaks in the winter and low temperature peaks in the summer. The cyclical peaks also are of greater magnitude than the averaged steady state temperature. From an economic standpoint, the cyclical temperatures occur at a lower depth than does the steady state temperature. The choice of cyclical temperatures results in an economically more successful solution for the deep earth underground house and economic calculations will be based upon this choice.

Alteration of Components

The annual average soil temperature for Stillwater, Oklahoma may be estimated at 63.5 degrees Fahrenheit. The comfort range in summer is 70 to 81 degrees Fahrenheit for low humidity periods and in winter, the comfort temperature range is 68 to 75 degrees Fahrenheit. To make up the difference between the deep earth soil temperature and comfort conditions for any season requires alteration of components in the process of heat transfer from the sun to the deep earth living space. The basic components of the heat transfer process that affect the deep earth house are the diurnal and seasonal radiation cycle, the conduction of the solar radiation heat from the surface of the earth to the soil and the radiation from the soil to the interior of the deep earth house.

The diurnal and seasonal cycle of receiving shortwave solar radiation and emitting longwave radiation is the primary source of soil heat gain and heat loss. By improving the reception of summer solar insolation and reducing the outward radiative losses for winter heating and by reducing the winter solar reception and reducing the radiative losses for the summer cooling, up to 50% of the absorbed solar radiation may be conducted into the soil and the average soil temperature may be raised (26, p. 38).

The conduction process of heat transfer from the surface layers to the deep earth introduces the concept of thermal lag. Thermal lag, the rate at which the surface heat is conducted to the lower soil layers is a function of the thermal diffusivity of the soil, surface topping, and the depth. For a given depth, the lower the thermal diffusivity, the longer the thermal lag. To lower the thermal diffusivity requires proper selection of backfill or the formulation of a required thermal diffusivity by mixing soils with insulative materials and by reducing moisture content.

Design of Soil Toppings

The receipt of maximum solar insolation and the prevention of longwave radiation emission in the summer for use in the winter or the complete reversal of the process during the winter results from the "heat valve" effect. The heat valve effect is caused by the seasonal variations in surface cover, coupled with phase change in the ground water and determines mean ground temperature and the amplitude of temperature variation at the ground surface (12). However, the heat valve can and must be improved upon or modified to increase soil temperature above the present annual earth temperatures. A major factor in the modification of soil temperature is the soil topping. The general design considerations for soil topping must be to maximize diffuse and direct solar insolation during the day and to minimize longwave emittance in the night during the summer. In winter, minimum solar insolation and maximum longwave emittance at night will be required. Soil topping must allow minimum heat loss due to evaporation during the summer and maximize any evaporation that is possible during the winter. The soil topping must provide predictable control of soil moisture content (and consequently thermal diffusivity). Soil moisture content could be controlled at a constant level or allowed to vary seasonally for any design purpose. However, a soil topping that allows seasonal fluctuation of the moisture content risks lack of control during abnormal periods of precipitation. Also, the topping must minimize wind and insulative effects at the surface boundary layer and promote positive heat transfer at the interface of the topping and the soil. Finally, utilizing a six month temperature lag, the soil topping must control surface temperatures relative to above-grade air temperatures to insure that the surface is hotter than the air temperature on summer days and colder than the air temperature in winter.

The Deep Earth System (Heating Mode)

The deep earth conditioning system operates in a heating and cooling mode. The heating mode is operated during the summer days and works through a six month lag time. The heating mode seeks to maximize the reception of solar insolation during the day and minimize the loss of radiation during the nighttime.

The deep earth conditioning system required to condition the deep earth house is very similiar in principle and design to a simple solar collector. The collector consists of an asphalt pad that acts as an absorber plate and a transparent or translucent cover plate. The asphalt pad serves the purposes of receiving and absorbing insolation, providing a thermally good bond with the earth, controlling moisture content of the soil, preventing evaporation losses from the soil, and stabilizing upper soil strata. The presence of the asphalt absorber means that there is no requirement for topsoil, allowing the upper layers of soil to be homogeneous and without the discontinuity due to differing layers of soil. By itself, the asphalt absorber is capable of raising steady state soil temperatures an average of two degrees Fahrenheit even in a relatively cloudy area simply by eliminating the normal soil evaporative losses (26).

The effect of the black surface of the asphalt pad is a net increase in the average temperature of the earth by a minimum of six degrees Fahrenheit (26). This will raise Stillwater's steady state soil temperature from 63.5°F to 69.5°F which is at the lower limits of the thermal comfort zone. Although 69.5°F would be a marginally acceptable temperature for a closed environment, additional measures must be taken if the deep earth underground house is to be flexible in responding to the intake of outside air.

The application of a cover plate above the asphalt absorber increases the asphalt absorber temperature by reducing the losses due to convective air movement and due to reradiation by forming a trapped air layer above the absorber and by converting the high energy shortwave solar radiation into longwave radiation. The lower energy longwave radiation can't escape into space through the cover plate and is absorbed into the asphalt pad and subsequently into the earth.

The addition of a cover plate reduces convective loss and increases the average temperature without affecting the amplitude. Although the effect of the cover plate depends upon the amount of solar radiation received (and solar radiation depends partly upon slope), the minimum effect for a horizontal collector will be an average temperature increase by two degrees Fahrenheit to 71.5°F.

The third component of the collector is an insulative panel or series of panels that can be easily applied over the cover plate. The panels must be lightweight and highly insulative with both sides foil-faced or highly reflective. The purpose of the insulative panels is to reduce night heat losses due to outward radiation. The overall effect is to increase the net radiation into the ground and through a six month thermal lag to the deep earth house, increase the average temperature.

Deep Earth System (Cooling Mode)

The cooling mode is operated in the late fall prior to earth freeze, to maximize radiation losses and prevent the reception of solar radiation during the winter days. The principle is similar to the passive conditioning sytems used by Hay to condition an above-grade house (14).

The reflective insulative panel is the most beneficial to the cooling mode. The reflection of incoming shortwave radiation reduces the radiation which would normally enter the soil by 20% (26). By opening the cover at night, the outgoing radiative losses allow the retained earth heat to be reduced by an additional 10%. Although the absorber plate raises the temperature of the soil by avoidance of evaporation during the summer, there is essentially no evaporation during the winter and therefore does not affect the cooling mode. Although the insulative effect of the cover plate trapping air reduces the heat lost, the effect is not much greater than the effect of grass on the surface. Considering the effects of the cooling mode, the average summer temperature will reduce the average soil temperature by a minimum of three degrees Fahrenheit to a soil temperature of 60.5°F.

Construction and Design

A house designed without primary heating and cooling systems and wholly dependent upon the soil for space conditioning must rely upon the building design and construction to benefit from the soil. As a result, the transfer of low-energy radiant heat gain or loss into the living area is of primary concern. The design and construction must be sensitive to heat gain and heat loss while maintaining the capacity for a contingency response to an extremely severe season, destruction of soil topping, natural disasters, etc.

Design must be considered especially at discontinuity of construction, such as entrances, utility entrances, daylighting openings, and at all potential thermal leak areas. To eliminate the discontinuity of construction reduces the possibility of condensation problems on the interior. Without pre-conditioning of the air entering the interior, a dehumidifying system such as a dessicant must be used for periods when high air temperature coincides with low soil temperatures.

The design must also stabilize conditions and eliminate the need for a quick recovery response. For example, the design of an entrance for a deep earth underground house must not present such high infiltration levels of hot or cold air that the house requires hours to recover to a steady state condition.

Architectural Implications

The general architectural problems with deep earth underground housing are also related to the benefits of deep earth housing. The problems are truly general problems that would be common to most of the deep earth underground houses and are included here only briefly.

The primary areas that create architectural problems and solutions may be classed into the area of safety and the area of psychological comfort.

The deep earth underground house represents both extremes of safety. The deep earth underground house is the ultimate in safety when wind storms and vandalism are involved. With a large amount of protective earth between the living area and the exterior, the deep earth house can be relatively impenetrable. The deep earth can offer little that is vulnerable to damage because there is typically very little access. However, the small amount of access also implies little opportunity for easy exit especially for handicapped persons and in times of fire and flooding. The small amount of available access area also implies that there is little opportunity to observe exterior areas from the interior. Although exposed areas represent a small target, the fact that they are probably unobservable from the interior of the house makes them a target nonetheless.

From the standpoint of withstanding a disaster, the deep earth underground house may easily withstand the extreme temperatures of a surface fire that would destroy an above-grade house, however, the occupants of the deep earth house may be asphyxiated by the heavier-than-air poisonous gases that result from surface fires and could collect in the low-level entrance to the deep earth house. This problem is compounded by the extreme airtightness that could easily be less than the .2 air changes per hour commonly associated with extremely tight construction in above-grade houses.

The extreme conditions of safety or danger may create psychological comfort or discomfort. However, the deep earth house occupant may have feelings ranging from claustrophobia to extreme happiness depending upon the perception of the "deep earth condition" and design. The perception of the deep earth underground house probably will be influenced by the relation of the interior to the exterior, especially in the admittance of daylight, and the observation of the change from day to night.

The architectural considerations may prove to be more important than energy consumption or thermal comfort in determining suitability and popularity as a housing alternative.

Conclusion

The deep earth house in Stillwater benefits from an average soil temperature that is near the thermal comfort range. By manipulating the solar insolation and by reducing losses from exposed area, infiltration, and ventilation, the deep earth house provides thermal comfort.

Although the deep earth house can provide comfort without energy input, the selection of climate and microclimate, the stabilization of the soil, and the selective acceptance or rejection of the solar insolation may restrict deep earth house use to climatic conditions similar to those of the United States.

CHAPTER VI

CONCLUSIONS

Introduction

The comparison of the underground housing types was based upon the premise that, using average climatic conditions of temperature and insolation and average conditions of usage and habitation, each of the underground types would be designed to provide thermal conditions in the statistical comfort range. The calculations for thermal comfort for each underground type are located in appendixes B, C, and D. The comparison of the cost to provide equivalent thermal comfort, found in Appendix E is based upon a twenty year life cycle with all costs paid at the beginning of the life cycle (i.e. present worth evaluation).

Life Cycle Cost Comparison

The most economical underground house is the passive underground house primarily because of the low cost of conversion from the base house to the passive and because the Oklahoma climate results in good solar performance for the passive house. Even using a thermostatically controlled air handler to smooth the temperature peaks associated with many passive solar applications, and using natural ventilation, the annual cost for space conditioning is $22.50. Including $3006 modification costs (from base to passive) and inflation, the total incremental cost for a present worth 20 year life is $3530.

The base house was more expensive than the passive house because the size and initial cost of the heat pump installation was larger than warranted by the small space conditioning load. Also, the base house does not advantageously use the cooling effect of the soil and, as a result, cooling energy was wasted in the Fall for the approximate length of the thermal lag. The space conditioning heating load was small enough that only 2216 kwh was required for annual heating and only 4794 kwh was required for annual cooling. The annual cost of space conditioning for the base house was $252 which equates to a 20 year present worth life cycle cost of $5850. The base house energy savings resulted from an extremely well-insulated, small area house and highly efficient heat pump.

The deep earth underground house was $10627 more expensive than the base house. The cost of constructing the deep earth was initially $16477 more expensive than the base house including credits. Primary reasons for the higher costs were the soil mixing costs and the asphalt pad costs. Reductions in the large construction costs are difficult to achieve because $2883 of the construction costs were necessary to complete the solar collection system and $14327 was needed to provide the soil mix. Without the soil mix, the deep earth depth would increase and structural and waterproofing costs would exceed the soil mixing cost.

Cost Effectiveness of Underground Features

Certain site and design conditions favor different types of underground houses and different underground components. Few components are mutually exclusive and could be applied to several underground housing types with varying results. The features that most affect the selection of underground type or features (after cost) are climate, soil and thermal lag, heat transfer management and levels of comfort required.

Effects of Soils on Performance

Soil design is most cost effective when the maximum thermal lag is achieved with the lightest loading. The larger the thermal lag, the more cost effective an economizer cycle or ventilation will be in using cool outside air to counter the effects of warmer lagging temperatures in the Fall.

One of the best ways to produce maximum thermal lag with minimum weight is by using lightweight cohesionless material as backfill. Cohesionless material allows easy de-watering, reduces hydrostatic pressure, reduces wall and roof backfill pressures and provides more stable thermal properties.

Effects of Climate

Extrapolating the effectiveness of an underground house to different climates, each type of underground house responds differently to the major climatic influences. The optimum type of underground house for various climates is shown in Figure 22.

The base house will be most advantageous in areas with winter or summer temperature extremes when compared to above grade houses. Additionally, the base house will perform better than other underground types in areas that have little sunshine or little diurnal or seasonal temperature variation. The base house would perform better than the other underground types in coastal and fog prevalent regions.

The passive house works better than all other underground types

	WINTER			
SUMMER	warm solar	warm cloudy	cold solar	cold cloudy
hot solar	base	base	deep earth (reject insolation)	deep earth
hot cloudy	base	base	deep earth	deep earth
cool solar	passive	deep earth	passive	deep earth
cool cloudy	passive	base	passive	base

Figure 22. Climate Matrix for Underground Type Selection

when adequate winter insolation exists and summer temperatures are not excessive. The passive house is well-suited for upper latitude midwestern and non-coastal regions.

The deep earth house performs best when definite seasonal temperature variations exist and summer insolation exists. The deep earth house performs most efficiently in the mid-western states.

Heat Transfer

The benefit from the soil and climate should be assisted with other passive techniques. The prevention of heat loss to nocturnal radiation greatly increases the efficiency of the underground house. Heat loss by nocturnal radiation could be reduced dramatically in the base house by the passive technique of closing insulative curtains during the night hours. Also, ventilation loads could be reduced by using non-vented kitchen "exhaust" systems to remove odors.

The use of natural ventilation is realistically of limited value in an area of dusty, pollen-filled air that is lowest in velocity during the periods of highest temperature and humidity. However, the limit on comfort is partially a matter of conditioning, and by adjusting life style and clothing, the levels of summer performance for the passive house may be totally acceptable to some persons.

Soil as a medium of favorable temperature differential or as a low-grade insulation is best utilized in the passive house. The passive house responds to the low temperature differential in winter with insulation and promotes heat loss from the interior during the summer when the insulation is removed.

Comfort Comparisons

Finally, the choice of underground type is dependent upon the level of comfort that is desired. Comfort has a statistical and a subjective meaning. The statistical comfort used in cost comparisons of the underground types is based upon the assumption that for average climatic situations, a suitable response by the underground house can be made. However, no assumptions have been made about the speed of response or the ability to cope with non-typical situations. Statistical comfort also assumes that environmental conditions can vary within the comfort zone of the Bio-Climatic chart and provide equivalent comfort.

Subjective comfort necessarily depends upon the individual and personal preferences in comfort. Subjective comfort at one extreme can adapt well beyond the upper or lower bounds of statistical comfort. At the other extreme, fluctuations of temperature, humidity and air quality within relatively narrow tolerances may be unacceptable.

Although cost comparisons of the underground types are based upon statistical comfort, for any degree of subjective comfort mechanical conditioning of the space will realistically be a necessity in any of the underground types. The mechanical conditioning can accommodate the conditions not addressed in statistical comfort, such as large numbers of visitors, long periods of massive air infiltration, high concentrations of dust and pollen and response to rapid extreme fluctuations in climate or non-typical situations.

From a comfort viewpoint, the use of a heat pump provides optimal flexibility in comfort and house design.

In the heating mode, the heat pump's air handler can smooth temperature differentials within the house by redistribution of solar input and could serve as a backup for cloudy periods greater than the heat storage capacity or to provide rapid recovery for large heat losses.

In the cooling mode, the heat pump can eliminate the use of natural ventilation during overheated periods, and provide stable or varying levels of air conditioned comfort. In the cooling mode, the heat pump can be most economical when the air handler incorporates an economizer or ventilation cycle. The larger the thermal lag of the soil and building, the more cost effective the economizer cycle becomes.

The heat pump influences house design in either heating or cooling mode in two ways. First, because properly designed underground house loads are relatively small and stable, it is important that the heat pump output correspond closely to the house loads, without much overdesigned capacity. In the case of the base house, the capacity of the smallest heat pump was well beyond the load requirements and the heat pump could have conditioned a larger underground house. Secondly, the heat pump influences house design by compensating when passive features cannot be used. For example, the heat pump can allow less southern exposure, provide flexibility in designing for views, or generally allow basic energy trade offs.

Conclusion

The effectiveness of various components on an underground house may be evaluated by cost or comfort criteria. The criteria are influenced by location and human subjectivism and as a result, a combination of criteria will determine the optimal fatures.

Features with optimum cost effectiveness for the Stillwater area include maximum surface area for a given interior volume. Optimally, plan and section incorporate the capability for natural ventilation. Depth of earth cover should be the minimum depth required for the maximum thermal lag plus a small topping for promoting plant growth. A soil mix of cohesionless material is most cost effective where soil must be totally replaced. A perimeter drainage system is essential in providing stable thermal conditions.

Optimal site orientation for the base and passive house is south when seasonal shading is provided. The feature of adjustable sunshading may be justified on the basis of promoting natural ventilation, but for sites with adequate quantities of wind, sunshading should be fixed.

One of the most cost effective features is the application of moveable insulative panels, especially at all openings. The moveable insulative panels can vary insulative properties by a large factor within minutes. Fixed insulation applied to underground houses that are not affected by diurnal changes is not cost effective in the Stillwater area because maximum cooling effect from the earth is required in summer, insulation that is applied outside the structure is easily damaged during backfilling, and the exterior fixed insulation adds little to the thermal resistance provided by the removeable insulative panels.

Large quantities of insulative glass in a southern orientation is more cost effective when double glazing is used instead of triple glazing because Stillwater receives relatively large quantities of insolation. Because the summer winds in Stillwater are generally from the south, operable panes placed at low levels for air intake are cost effective. Because skylights will generally be required at the rear of the house for daylighting, operable, large area skylights and entrance openings can serve as exhausts for natural ventilation for use in other than overheated periods.

Because comfort is subjective and degree of comfort control and the cost of conditioning are important factors, the cost effectiveness of any combination of underground features remains a design decision based upon owner preference and site conditions.

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APPENDIXES

APPENDIX A

CALCULATION OF UNDISTURBED SOIL TEMPERATURES

Introduction

The temperature of the soil at a given depth and time is determined by the amount of solar radiation received, by the seasonal variation of soil moisture content, by the seasonal variation of soil cover, by the type of applied soil topping, and by the soil property of thermal diffusivity.

Because of microclimatic effects, the exact temperature of undisturbed earth cannot be accurately predicted for any given time. However, for purposes of estimating undisturbed soil temperatures and soil temperatures when interior temperature equals soil temperature and for determining effective heat loss (20)

$$T_{(x,t)} = T_m + A_s e^{-k'x} \sin (wt-kx-\phi) \tag{9}$$

where $T_{(x,t)}$ = ground temperature at depth x in feet on day t.

T_m = mean annual ground temperature (deep earth steady state condition, assumed to equal well water temperature. For Stillwater, T_m = 63.5°F.

A_s = Annual temperature amplitude at the surface (x=0) A_s = 21.24°F for Stillwater (23).

k' = $(w/2c)^{1/2}$

w = $2\pi/365$ radians per day

c = thermal diffusivity of the soil in sf/day.

ϕ = $2q\pi/365$ where

q = number of days from 31 December to the time when the bare ground surface temperature first equals T_m. q = April 15 (day q = 105 for Stillwater.)

t = time in days from 31 December.

Undisturbed soil temperatures are listed in Table VII for the Stillwater area for thermal diffusivity (c) values associated with the base house, the passive underground house, and the deep earth house, as well as an intermediate c=.10 sf/day value.

TABLE VII

CALCULATED UNDISTURBED SOIL TEMPERATURES

Depth	c	1Jan Day 1	21Jan Day 21	21Feb Day 51	21Mar Day 81	21Apr Day 111	21May Day 141	21Jun Day 171	21Jul Day 201	21Aug Day 231	21Sep Day 261	21Oct Day 291	21Nov Day 321	21Dec Day 351
2 ft	.50	49.07	47.33	48.31	53.26	60.91	69.23	76.05	79.58	78.89	74.17	66.64	58.30	51.32
	.30	50.71	50.71	49.04	53.15	59.96	67.71	74.35	78.15	78.10	74.23	67.54	59.79	53.02
	.10	55.52	52.96	51.71	53.56	58.00	63.90	69.69	73.85	75.30	73.65	69.35	63.51	57.66
	.05	58.94	56.48	54.42	54.73	57.35	61.58	66.31	70.30	72.52	72.36	69.89	65.74	60.99
4 ft	.50	54.31	54.31	51.02	53.36	58.36	64.70	70.73	74.87	76.02	73.89	69.04	62.73	56.63
	.30	56.83	56.83	52.73	53.93	57.64	62.89	68.30	72.44	74.25	73.23	69.66	64.49	59.04
	.10	62.38	60.26	57.87	56.94	57.74	60.05	63.26	66.54	69.02	70.05	69.36	67.14	63.96
	.05	64.75	63.38	61.40	59.97	59.47	60.02	61.49	63.48	65.48	66.96	67.50	67.05	65.63
6 ft	.50	58.53	55.92	53.95	54.50	57.29	61.89	66.82	70.87	72.99	72.62	69.86	65.43	60.49
	.30	61.02	58.71	56.37	55.90	57.42	60.54	64.43	68.08	70.53	71.14	69.74	66.71	62.83
	.10	64.97	63.76	61.01	60.50	59.87	60.19	61.37	63.12	64.96	66.42	67.12	66.86	65.73
	.05	65.10	64.76	64.00	63.10	62.30	61.82	61.78	62.20	62.95	63.85	64.65	65.16	65.23
8 ft	.50	61.46	59.06	56.70	56.12	57.47	60.41	64.15	67.73	70.20	70.90	69.67	66.82	63.10
	.30	63.56	61.70	59.38	58.14	58.30	62.32	65.12	67.49	68.82	68.75	67.31	64.86	64.86
	.10	65.21	64.48	63.47	62.47	61.74	61.47	61.74	62.46	63.46	64.47	65.22	65.97	65.30
	.05	64.20	64.26	64.19	63.93	63.56	63.17	62.87	62.74	62.80	63.05	63.41	63.80	64.11
10 ft	.50	63.31	61.39	59.04	57.86	58.16	59.85	62.51	65.42	67.83	69.10	68.91	67.30	64.68
	.30	64.83	63.52	61.58	60.16	59.60	60.07	61.44	63.34	65.30	66.77	67.39	66.99	65.67
	.10	64.63	64.50	64.11	63.50	62.99	62.56	62.38	62.48	62.86	63.40	63.97	64.41	64.60
	.05	63.61	63.71	63.81	63.83	63.76	63.62	63.45	63.30	63.20	63.19	63.23	63.97	64.60

TABLE VII (Continued)

Depth	c	1Jan Day 1	21Jan Day 21	21Feb Day 51	21Mar Day 81	21Apr Day 111	21May Day 141	21Jun Day 171	21Jul Day 201	21Aug Day 231	21Sep Day 261	21Oct Day 291	21Nov Day 321	21Dec Day 351
12 ft	.05	64.50	62.99	60.90	59.50	59.13	59.91	61.64	63.85	65.97	67.44	67.88	67.17	65.50
	.30	65.26	64.02	62.60	61.42	60.78	60.78	61.63	62.97	64.31	65.51	66.19	66.17	65.44
	.10	63.26	63.50	63.64	63.70	63.61	63.82	63.87	63.92	63.96	64.00	64.04	64.07	64.10
	.05	63.43	63.48	63.55	63.61	63.64	63.63	63.60	63.53	63.45	63.40	63.36	63.36	63.40
14 ft	.50	65.10	64.00	62.28	60.88	60.17	60.33	61.33	62.88	64.61	66.04	66.81	66.71	65.76
	.30	65.20	64.20	63.82	62.32	61.88	61.55	61.63	62.20	63.49	64.12	64.97	65.43	65.38
	.10	63.63	63.73	63.63	63.84	63.77	63.62	63.44	63.27	63.18	63.16	63.23	63.37	63.55
	.05	63.44	63.48	63.51	63.1	63.54	63.56	63.56	63.55	63.50	63.49	63.45	63.44	63.44
16 ft	.50	65.28	65.54	63.22	61.98	61.14	60.92	61.37	62.38	63.69	64.95	65.82	66.10	65.68
	.30	64.88	64.70	64.18	63.40	62.78	62.28	62.09	62.27	62.77	63.47	64.11	64.69	64.90
	.10	63.46	63.53	63.62	63.68	63.69	63.66	63.58	63.48	63.40	63.32	63.31	63.34	63.42
	.05	63.50					STABLE							63.50
18 ft	.50	65.20	64.74	631	62.80	61.96	61.53	61.62	62.20	63.12	64.14	64.00	65.45	65.40
	.30	64.50	64.50	64.25	63.82	63.30	62.85	62.56	62.51	62.73	63.15	63.66	64.13	64.43
	.10	63.50					STABLE							63.50
	.05	63.50					STABLE							63.50
20 ft	.50	64.97	64.74	64.12	63.35	62.61	62.11	61.97	62.23	62.83	63.60	64.35	64.87	65.03
	.30	63.50					STABLE							63.50
	.10	63.50					STABLE							63.50
	.05	63.50					STABLE							63.50
22 ft	.50	64.68	64.60	64.24	63.70	63.10	62.60	62.34	62.39	62.7	63.27	63.87	64.38	64.65
	.30	63.50					STABLE							63.50
	.10	63.50					STABLE							63.50
	.05	63.50					STABLE							63.50

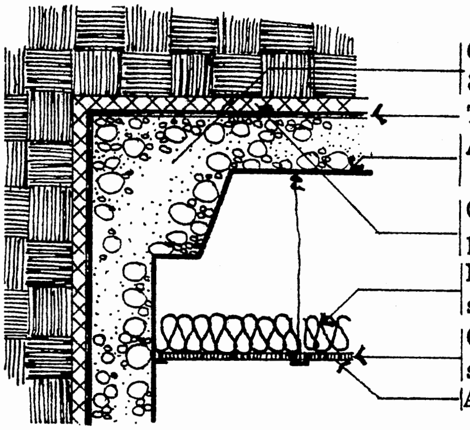
APPENDIX B

BASE HOUSE ENERGY ESTIMATE

Insulation standards are those required by ASHRAE 90-75 for Type "B" structures (3, p. 14-19). Earth cover of 24" is typical of Oklahoma underground house applications. Clay with a thermal diffusivity of .5 ft^2/day is used for backfill. Thermal breaks are installed and prevent short circuiting of heat transfer. Odor removal is by air handler and exhaust fans.

Insulation Standards

Base House area=1092 sf. Wall height=8'-0" @ 0'-8" thickness and 1'-0" height at 1'-2". Floor thickness=0'4". Roof thickness=0'-6" slab thickness + 1'-0" beam depth. Weighted average ceiling depth=8.89". "U" value for ceiling (U_{clg}) required for type "B" structures for 3860 degree days = .05 Btuh/sf/°F.



Concrete (cement mortar) 8.89" depth	1/k=.20x R= 1.778
Three-ply built up roof.	R= .33
Air film horizontal (inside surface still air)	R= .61
One inch closed cell polyurethane insulation	R= 6.25
R-11 glass fiber insulation.	R=11.0
Glass fiber board suspended ceiling	R= 1.25
Air film horizontal	R= .61

R_{total} = 21.82

U = .048

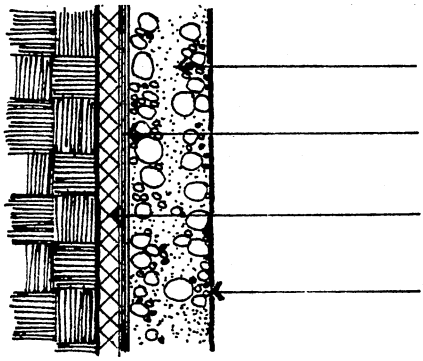
Figure 23. Base House Typical Roof Section

"U" Calculation for Wall Areas

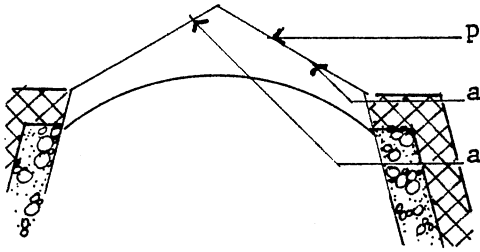
"U" value required through the exterior walls is .25 Btuh/sf/^{o}F.
Window area = 33% of the south elevation = 175 sf.
Door area = 32 sf for the north elevation and 42 sf for the south elevation.
Wall area = 980 sf.
Total wall area including windows and doors = 1152 sf.
U_{window} (insulated double pane with air space) = .58 x .95 adjustment = .55 Btuh/sf/^{o}F.
U_{door} = .49 Btuh/sf/^{o}F for solid wood doors
$U_{storm\ door}$ = .30 Btuh/sf/^{o}F
Combination of $U_{door} + U_{storm\ door}$ = .19 Btuh/sf/^{o}F.

$$\text{for } U_{wall} = \frac{U_{wall}\,A_{wall} + U_{window}\,A_{window} + U_{door}\,A_{door}}{A_{total} = 1152 \text{ sf}} = .25$$

then U_{wall}= .17 Btuh/sf/^{o}F.



eight inch concrete R= 1.6
three-ply built up roof R= .33
one-half inch polystyrene insulation R= 3.13
vertical still air R= .68
Total R= 5.74
U=1/R= .17 Btuh/sf/oF



pyramidal type skylight R= .70
air film horizontal R= .61
air film exterior R= .11
Total R= 1.48
U=1/R=.68 Btuh/sf/^{o}F

$U_{skylight}A_{skylight}$= .17 Btuh/sf/^{o}F x 24 sf= 16.32 Btuh/^{o}F.

Figure 24. Heat Transmission Coefficient Calculation

Peak Design Heat Loss

Exposed Wall Heat Loss

Exposed wall surface area is 92 sf and U = .17. AU = 92 sf x .17 = 15.62 Btuh/°F.

Exposed glass (south wall and north entrance) area is 207 sf and U = .55. AU = 114.2 Btuh/°F. Skylights AU = 897 Btuh/°F. Exposed glass doors (2 each). AU = 7.8 Btuh/°F.

Combined heat loss for exposed wall areas = 154 Btuh/°F. For a design temperature of 13°F exterior and 68°F interior, exposed heat loss is 8470 Btuh.

Soil Covered Area Heat Loss

The "base" house is the least effective in using thermal lag to reduce the heat loss in the soil covered areas. The shallow depth and large thermal conductivity of the soil allows heat loss to be a function of ambient air temperature and the thermal conductivity of the soil. For roof areas, the resistance of the two feet depth of c = .5 sf/day clay is

$$2\text{ ft}\ \Big|\ \frac{\text{ft hr }^{\circ}\text{F}}{.75\text{ Btu}} = \frac{2.67\text{ sf hr }^{\circ}\text{F}}{\text{Btu}}$$

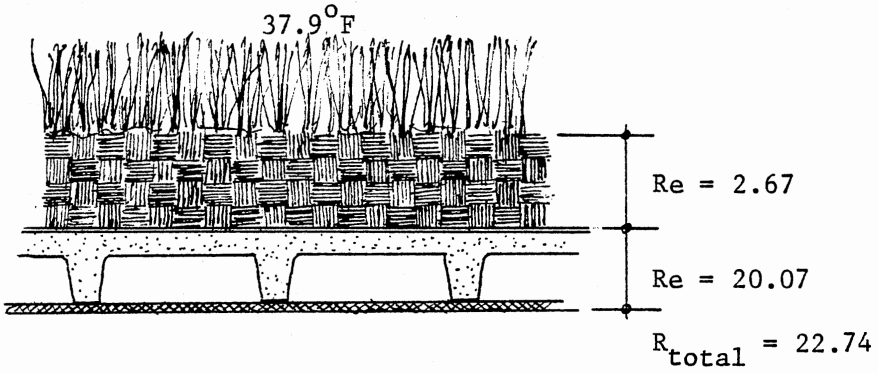


Figure 25. Soil Effective Resistance

The 15 day thermal lag to the roof eliminates daily temperature fluctuations and allows only average temperatures to be transmitted below. The 15 day thermal lag through the two feet of clay allows the lowest soil temperatures to occur when outdoor air temperatures are also lowest. Based upon a lowest average air temperature of 37.9°F for January, the quotient of the temperature difference and the effective resistance is 1.33 Btuh/sf heat loss. For 1092 square feet of roof area, the roof heat loss is 1450 Btuh.

Since the c = .5 sf/day backfill soil is the same as the in-situ material, based upon Table VII values, a four feet depth temperature of 52°F gives a heat loss of 968 Btuh and an eight feet depth of 58°F allows 605 Btuh of heat loss for lower wall areas. Total heat loss for worst condition 21 January temperatures is (8470 + 1450 + 968 + 605) 11490 Btuh.

Heat Pump System Design

Introduction

The heat pump was selected for use in the "base" underground house because it is not only a typical choice but also a logical choice for underground application. The heat pump provides highly efficient use of electrical energy, does not require combustion air for heating and does not produce carbon monoxide. The heat pump also has a very high degree of energy uninterruptability in the case of a fuel reduction. The split system heat pump additionally provides extreme planning flexibility and electric heating coils can be incorporated within the blower module to temper air during reverse-cycle defrosting.

Design Parameters

The selection of an air-to-air heat pump was based solely upon typicality of the application and not upon maximum energy conserved. Because of the low loads, the design procedure is based upon manufacturer's data and sizing information from the Trane Corporation publication for <u>Split Systems Heat Pumps and Furnace Coils</u>. Sizing information and energy consumption calculations are based upon the manufacturer's data for an RPHB 202 with BPCB 202 or EPCB 20C coil rated at 800 cfm with performance as shown in Table VIII (30, p. 1-19). It should be noted that the heat pump was selected based upon maximum heating load and assumed no electrical resistance coils. Because of the small load, the smallest heat pump still meeting the heating design load must be selected. For design conditions of 97°F dry bulb and 74°F wet bulb, the selected heat pump provides 25.17 MBtuh with a

TABLE VIII

TRANE HEAT PUMP PERFORMANCE DATA

Outside ambient Temperature	-10	0	10	17	20	30	40	47	50	60	70
Capacity (MBtu)	8.5	10.5	12.5	14.0	15.1	18.8	22.4	25.0	26.0	29.7	33.3
Coefficient of Performance	1.1	1.3	1.5	1.7	1.7	2.1	2.4	2.6	2.7	3.0	3.3
Kilowatt consumption	2.3	2.4	2.49	2.55	2.58	2.66	2.74	2.80	2.82	2.90	2.97

1. Cooling capacity is 2.45 MBtuh for an EER of 7.8.
2. Net cooling capacity for an outside air temperature entering condenser (by interpolation) for 97°F and a 72°F wet bulb temperature entering the evaporator results in a 25.17 ton capacity and a .70 Sensible Heat Ratio.

SHR = .70. It should also be noted that the heating and cooling load is extremely small for the size of the heat pump and the climate of Stillwater does not exact a great penalty in winter performance. Calculated performance data and energy requirements for the heat pump are given in Table IX and Table X.

Energy Calculation

The "bin" method recommended by ASHRAE and based upon the elimination of daily temperature fluctuations, is a reasonable method to estimate both heating and cooling energy consumption based upon both cooling and heating season hours when soil temperatures are above or below 65°F. The 65°F reference temperature for cooling is based upon internal, electrical, exposed wall loads, infiltration loads, as well as the soil loads. The calculations assume that the heat pump does all the conditioning, and that an economizer cycle is not used for modifying the space air temperatures.

Cooling Degree Day

The selection of the 65°F basis for the cooling degree day for the "base" house assumes a 45 day thermal lag between outdoor temperature and affected soil temperatures. The base for a cooling degree day is a function of the thermal diffusivity of the soil, the thermal lag, the internal and the external loads. Another important determinant of the base temperature is the assumption that the solar insolation does not enter the space or touch the exposed surface area.

Cooling degree day is defined as the area under the curve described by equation (9). The area is determined by integration, where

TABLE IX

HEAT LOSSES FROM EXPOSED AREAS (YEARLY)

Outside Temp. 5^{o}groups	Btuh Loss/ per ^{o}F of soil temp.	Δt	Btuh Loss	Ht. Pump Capacity MBtuh	Run Time %	Ht. Pump Input kw	Seasonal Heating hours	Seasonal Energy input
62^{o}	153.96	3	461	29.8	01.60	2.91	717	33.38
57	"	8	1262	28.7	04.50	2.88	643	83.33
52	"	13	2052	25.5	08.30	2.81	645	150.43
47	"	18	2840	25.0	11.18	2.80	611	191.27
42	"	23	3630	23.2	16.11	2.76	641	285.01
37	"	28	4419	20.9	21.78	2.72	570	337.68
32	"	33	5208	19.5	27.50	2.67	468	343.68
27	"	38	5996	17.7	34.89	2.63	287	263.35
22	"	43	6786	16.3	42.80	2.59	173	191.77
17	"	48	7575	14.0	56.00	2.55	77	109.96
13	"	52	8206	13.3	49.46	2.51	36	45.15
							KWH=	2035.00

TABLE X

HEAT LOSSES FROM SOIL COVERED AREAS (YEARLY)

Outdoor Temp.		Outside Temp. 5^{o}groups	Btuh Loss/ per ^{o}F of soil temp	Δt	Btuh Loss	Ht. Pump Capacity MBtuh	Run Time %	Ht. Pump Input kw	Seasonal Heating hours	Seasonal Energy input
72	May	62	130.08	3	390	33.4	01.10	2.98	1032	33.83
64	Apr	57	"	8	1040	29.9	03.48	2.93	1440	146.83
										KW=180.66

Yearly heating energy consumption= 2035 kwh (Exposed Area)
+ 181 kwh (Soil Covered Area)
2215 kwh/year

soil diffusivity $c = .5 ft^2/day$, soil temperature variation at a two inch depth $A = 21.24°F$, depth "x" is given, and where times t_1 and t_2 are the dates when soil temperatures rise and recede to 65°F. Times t_1 and t_2 are taken from soil temperatures plot Figure 8. The integrand of equation (9) is:

$$ {}^{t_1}_{t_2}(-A_1 e^{-\acute{k}x/w}) \cos(wt-\acute{k}x-\phi) \tag{10} $$

As calculated for a thermal diffusivity $c = .5 ft^2/day$, $w = .0173$, $\phi = 1.8075$ and $\acute{k} = .13138$. The cooling hours for the various depths are shown in Table XI and are based upon a 65°F reference temperature.

TABLE XI

COOLING DEGREE DAYS

x=	t_1	t_2	Cooling Hours	Area Per Cent	Product
2 ft	297	129	1874	30	562
4 ft	312	144	1440	17.5	252
6 ft	324	162	1105	17.5	194
8 ft	336	177	816	17.5	143
10ft	348	198	650	17.5	114
				Cooling Degree Days =	1265

Using an area weighted average for the "base" house, roughly 30%

of the area of the "base" house is at the two foot depth, and the remaining 70% (17.5% each) is divided among the depths to ten feet. The 1265 cooling degree days are the product of the cooling hours and the contribution of each section of wall area to overall space temperature.

Cooling Electrical Consumption

Since the cooling degree days are based upon the constancy of cooling load and the lack of an economizer cycle for the heat pump, the cooling degree days may be considered to be full load operating hours and cooling energy requirements may be computed by the following equation

$$\text{Cooling Energy} = (\text{kw})(\text{cooling degree days}) \qquad (11)$$

The Trane heat pump selected has a 3.141 kw rating at 24,500 Btuh, which compares to a window size unit. For a typical window unit of size comparable to the required heat pump, the fan load is .32 kw for each design ton of air conditioning for a total auxiliary load of .65 kw. Total heat pump consumption for each cooling degree day is 3.79 kwh. Cooling energy required is therefore the product of 3.79kw and 1265 cooling degree days, which equals 4794 kwh yearly.

APPENDIX C

PASSIVE UNDERGROUND HOUSE DESIGN

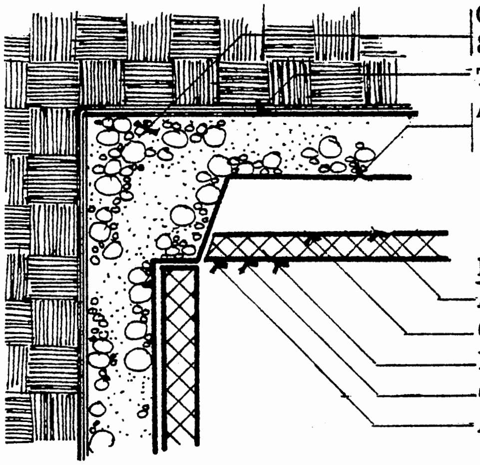
Design for Natural Ventilation

The design for natural ventilation is based upon a wind velocity of 7.5 miles per hour and one foot wide horizontal operable windows continuous about the front of the passive house. The area of the inlet is 33 square feet and the exhause area is 73 square feet (entrance door and skylight). The ratio of outlet area to inlet area equals 2.2 and by interpolation from Table VI, K=4050 which gives an air flow velocity "Q" =1626 feet per minute at the inlet which means that the windows must be adjusted to restrict flow to prevent draft. Because of the velocity of the wind and the safety factor in wind design speed, an adjustable wind collector/shading device may not be required.

The potential of natural ventilation is limited to a maximum effective wind velocity of 700 feet per minute and an extension of the comfort zone to a maximum of 89^{o}F dry bulb for humidities lower than 60%. Therefore, the use of ventilation should be restricted to temperatures below 89^{o}F, even considering the potential cooling effects of mean radiant temperature. From data for Tulsa, Oklahoma, temperatures occur above that range for seven hours in May, 87 hours in June, 175 hours in July, 160 hours in August, 67 hours in September, and six hours in October for a total of 511 hours (33, p. 3-311). During the 511 hours of overheated period (of which 152 hours occur after 5:00 p.m.), windows and insulative curtains should be closed and mean radiant temperature from the walls and ceilings allowed to lower the temperature.

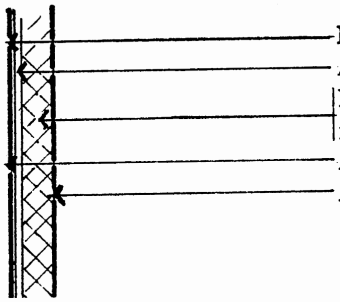
Insulation Standards

Passive House area = 1092 sf.
Wall height = 8'-0" at 0'-8" thickness and 1'-0" height at 1'-2".
Floor thickness = 0'-4" to 1'-4".
Average ceiling thickness = 8.89" of concrete.
Calculation of U values for roof and window insulative panels are shown in Figure 26.



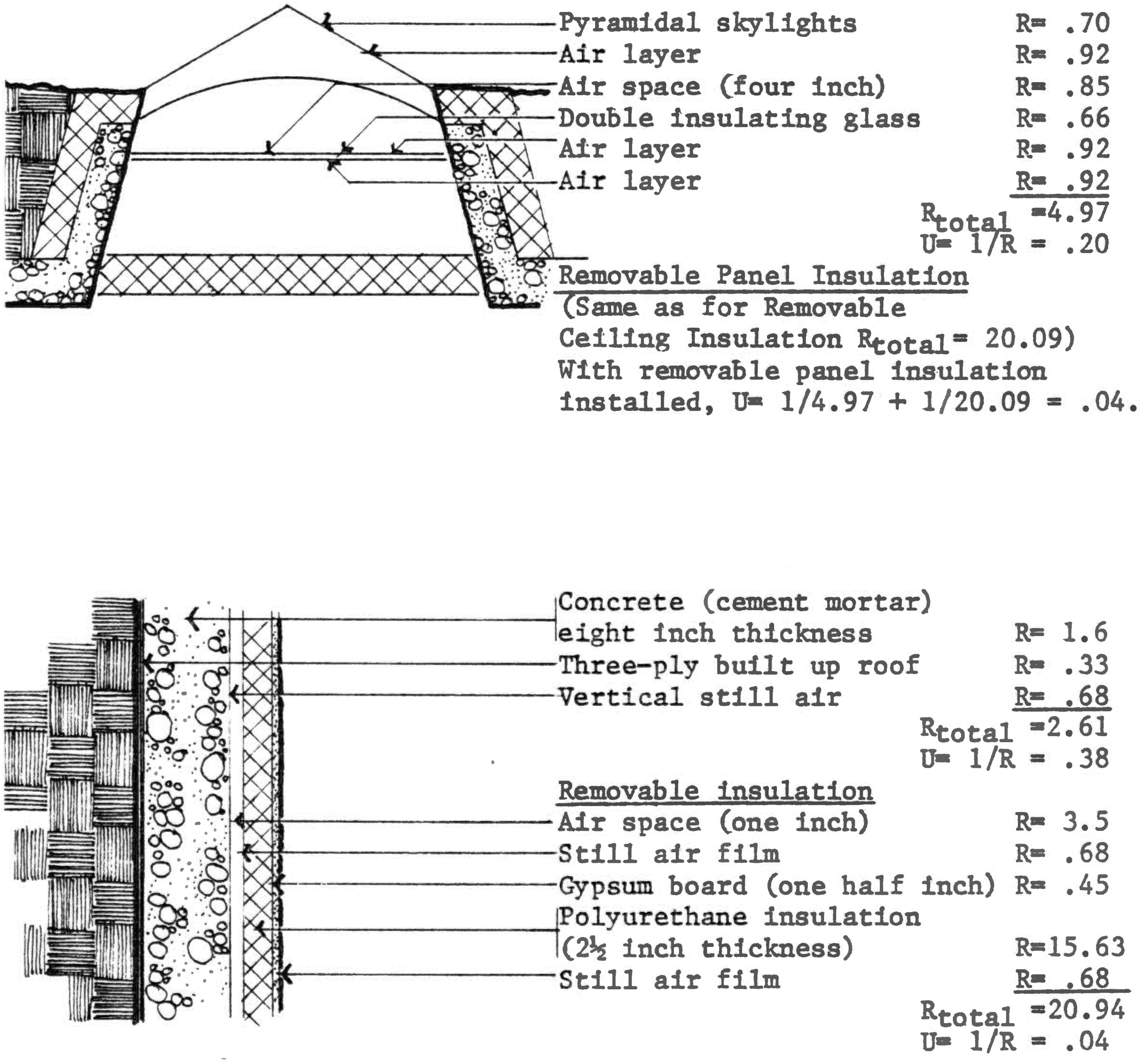
Concrete (cement mortar) 8.89" depth	R= 1.778
Three-ply built up roof	R= .33
Air film horizontal (inside surface still air)	R= .61
R_{total}=	2.72
U= 1/R=	.36

Removable insulation	
Air film horizontal	R= .61
Canvas	R= .06
Polyurethane insulation (3")	R= 18.75
Canvas	R= .06
Air film horizontal	R= .61
R_{total}=	20.09
$U_{overall}$ =	.04



Double glazed window	R= 1.8
Air space (one inch)	R= 3.5
Polyurethane insulation in canvas (2½ inch)	R= 15.625
Air film	R= .68
Air film	R= .68
U_{total} =	.04

Figure 26. Heat Transmission Coefficient Calculation



Pyramidal skylights R= .70
Air layer R= .92
Air space (four inch) R= .85
Double insulating glass R= .66
Air layer R= .92
Air layer R= .92
R_{total} =4.97
U= 1/R = .20

Removable Panel Insulation
(Same as for Removable
Ceiling Insulation R_{total}= 20.09)
With removable panel insulation
installed, U= 1/4.97 + 1/20.09 = .04.

Concrete (cement mortar)
eight inch thickness R= 1.6
Three-ply built up roof R= .33
Vertical still air R= .68
R_{total} =2.61
U= 1/R = .38

Removable insulation
Air space (one inch) R= 3.5
Still air film R= .68
Gypsum board (one half inch) R= .45
Polyurethane insulation
(2½ inch thickness) R=15.63
Still air film R= .68
R_{total} =20.94
U= 1/R = .04

Figure 27. Heat Transmission Coefficient Calculation

Window area = 205 sf (plus two 3'0" x 7'-0" sliding glass doors). "U" of triple-glazed glass patio doors (half inch air space) equals .36 (U) x 1.20 derating factor = .43 for metal frames.

During winter days, heat loss through exposed door areas (AU) equals 50.4 Btuh/°F. AU through windows equals 88.15 Btuh/°F.

Effective Resistance

A method of computing the effective heat flow from the interior has been proposed by Blick (5). For the roof, the effective heat resistance (Re) of the two foot depth of soil for c = .3 sf/day is

$$k = \frac{10.5 \text{ Btu in}}{\text{sf hr }^{\circ}\text{F}} \bigg| \frac{\text{ft}}{12 \text{ in}} = \frac{.875 \text{ Btu}}{\text{hr ft }^{\circ}\text{F}}$$

Therefore Re = x/k = 2.29 and total air to air resistance for the ceiling with insulative panels installed is 27.75. From Figures 1 and 9, the coldest soil temperature (15 February) occurs at an average air temperature of approximately 40.0 °F (late January). For an interior temperature of 40.0°F, heat flow through the 1092 square feet roof area is 1059 Btuh.

Horizontal heat flow through walls appears to stabilize approximately six feet from the outer surface (7). For the six foot soil width, the Re for c = .3 sf/day is

$$Re = \frac{6 \text{ ft}}{} \bigg| \frac{\text{ft hr }^{\circ}\text{F}}{.875 \text{ Btu}} = 6.87 \frac{\text{sf hr }^{\circ}\text{F}}{\text{Btu}}$$

and for subsequent depths, horizontal heat flow is determined by a total resistance of

$$6.87 + 23.55 = 30.42 \frac{\text{sf hr }^{\circ}\text{F}}{\text{Btu}}$$

and by the temperature difference between the undisturbed soil temperature corresponding to the depth of the wall at six feet horizontally from the wall and the air temperature.

For a four feet average depth (two to six feet depth), the isotherms for upper layers tend to migrate upward at rates similar to lower level isotherms (63) therefore, it is assumed that upper level heat flow is horizontal. From Table VII for January 15, soil temperature at four foot depth = 56.8 °F. For an interior temperature of 68 °F,

$$\text{heat flow rate} = \frac{56.8 - 68^{\circ}\text{F}}{(30.42 = \text{Re})} = .38 \text{ Btu/hr sf}$$

For a soil covered wall area of 416 square feet between two and six foot depth, the heat loss is 158 Btuh.

For the eight feet average depth (six to ten feet depth), total resistance for six feet horizontal heat flow is 30.42 and from Table VII undisturbed soil temperature at eight feet depth is 62.0°F. Therefore, heat loss is .20 Btuh/sf and for 416 sf soil covered area, total heat loss is 82 Btuh.

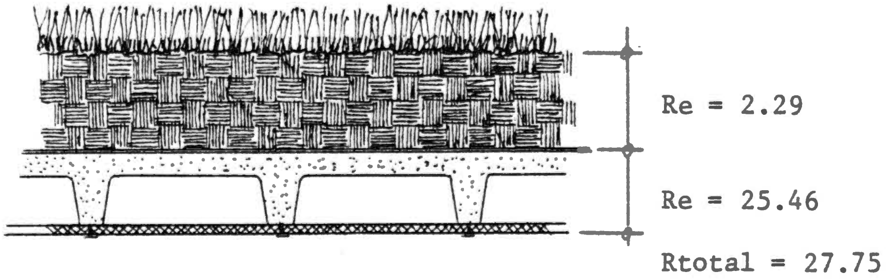


Figure 28. Soil Effective Resistance

Combined worst condition 24 hour heat loss for all soil-covered areas is 31176 Btu. Since heat loss through exposed doors and windows is 138.5 Btuh/ °F for the worst case condition of no insulative curtains drawn and design temperature differential between interior and ambient air temperature of 55°F, the total heat loss from exposed area for 24 hours is 182,820 Btu. Combined with the soil covered areas, the daily total heat loss is 214,000 Btu.

Even assuming the worst case of opened insulative curtains through the night, the January daily insolation is sufficient to provide daily heat. However, the more reasonable practice of closing insulative curtains at night will reduce heat loss to 7313 Btu during twelve hours of closure and daytime heat loss is 91410 Btu, which provides a heat loss of 130,000 Btu/day. Assuming opening of insulative curtains during the sunny periods and closure during nighttime, the passive house could easily withstand two consecutive days without solar insolation.

Comfort Evaluation

Assuming that excesses in solar storage during the winter will be vented to comfortable levels, comfort must be evaluated for the summer months and passive cooling. Work by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (1, p. 12.13) has confirmed that ventilation will not be adequate for providing year-round comfort in Oklahoma.

Using the ASHRAE plane temperature rise method for a plane wall, case 3 (ventilated shelter with earth conduction effects), the temperature rise when ventilation is stopped and the passive house is sealed is determined by

$$F = \frac{c \times \text{hours of overheated period}}{24\ (\text{shelter radius})^2} \qquad (12)$$

where F= dimensionless time function
c= .3 sf/day
8= statistical overheated hours (typically 10:00 a.m. to 6:00 p.m.)
shelter radius = $\sqrt{(\text{inner surface area})}$ = 63.2 ft

and the rise in temperature can be found by

$$\Delta t = \frac{f \times q \times \sqrt{(\text{inner surface area})}}{\text{inner surface area} \times (k)} \qquad (13)$$

where f = dimensionless temperature rise function for F= .0016 and f=.045 (1, p. 12.14)
q = heat generated in the sealed shelter (four persons at 290 Btuh sensible heat)
3994 sf = inner surface area
k= .875 Btuh ft ^{o}F for c=.3 sf/day (1, p. 12.14)
and Δt=.94^{o}F.

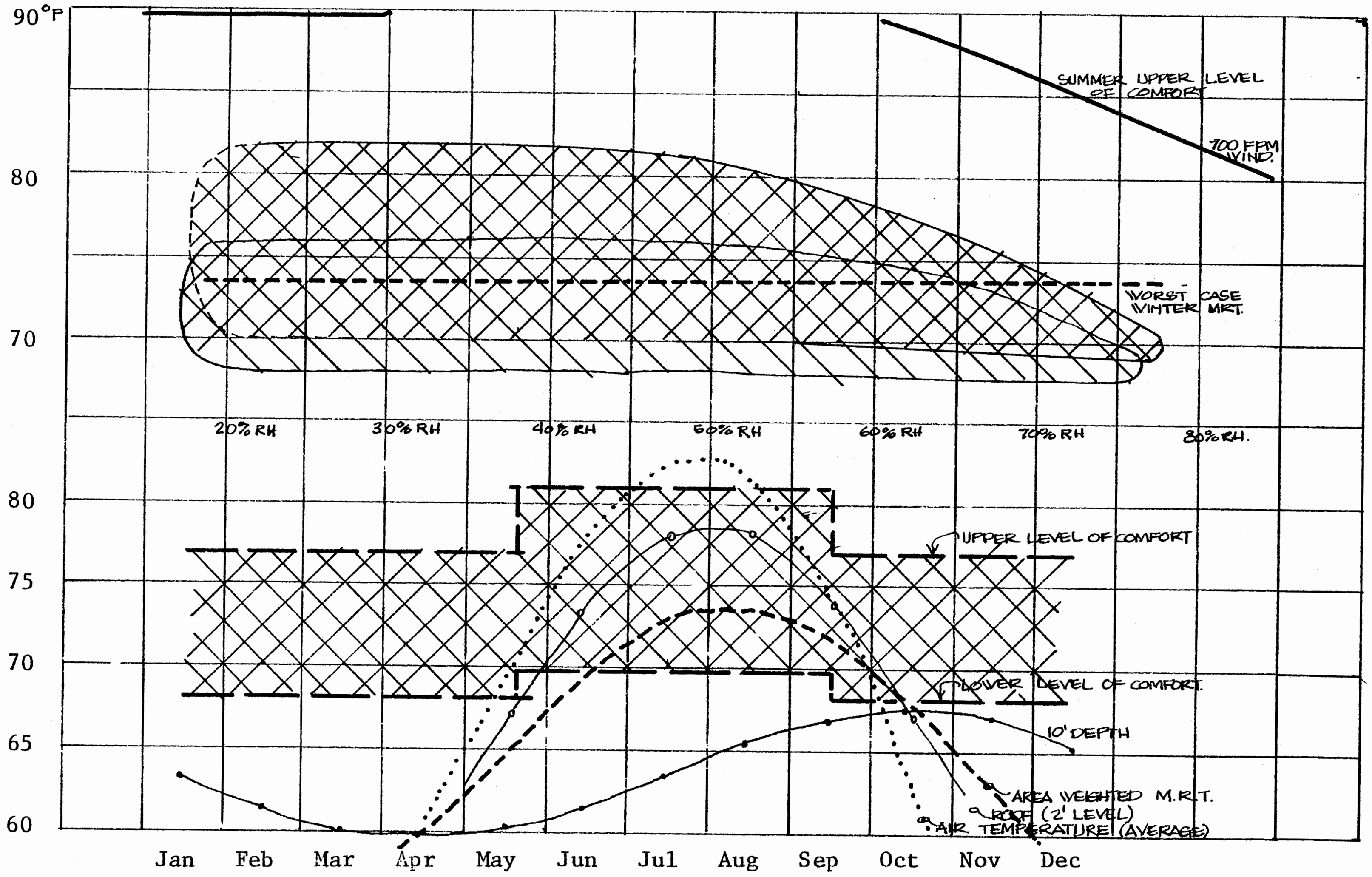


Figure 29. Thermal Comfort--Passive Underground House

Passive Solar Design

The objective of the passive underground house solar design is to eliminate solar radiation input from May 21 through October 21. Maximum air temperature is 77.9°F to 75.0°F in October and average soil temperatures (for soil with thermal diffusivity of .3 sf/day) range from 62°F at an average six feet depth.

The solar shading device must be capable of trapping wind and creating a high pressure area in front of the house. The creation of a high pressure area without creating large inertial losses due to sharp turns in direction of air flow could pose a problem; however, one solution is to use a sun shading device that is adjustable to catch and compress wind. An adjustable sunshade made of materials such as heavy nylon or cloth could be alterable from a maximum extension shade angle of 76° for noon May 21.

Based upon the shaded angles and non-shaded angles, Table XII gives the daily solar insolations levels for clear days for Oklahoma City (1, p. 12.14). Solar insolation levels are based upon 288 sf glass area, a .64 transmittance value for the double glazed glass, and a .98 Clearness factor. Solar insolation levels are expressed in Btu.

TABLE XII

DAILY SOLAR INSOLATION

Sep. 21	Oct. 21	Nov. 21	Dec. 21	Jan. 21	Feb. 21	Mar. 21	Apr. 21	May 21
217482	276189	296599	302380	302020	286484	223443	141977	98806

APPENDIX D

DEEP EARTH CALCULATIONS

Introduction

The deep earth underground conditioning system depends upon large thermal lag, lightweight, low thermal diffusivity soils that receive altered amounts of solar insolation. Deep earth underground housing must provide sufficient thermal lag to offset cool ambient air temperature with high soil temperatures and vice versa. Thermal lag becomes most cost effective when structural load is reduced, usually by the use of lightweight soils of low thermal diffusivity. The soil weight and thermal diffusivity can be lowered by soil mixing. Finally, the soil temperatures can be raised or lowered by increasing or decreasing solar insolation.

Thermal Lag

The most effective thermal lag is 180 days. For a lag of 180 days, the optimum depth may be determined by equation (18). For soil with thermal diffusivity of .05 sf/day (corresponding to a sand and vermiculite mix) and a desired thermal lag of 180 days, the minimum depth is found to be 7.4 feet (21).

$$\text{lag time} = \frac{\text{depth}}{2}\sqrt{\frac{\text{365 days/yr}}{\text{diffusivity (c)}}} \quad \text{for 180 day lag} \qquad (18)$$

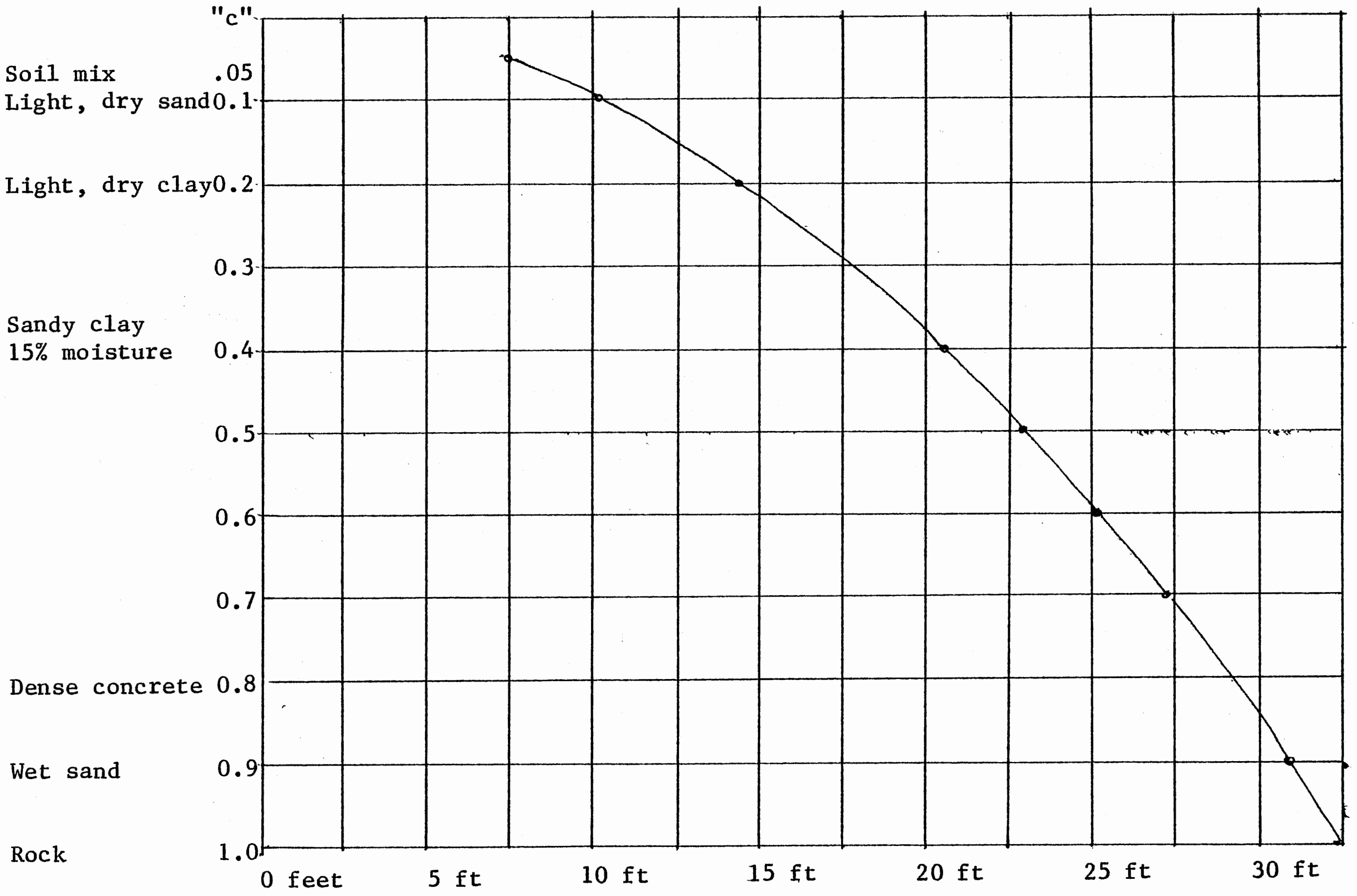


Figure 30. Stable Soil Temperature Depths

Soil Mixing

Soil mixing is the proportioning of the proportional properties of thermal conductivity and specific heat at a given soil density. The method consists of assuming a density and using equation (5) to compute the quantities of soil and insulative capacitance material.

For a fine light sand found in Oklahoma and vermiculite, the calculations are as follows

Specific heat for the light, fine sand is S=.197 at a density of 100 pcf. Thermal conductivity is 4.5 (17, p. 44-57). The vermiculite has a density of 5.0 pounds per cubic foot, Specific heat S=3.20 and k=.47.

Assuming a density of 20 pounds per cubic foot for the mixed soil, and the percentage of sand by weight in the mixture represented by "x", the equation for a required thermal diffusivity of c = .05 sf/day is

$$c = \frac{k}{24 \rho S} \tag{5}$$

$$.05 = \frac{x\ (4.5 + (1-x)\ (.44)}{24\ \rho\ (.197x - 3.20x + 3.20)}$$

Solving for a density of 20 pounds per cubic foot, the percentage of sand in the mix "x" is 18%. Approximate density for the 18% sand, 82% vermiculite mix is 20 pounds per cubic foot.

Alteration of Solar Insolation

Figure 31 indicates that below seven feet, the undisturbed soil temperature for c = .05 sf/day is not within the comfort range. However, Raff has shown that even for areas with less solar insolation than Stillwater, but similar average yearly temperatures, the amount of solar insolation transmitted into the earth may be increased (26). Kusuda has found that black bituminous pavement applied over the earth increases the deep earth soil temperature by absorbing more solar insolation than the soil (18). For sufficiently wide areas, the pavement also controls soil moisture content from above and most importantly reduces heat loss due to evaporation. The effect of the pavement is to raise deep earth temperature by 3.4°F.

Pavement temperatures and the amount of heat transmitted to the soil can be further increased by 3.8°F by adding a transparent cover plate to reduce convective heat loss. By adding reflective insulative panels during the nighttime and cloudy periods, heat lost by radiation can be reduced and the deep earth temperature raised even more. Conversely, to reduce the deep earth soil temperatures in the summer, the panels can be applied during the winter day and opened during the winter night.

Including an estimated two degree lighting and human heat load, the soil temperature is within the comfort range as shown in Figure 31.

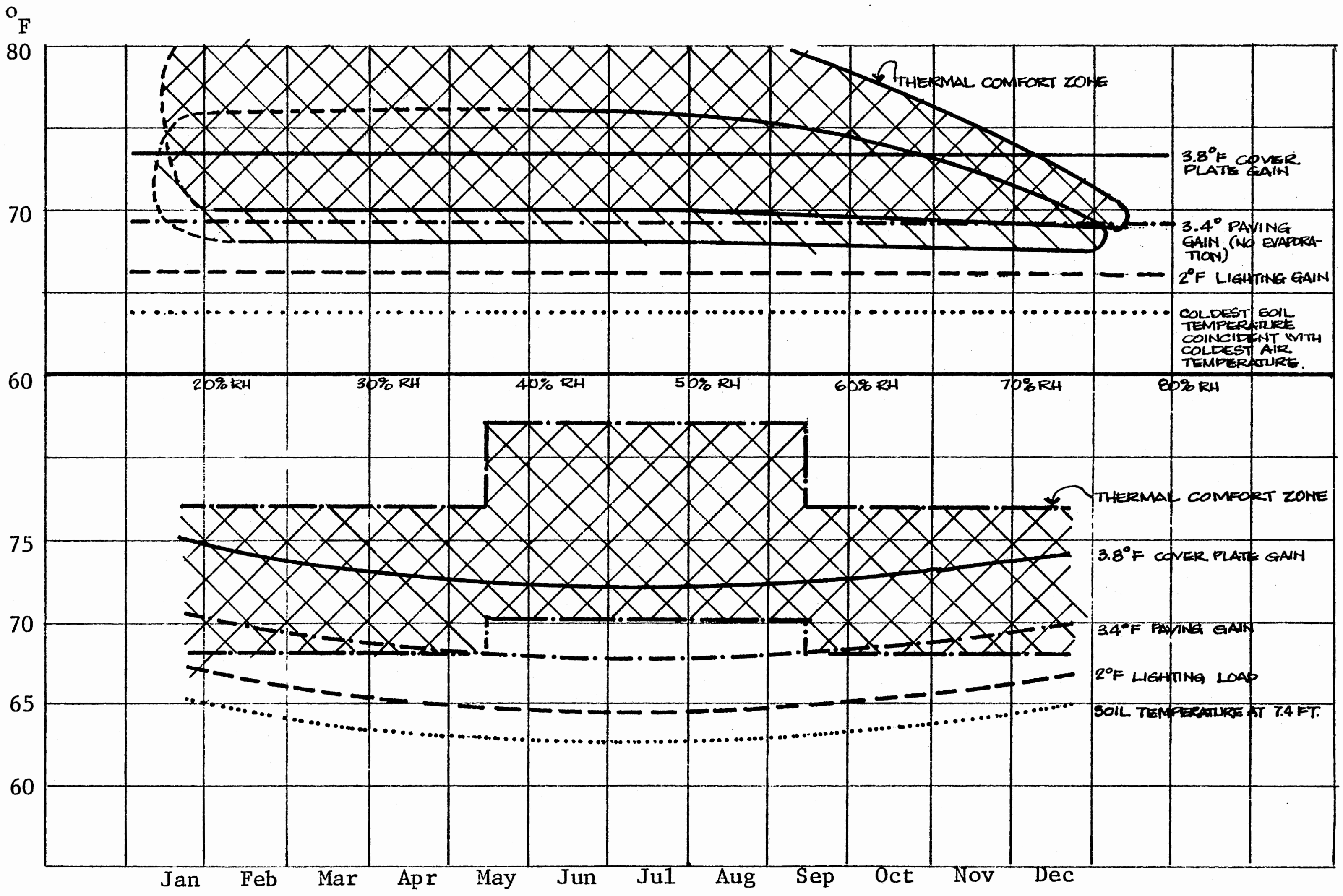


Figure 31. Thermal Comfort--Deep Earth Underground House

APPENDIX E

COSTS AND ASSUMPTIONS

Introduction

The basis of the construction costing data is Means Construction Data 1979 (13, p. 1-254). Costs quoted are primarily based on new commercial and multi-family housing construction; however, for purposes of comparison among similar types of construction it is sufficiently accurate. Electrical energy costs are based upon 1979 Stillwater electricity rates.

Costing Assumptions

Costs quoted in this estimate assume that construction will be accomplished by the same contractor without the assistance of specialty subcontractors and within the same time period. It is further assumed that the contractor is equally able to construct all types of underground houses and that the same overhead and profit will be charged.

Results and Findings

The energy costs for running the heat pump for 7010 kwh/year resulted in a $252 per year energy cost. The cost of operating a ventilation fan in the air handler for the passive house is $22.50 per year. Using interest rates of 12% and an electrical inflation rate of 15%, the present worth energy cost of operating the base house is $5850 for a 20 year life cycle.

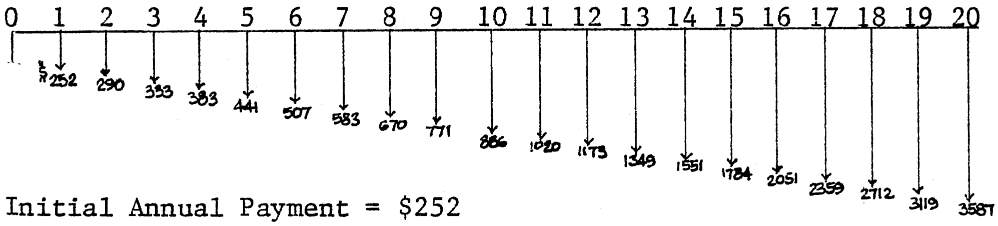
Base House Life Cycle Cost Computation

From the heat loss calculations, all heat pump heating will occur during the off-peak season. Heating requires 2216 kwh/ year. Based upon the Stillwater off-peak rate of \$.03095/kwh for fewer than 600 kwh/month, the heating cost including five per cent tax, six per cent surcharge, and \$.00004573/kwh fuel adjustment is \$76.

2216 kwh x \$.03095 /kwh x 1.05 tax x 1.06 surcharge)
+(2216 kwh x \$.00004573 fuel adjustment / kwh) = \$76.

Cooling costs are based upon 4794 kwh consumption at the peak rate of \$.03295. From the heat pump cooling calculations, 4794 kwh costs \$176 yearly.

Total yearly conditioning costs are \$252. The twenty year life costs including 15% electrical inflation rate are shown in Figure 32.



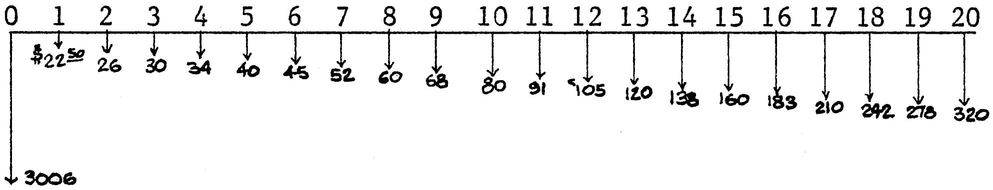
Initial Annual Payment = \$252
Interest Rate = 12%
Electrical Inflation Rate = 15%

$$\text{Present Worth} = \frac{\$252\left[1-(1+15\%)^{20}(1+20\%)^{-20}\right]}{12\%-15\%} = \$5852$$

Figure 32
Life Cycle Cash Flow Diagram
Base Underground House

Passive House Life Cycle Cost Computation

The passive underground house requires the use of the air handler to circulate air and equalize the passive solar input at least during the occupied hours of the day. The energy consumption of the fan based upon ten hours daily usage is 56 kwh monthly. During off-peak rates as calculated for the base house, the eight month winter period use costs \$15.50. Using the air handler to improve heat transfer with the soil during summer overheated periods requires an additional seven dollars cost per year. Using a 15% inflation rate for electricity, the 20 year life cycle cost is \$3530 as shown in Figure 33. The life cycle cost includes the additional construction cost of \$3006 required to incorporate the passive features of the base house. Since the construction cost is due at the beginning of the time period, the difference in cost between the base house and the passive house is a present worth cost. Construction costs are estimated in Table XIII.



Initial Annual Payment = \$22.50
Interest rate = 12%
Electrical Inflation Rate = 15%

$$\text{Present Worth} = \$3006 + \$22.50\left[\frac{1-(1+15\%)^{20}(1+12\%)^{-20}}{12\% - 15\%}\right] = \$3529$$

Figure 33. Life Cycle Cash Flow Diagram
Passive Underground House

Deep Earth House Life Cycle Cost Computation

The deep earth house will provide adequate space conditioning without energy input based upon worst case calculations. Construction cost required to convert the base house to a deep earth house is $16477 based upon the construction estimates in Table XIII.

TABLE XIII

CONSTRUCTION COST ESTIMATES

Description	Quantity	Labor	Material	Cost
Passive underground house				
Backfill excavation	152 c.y.	---	$616	$616
Additional concrete (floor)	1092 s.f.	$816	$306	$1122
Additional polyurethane insulation (with frames)	1984 s.f.	$397	---	$397
Window walls (double glazed)	250 s.f.	$120	$288	$408
Floor finish (delete carpet, add quarry tile)	320 s.f.	$93	$370	$463
Draperies (delete for insulative curtains)	job	---	$250	($250)
Passive Underground House construction cost =				$3006
Deep Earth Underground House				
Additional excavation	502 c.y.	$406	$281	$687
Vermiculite	122 c.y.	---	$5327	$5327
Mix sand and vermiculite	1219 c.y.	$3352	---	$3352
Additional backfill	502 c.y.	---	$2987	$2987
Sand	1097 c.y.	$878	$1097	$1974
Compaction (6" lifts)	502 c.y.	---	$2033	$2033
Bituminous pavement	254 s.y.	$597	$206	$803
Additional Concrete and steel	8 c.y.	$216	$426	$742
Glazing for collectors	2300 s.f.	$24	$23	$47
Additional Skylights	2 each	$180	$250	$340
Delete heat pump				($1080)
Delete one door				($268)
Delete sodding				($367)
Deep Earth Underground House construction cost =				$16477

VITA

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