EARTH SHELTER TEST FACILITY AT OKLAHOMA STATE UNIVERSITY FOR ENERGY RELATED INVESTIGATIONS: PROGRAM AND CONCEPT DESIGN

By

JOSEPH HENRY HACKNEY

Bachelor of Architectural Studies

Oklahoma State University

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Thesis Approved:

Lester L Boyer
Thesis Adviser

Walter

James E Bose

Norman N Durham
Dean of Graduate College

PREFACE

This study is concerned with the development of an emperical means of qualifying and quantifying various energy-related aspects of earth sheltered buildings in temperate to warm climates such as found in Oklahoma. The underlying goal is to develop a program and provide conceptual design alternatives for a test facility which will provide the necessary data to determine the energy-saving potential of earth sheltering as a design alternative. A questionnaire, sent to selected professionals in the field of earth sheltering, aided in the identification of useful investigations and testing procedures. These investigations may be performed to provide information to professionals involved in research, design, and engineering concerning the relative impact of various design strategies on the total energy performance of earth sheltered buildings.

The author wishes to thank his major adviser, Dr. Lester L. Boyer, for his guidance, assistance, and instruction throughout this study. Gratitude is also extended to Professor Walter Grondzik for his invaluable assistance and support and for introducing me to a cognizance of earth sheltering far beyond the scope of this study. Much appreciation is given to Dr. James Bose for his interest and criticism in the preparation of the final manuscript. Thanks are also extended to Professor James Knight for his assistance in the area of design.

A special note of appreciation is also given to the professionals throughout this country and abroad whose responses to the questionnaire provided an invaluable base on which to develop a reasonable thermal model for earth shelter investigations.

Finally, to my wife, Laura, I owe the largest thanks for her unending support and for countless hours at the keyboard typing this manuscript.

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NOMENCLATURE

A_s	Amplitude of surface temperature wave (F)
α	Thermal diffusivity of soil (ft^2/day)
Btu	British thermal unit
C	Degrees Centigrade
CDD	Cooling degree days
cm	Centimeter(s)
$^\circ$	Degrees
e	Exponential
EPS	Expanded polystyrene
F	Degrees Fahrenheit
F factor	Window opening (height)/projection
ft	Feet
ft^2	Square feet
ft^3	Cubic feet
HDD	Heating degree days
hr	Hour(s)
in.	Inch(es)
J	Joules
K	Degrees Kelvin
km	Kilometer(s)
l	Liter(s)
m	Meter(s)
m^2	Square meter

m/s	Meters per second
MHFA	Minnesota Housing Finance Agency
mi	Mile(s)
mph	Miles per hour
min	Minute(s) (time)
'	Minutes (angular)
mm	Millimeter(s)
π	Pi
T_m	Mean annual soil temperature
$T_{(x,t)}$	Temperature of soil at depth x at time t (F)
t	Time of year (days, where 0=midnight Dec. 31)
t_o	Phase constant (days)
x	Depth below surface (ft)
W	Watt(s)

CHAPTER I

INTRODUCTION

The number of earth sheltered buildings being built in Oklahoma and other areas throughout the country has increased substantially since the late 1970's. Earth sheltering is also growing in other parts of the world where energy costs and availability impose as great or greater restraints on architectural design as have been experienced in this country.

Space heating and space cooling energy requirement reductions are undoubtedly the most important reasons for using earth sheltering (1). However, how does one evaluate these benefits in a quantitative manner to decide if earth sheltering is a cost-effective alternative to other conventional and low energy types of structures? And how may energy-related features of a particular design be optimized for a given climate?

Background

Williamson Hall

A limited number of research facilities have been developed around the country in recent years to investigate the energy potential of various earth shelter design strategies. Most facilities are occupied buildings which provide heat transfer information, as well as total energy performance data. One of the largest occupied buildings monitored is Williamson Hall, a large three-story, 83,000 ft^2 (7711 m^2) earth sheltered building housing a student book store and records and admissions offices for the University of Minnesota. The monitoring of Williamson Hall is paired with the development of a transient two-dimensional heat transfer model. Aspects of the thermal characteristics of earth sheltered walls are investigated, including variables such as soil thermal properties and different types of ground cover (2).

Minnesota Housing Finance Agency

The Minnesota Housing Finance Agency (MHFA) has underwritten construction costs of seven occupied earth sheltered housing projects, two of which have fairly extensive instrumentation to determine the heat transfer through the building envelope and monitor each component of the building's energy use separately. The remaining projects are mainly being monitored for interior/exterior conditions and total energy use (3).

One of the main objectives of the MHFA research is to compare energy consumption for earth sheltered housing against conventional above-ground counterparts. Comparisons made between individual test houses are also helpful in design optimization.

Ohio State University

Residential heating and cooling loads were studied as part of an extensive research project at Ohio State University which included monitoring an unoccupied house basement to develop a calculational procedure to determine the design heat loss through basement walls (4). The modeling method which accompanied the monitoring program was a finite difference analysis using a two-dimensional grid spacing of 8 in. (20 cm) which was dictated by the eight inch concrete block basement walls of the test house. The model was found to be reasonably accurate although several parameters were either neglected (solar radiation) or averaged to simplify the model; e.g., the outside ground surface convective heat transfer film coefficient and deep ground water temperature. Also, the thermal conductivity of the soil was considered constant over each season. The researchers did not expect any major inaccuracies as a result of these assumptions (4).

Passive Technologies Test Facility

Smaller, more controlled spaces may be monitored to provide specific information concerning design strategies. An earth sheltered research facility known as the Passive Technologies Test Facility was constructed at Ames

Laboratory Applied Sciences Center, Ames, Iowa, to check the accuracy of a two-dimensional simulation model (5). The facility was designed to investigate both passive solar and earth sheltered building thermal performance. Three passive solar test cells are housed in the earth sheltered building, sufficiently isolated by insulation to allow the independent testing of each cell. Instrumentation is designed to measure the heating and cooling requirements of the building, heat exchange between the building and surrounding soil, and heat gain from solar energy. The facility has been used to validate a two-dimensional transient Fourier heat conduction equation, indicating that the annual cycle energy performance of earth sheltered buildings can be predicted accurately using the simulation model (6).

Los Alamos National Laboratory

Passive solar research is closely related to earth shelter research both in principle and in monitoring techniques. Thermal massing is inherent in both strategies and both involve the thermal performance of buildings. Los Alamos National Laboratory (LANL) has been the site of extensive research using passive solar test cells for validation of simulation models, comparison testing, and heat transfer measurements (7). Small test boxes are used for comparison testing where convective flow is not a parameter, and test rooms, full scale in height, allow direct analogies to actual building performance where vertical convection effects are important. The test rooms are usually constructed at a reduced scale in width and depth, but the ratio of heat loss to collection area is maintained similar to that of actual passively solar heated buildings. More recently, a test apparatus was built at LANL to study natural convection solar collector thermal performance (8).

National Center for Appropriate Technology

The National Center for Appropriate Technology in Butte, Montana has conducted research in passive solar heating by investigating direct gain and Trombe wall performance with test cells (9). Thermocouples are used to measure temperature profiles through the Trombe wall mass and direct gain floor and wall masses, as well as interior and exterior ambient temperatures. A pyranometer mounted on a vertical south-facing surface measures solar radiation at the site. These variables were used to develop a computer simulation model which describes the flow of energy through the Trombe wall and direct gain masses.

The different theoretical methods used in these projects indicate that no explicit guidelines exist in describing the thermal behavior of underground buildings and surrounding soil. In fact, a questionnaire sent to selected professional experts in the field of earth shelter research reveals that a great difference of opinion exists in identifying the thermal behavior of soil near underground buildings (Appendix A) (10). An acceptable method is needed to delineate the energy-related aspects of earth sheltering. Computer simulation models should be developed for this purpose, but physical monitoring of various earth shelter design concepts is required to validate to such models.

Most of the earth shelter research facilities which exist today are located in cold climates. Consequently, very little monitored data is available for passive cooling characteristics of underground buildings in temperate and warm climates. A major thrust of research at an Oklahoma facility would be directed toward providing valuable information related to summer thermal phenomena associated with earth sheltered buildings.

A majority of current energy-related earth shelter investigations are based on monitoring existing buildings. Usually, individual components which may affect the energy performance of a building have not been isolated to determine their thermal characteristics and relative importance. The earth shelter research facility proposed here will be used to investigate individual building components, construction assemblies, and systems to provide documentation for design optimization. And, because the facility is geared toward the monitoring of isolated building elements rather than buildings themselves, many investigations may be carried out on a small scale using a flexible facility designed with easily changeable elements.

Goals and Objectives

The underlying goal of this thesis is to develop a program and concept design alternatives for a test facility which will provide the necessary data to determine the energy-saving potential of earth sheltering as a design alternative. In order to provide a useful and flexible facility, the following objectives must be considered in the design:

1. The energy performance aspects of various construction materials should be investigated with the facility.

2. The facility should be used to determine the potential of earth contact cooling.

3. The potential for combining earth sheltering with passive solar heating strategies should be incorporated into the design of the facility.

4. The design should also permit validation of existing mathematical simulation models by maintaining appropriate physical and thermal properties for the models.

Scope and Limitations

The scope of this thesis includes the submission of several possible concept design strategies for a test facility as well as the identification of associated monitoring equipment and systems and materials to be tested. A required size of the facility is determined and information leading to the size requirements of the data acquisition system is given.

The design of the facility is limited in that not every type of design strategy can be economically modeled, constructed and operated to provide specific guidelines for design optimization. Even the systems that are designed for testing may provide only a theoretical approximation of "real-world" energy performance, since there are far too many variables in actual occupied buildings which cannot be controlled under testing situations. Therefore, many of these variables must be assumed constant or maintained at constant values to allow specified variables to be measured accurately. The design of the facility is focused toward testing strategies that are widely used or potentially favorable in the Oklahoma region. This is not to say the data collected from a facility in Oklahoma cannot be useful in other areas. General statements about optimum earth shelter design strategies may be made for many regions throughout the world which are climatically similar to Oklahoma.

Procedure

The thermal behavior of an earth sheltered building, as with any building, is totally dependent on the environmental conditions to which the building is exposed (ignoring the effects of occupants on the thermal behavior of the building). This thesis explores the environmental factors associated with the proposed site of the facility in order to develop a base for determining the appropriateness of possible investigations. Questions concerning earth sheltering and parameters of investigation to be addressed with the facility are then outlined. A description of the facility is given and site planning considerations are discussed. A description of the monitoring sensors, as well as their location, is provided. Finally, the size of the facility is determined based on the investigations outlined and recommendations concerning the size of test rooms and layout of the facility are given.

CHAPTER II

CLIMATE OF STILLWATER, OKLAHOMA

In order to determine the appropriateness of investigating certain thermal concepts with respect to earth sheltering in Oklahoma, the region's climate must be known. A thorough description of Oklahoma's climate will provide a base from which to weigh the relative benefits of each concept. For instance, investigating the thermal effects of snow cover on underground buildings is not appropriate in temperate and warm climates because the condition rarely exists.

The earth sheltered test facility is proposed to be located on Oklahoma State University property near the main campus. Figure 1 shows the area surrounding Stillwater which is owned by the University. For the purpose of determining the climate at the site, the facility is assumed to be located on this property.

Stillwater is located 65 mi (105 km) northeast of Oklahoma City at coordinates 36°07' latitude, 97°05' longitude with a ground elevation of 895 ft (273 m). The terrain is rolling hills and broad, flat floodplains fed by many small streams. Neither lakes, rivers, nor numerous livestock and flood control ponds seem to affect the area's climate.

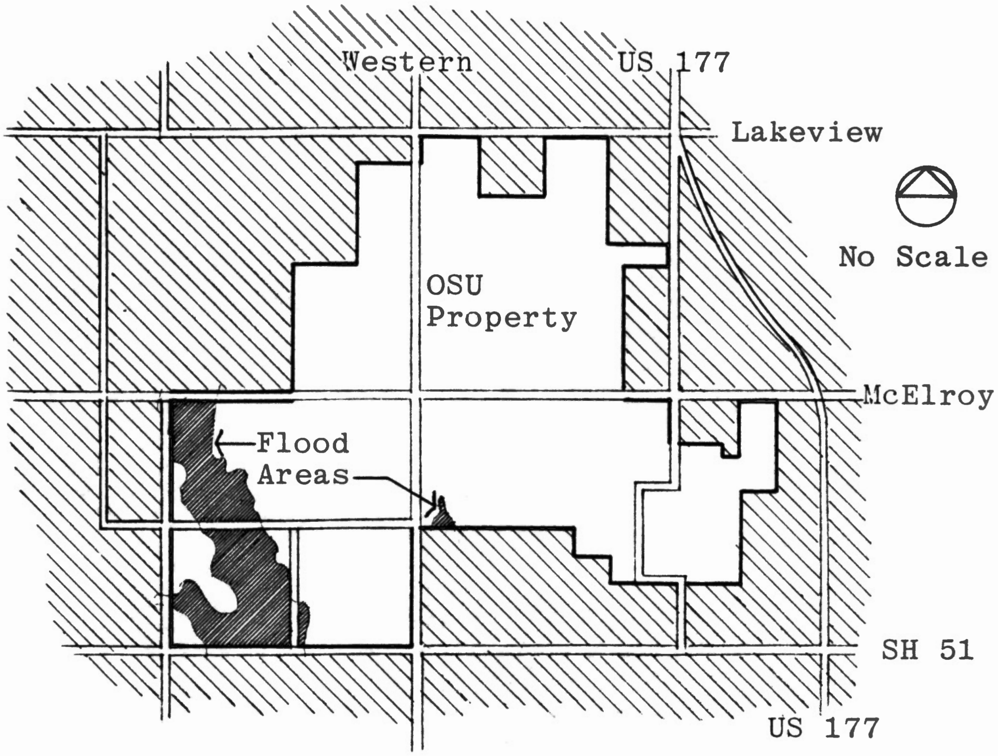


Figure 1. Probable Facility Location, Avoiding Adjacent Flood Areas

The climate of Stillwater is temperate to warm with wide seasonal variations and occasionally wide daily variations in both temperature and precipitation. The winter months of December, January, and February are generally moderate with extreme cold temperatures on some occasions. The average maximum winter temperature is 50.4F (10.2C) and the average minimum is 26.9F (-2.8C). Only twelve percent of the annual precipitation is recorded during this season. The seasonal snowfall averages 8.28 in. (21 cm) with the number of days of snowfall amounting to one in. (2.5 cm) or more being 2.3 days (11).

The summer season of June, July, and August sees quite warm temperatures and a high percent chance of sunshine. However, low humidities and good southerly breezes sometimes lessen the discomforting affect of the high temperatures. The average maximum summer temperature is 91.4F (33.0C) and the average minimum temperature is 68.2F (20.1C). The greatest amount of rainfall occurs during this season with 30 percent of the annual rainfall being recorded.

The spring season of March, April, and May is the most changeable time of the year when extreme conditions may occur. Approximately 31 percent of the annual rainfall and 24 percent of the annual snowfall occur during this season and severe thunderstorms and tornadoes may develop.

The fall season, September, October, and November, is a much more pleasant transition period than the spring. A high percent chance of sunshine exists and 26 percent of the annual rainfall occurs as steady rains. About 8 percent of the annual snowfall occurs toward the end of the season.

The total precipitation averages 32.71 in. (83 cm) annually, including the seasonal snowfall average of 8.28 in. (21 cm). The potential evaporation from April through October is 61.48 in. (1.56 m).

The percent possible sunshine, derived from interpolation of data from Oklahoma City and Tulsa, is approximately 55 percent during the winter and 75 percent during the summer (Table I). The mean annual percentage of possible sunshine for Stillwater is 65 percent (11).

TABLE I

Mean Monthly Percentage Sunshine
for Stillwater, Oklahoma

JAN	55%	MAY	62%	SEP	75%
FEB	55	JUN	70	OCT	70
MAR	60	JUL	75	NOV	65
APR	60	AUG	75	DEC	55

Prevailing winds are southerly during most of the year but northerly winds predominate during the winter months. The average yearly wind speed is in the neighborhood of 12 mph (5.4 m/s).

The soil in the proposed area of the facility consists of very fine sandy or silty loams (12). A more definitive description of the soil at a particular site, including soil type and particle size, must be determined by a soil test.

The water table is a very important consideration in the choice of a site for underground buildings. More importantly, water table information is not readily available to prospective buyers. Therefore, test holes must be drilled at a proposed site to determine the water level, which may vary greatly from neighboring sites. In light of this, test hole information from other sites may be somewhat helpful in a preliminary evaluation of a potential site for the facility. Test holes drilled within a five mile radius of Stillwater record water tables between 11 and 32 ft (3.3 and 9.8 m). Of course, test holes will have to be drilled at the potential site, when chosen, for the determination of the ground water depth for the site.

The ground water temperature is useful in determining the soil temperature at a particular site. Labs (13) states that the best estimate of steady state ground temperature may be obtained by taking the temperature of nonthermal water wells. Five test holes for which water temperature has been measured, located in various regions of Payne County, were within 1.8F of 62.6F (1C of 17C) indicating that the expected ground water temperature at the site will be near 62.6F (17C) (14).

The potential threat of flooding of the facility should also be considered, as this would be disastrous for any expensive equipment at the site, as well as the testing which may be required to run continuously without disruption for months or years. Figure 1 shows the standard projected flood areas of the region (15). Standard projected floods are floods of rare occurrence and, on most streams, are considerably larger than any floods that have occurred in the past.

The slope of the site is not of utmost importance since very little of the land in the Stillwater area exceeds a 15 degree slope. The site is assumed to be relatively flat so that berming and covering will probably be required for much of the facility. However, this allows for control and flexibility in the design of the facility and soil type used for backfill and berming.

CHAPTER III

PARAMETERS UNDER INVESTIGATION

From the previous discussion of the climate and site characteristics, it is evident that several energy conservation concepts are valid for earth shelter design in Stillwater's climatic region. In fact, the concepts which will be identified here are valid for any area where similar climatic characteristics exist.

After developing a list of questions concerning energy performance of earth sheltered designs (Appendix A), several general areas of energy-related design may be identified which warrant investigation. These include materials of construction, ground temperature control, earth coupling, insulation, earth shelter/passive solar integration, and model validation. Various aspects of these designs may be tested for "proof of concept", performance, and comparison. Proof-of-concept testing will determine if a given design strategy actually has useful potential under certain conditions. Performance testing will determine how well a concept works, and comparison testing will determine which concept works best.

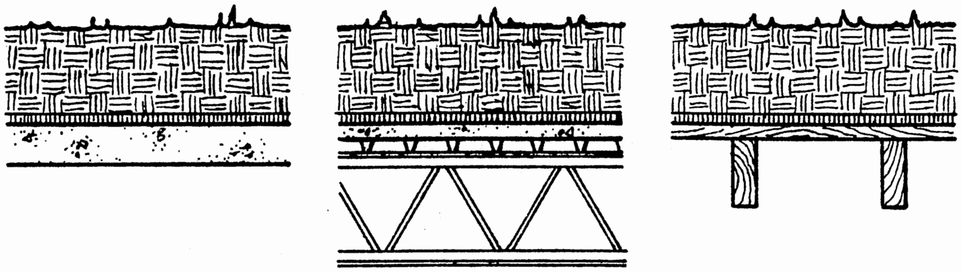
These particular investigations are chosen for several reasons. First, most of the concept investigations which are developed here have little or no existing documentation. Therefore, results from testing these concepts will provide new information to develop simulation programs, design tools and evaluation methods for earth sheltered buildings. Second, many of these concepts are useful only in temperate to warm climates where the facility will be located and where an existing data base of technical information is deficient. Finally, some of the investigations are developed in order to determine the extent of degrading effects of commonly known poor design elements. For instance, the fact that the use of under-floor insulation is not beneficial to an underground building's total energy performance is universally agreed upon, but, the actual effect of this feature on the total energy performance has not been determined. This information may be important to owners with regard to the comfort of the cooler temperature of a floor without insulation. The investigations outlined here reflect an attempt to gather as much data about the various design elements of earth sheltering as possible in order to gain a complete understanding of the energy aspects of underground buildings.

Materials Of Construction

Earth shelter design is not limited to a single type of building construction techniques. Many materials are available which work well in underground applications. The most common materials for earth sheltered buildings are concrete, concrete block, steel, and wood. Because these materials possess different thermal characteristics, one might be chosen over another in a given situation for energy reasons. However, there are other factors involved in selection of materials such as cost, availability and aesthetics. The question is whether the energy aspects of a certain material outweigh the other factors. With this in mind, the relative thermal performance of the available materials of construction should be determined to provide energy conscious designers with documentation for making material selections.

These materials are commonly used in the construction of earth covered roofs; concrete, steel deck and joist, and wood plank and beam. Because most earth sheltered buildings are designed with 2 to 3 ft (0.6 to 0.9 m) of earth cover over the roofs, all of these materials may be appropriate with respect to structural performance. However, no documented information is available to aid designers in the assessment of these materials with respect to thermal performance.

With a specified amount of insulation and earth cover, these materials will produce roof assemblies with different thermal characteristics. For example, Figure 2 shows three roof assemblies using the same amount of insulation and earth cover. The concrete roof construction obviously possesses the most mass, which will improve the thermal stability of a building. However, the extra construction costs of concrete over steel deck roofs may not justify the mass added to the building. Also, the thermal resistance of wood may make the wood plank and beam construction more appropriate. By conducting investigations using monitored building assemblies the relative importance of the thermal characteristics of these roof materials may be determined.



a) Concrete b) Steel c) Wood

Figure 2. Roof Assemblies

Earth-backed walls are usually constructed of concrete, concrete block, or wood. These materials may be tested in a similar manner as roof assemblies to provide thermal performance data for design optimization. Concrete and concrete-filled blocks possess similar thermal characteristics, but both may be tested to determine actual thermal properties for the development of design tools. Wood obviously will decouple an underground building from the surrounding soil due to its insulative properties. The determination of the extent of the decoupling will be useful in the consideration of wood as a construction material in temperate climates.

A thermal phenomenon which may be worth considering in earth sheltered buildings is the relatively high thermal conductance of reinforcing steel. When earth-backed walls are constructed of concrete, they contain a substantial amount of reinforcing steel running in both the vertical and horizontal directions. During winter months, an undetermined amount of heat may migrate upward through the walls of earth-backed walls increasing heat loss from the building. Frost and freezing have occurred inside some buildings because of this phenomenon. This heat flow reverses in direction during summer months and may displace any passive cooling potential that the building may have. Monitored reinforcing steel temperatures at various heights in an earth-backed wall may provide data to determine the relative effect of this phenomenon on the overall energy performance of a building, as well as the extent of localized effects.

Table II outlines the construction materials investigations to be performed. These materials will probably not be tested independently, but may be used in conjunction with other parameters mentioned later.

Investigation #1 - What building materials, in sequence, are the most thermally appropriate for use with a given amount of insulation and earth cover?

This investigation will compare the effects of various roof construction materials on the thermal characteristics of the total roof assembly (Tests 1 through 4; Table II).

TABLE II

MATERIALS OF CONSTRUCTION

PARAMETER	VARIATION	TEST 1	2	3	4	5	6	7	8
Roof	8 in. (0.2 m) Poured Conc	X							
	12 in. (0.3 m) Poured Conc		X						
	Steel Deck/Joist			X					
	Wood Panel/Beam				X				
Wall	8 in. (0.2 m) Concrete					X			
	12 in. (0.3 m) Concrete						X		
	8 in. (0.2 m) Conc Block							X	
	Wood Panel/Stud								X

Investigation #2 - How do concrete, concrete block, and wood compare with respect to thermal performance of earth-backed walls?

This investigation will determine the difference in overall thermal performance of various earth-backed wall materials (Tests 5 through 8; Table II).

Investigation #3 - What thermal degradation effects, if any, are caused by heat flow along reinforcing steel rods?

The relative importance of this phenomenon will be determined by monitoring the reinforcing steel in an earth-backed concrete wall (Tests 5 and 6; Table II).

Ground Temperature Control

The use of soil as a buffer to decrease thermal load penetration and, therefore, energy use in buildings has increased rapidly within recent years. However, very little attempt has been made, either in design or in practice, to modify existing soil temperatures to improve thermal performance. Raff (16) contends that the average ground temperature in the Washington, D.C. - Baltimore area could be brought into the comfort zone if raised by 13F (7C) or more. In the Stillwater, Oklahoma area, the annual average undisturbed deep ground temperature is approximately 63F (17C) (13,14). This average value is only 5F (2.8C) below the lower limit of the winter comfort zone as defined by Olgyay (17). At shallower soil depths which surround underground buildings, the soil temperature may be cooler than 5F below the comfort zone in winter, but as the building loses heat to the surrounding soil, the disturbed temperature of the soil will rise closer to comfort conditions, decreasing the short-term heat loss from the building even more. Ground temperature control methods may raise the ground temperature to further decrease heat loss during cold months and also lower the ground temperature to decrease heat loss to the soil during warm months.

The temperature at any given soil depth and time of year may be approximated by the equation:

$$T_{(x,t)} = T_m - A_s \cdot e^{-x\sqrt{\pi/365\alpha}} \cdot \cos\left[2\pi/365(t - to - x/2\sqrt{365/\pi\alpha})\right]$$

where
$T_{(x,t)}$ = temperature of soil at depth x at time t (F)
T_m = mean annual soil temperature (F)
A_s = amplitude of surface temperature wave (F)
x = depth below surface (ft)
α = thermal diffusivity of soil (ft^2/day)
t = time of year (days, where 0=midnight Dec. 31)
t_o = a phase constant (days)

Figure 3 shows the monthly deviations from Olgyay's comfort zone of predicted undisturbed ground temperature at various depths for the Stillwater area derived from this equation (13). The solid lines represent undisturbed soil temperatures at depths from 2 to 12 ft (0.6 to 3.6 m). As depth increases, the undisturbed winter ground temperature moves closer to comfort conditions. Also, the summer ground temperature at greater depths becomes lower than comfort conditions. This would not necessarily eliminate the space cooling load of an earth sheltered building, but the lower portion of the building may actually be losing heat to the soil, resulting in a smaller load. It is important to note that errors would result from designing for earth contact cooling when using undisturbed ground temperatures without considering the thermal effects the building will have upon the soil surrounding it.

Akridge's (18) Decremented Average Ground Temperature Method takes into account the thermal effect of an underground building on adjacent ground temperatures. This method may be used to estimate to what extent the adjacent ground is heated up by the building. For Oklahoma's climate, an underground building with the interior temperature maintained at 70F (21C) will raise the temperature of the adjacent soil by more than 5F (2.7C) if no insulation is used. Therefore, soil temperatures averaged over a depth of 2 to 12 ft (0.6 to 3.6 m) appear to indicate only a small potential for passive earth-contact cooling availability during summer months but this may be increased using ground temperature control techniques. Also, maintaining winter interior temperatures at 68F (20C) and summer interior temperatures at 78F (26C) may further increase this potential.

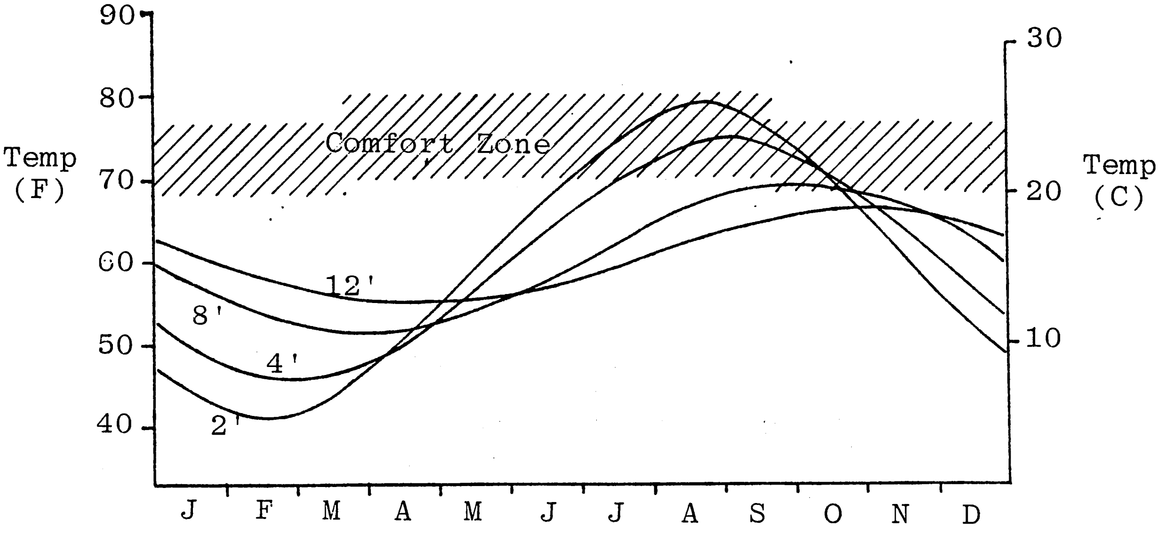


Figure 3. Undisturbed Soil Temperatures in Stillwater, Oklahoma

Natural parameters which affect soil temperature can be classified into three groups (19). Geographical parameters include latitude, altitude, local air temperature variations, rainfall, snowfall, wind, and solar radiation. Nighttime radiation potential, in which the ground surface re-radiates heat to the night sky, is also based on geographical location. Site parameters include the ground surface conditions, landscaping, shading, irrigation, and water table. Soil properties including thermal and physical properties, such as moisture content and packing density, also affect soil temperature.

Many of these parameters can be controlled to modify the ground temperature surrounding an earth sheltered building. Variations in soil thermal conductivity may be caused by seasonal fluctuations in moisture content. The soil moisture content may be manipulated to improve the thermal regime surrounding an earth sheltered building. For a given moisture content, the thermal conductivity of a soil is inversely proportional to the liquid and plastic limits. 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. Various methods may be used to lower these limits to improve the thermal diffusivity of the soil. Mixing insulative materials such as perlite or vermiculite into lime modified soils could reduce the thermal diffusivity of the soil to improve its damping effect from outside temperatures (20).

Another method of soil temperature modification might be to layer soils with differing thermal characteristics to improve the total thermal regime surrounding earth sheltered buildings. In temperate to warm climates, where passive earth cooling may be very beneficial, a high thermal diffusivity is preferred at greater depths to assist the heat sink effect. However, near the ground surface, a low thermal diffusivity is preferred to decrease heat gain to the building. This is shown graphically in Figure 4. The determination of the design depth of the neutral plane (where the heat transfer changes in direction) is necessary for the layering method to be most effective.

Givoni (21) has conducted research in the area of ground temperature control using gravel layers surrounding buildings to provide cooling storage during the winter (Figure 5). This may work well in temperate to warm climates such as Oklahoma because the thermal conductivity of the gravel layer can be changed using irrigation during different seasons. In the winter, the gravel will be kept as dry as possible to decrease heat loss. In early spring, the gravel may be irrigated and cool outside air may be introduced to develop a cool reservoir. As summer progresses, irrigation will improve the heat sink effect at lower portions of the building. It would be beneficial to introduce the moisture at the gravel layer, keeping the layer above dry to decrease heat gain to the building.

During cold months, the soil should be kept dry to decrease heat loss from the building. Umbrella-type construction, where the roof insulation is extended horizontally beyond the perimeter of the building, not only increases the effective thermal mass of the building, but can protect the ground surrounding the building from moisture, thus decreasing heat loss from the building during the winter (Figure 6).

These concepts may be investigated separately to determine their effect on total energy performance. Both concepts may also be combined to provide ground temperature control in both heating and cooling seasons. This could be accomplished by locating irrigation pipes below the insulation to raise the moisture content and, thus, thermal conductivity of the gravel or soil layer below to increase the passive cooling potential of the earth-backed walls. The soil above the insulation would remain dry, decreasing heat gain to the building through the roof.

Ground surface treatment can also affect soil temperature. Grass or natural ground cover will shade the ground surface by intercepting solar heat and will dissipate this heat through evapo-transpiration. Evaporation rates from irrigated grass range between 1 and 2.5 in. (2.5 and 6.3 cm) of water per week, depending on climatic region, for the dryest month of the cooling season. Water absorbs

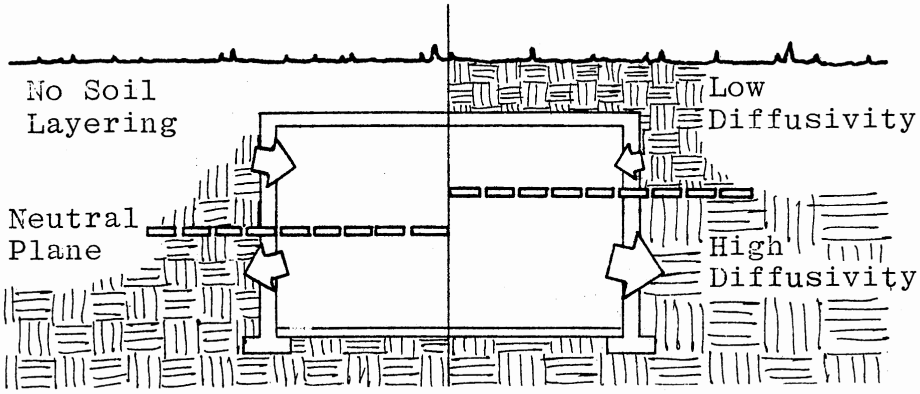


Figure 4. Ground Temperature Control Using Soil Layering

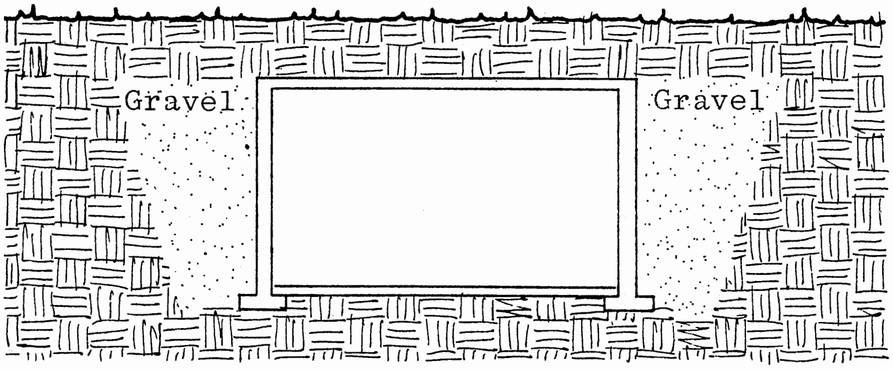


Figure 5. Ground Temperature Control Using Gravel

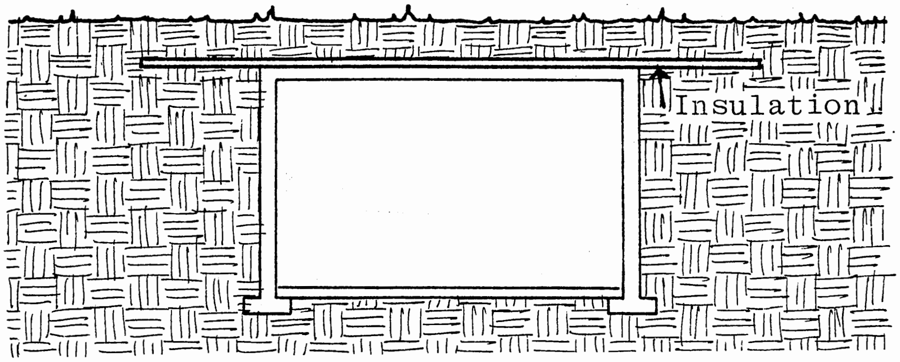


Figure 6. Ground Temperature Control Using Umbrella Construction

approximately 5,000 Btu/ft^2/in. (2.24 x 10^7 J/m^2/cm) depth of water during evaporation, so for a typical inland climate, a 1,200 ft^2 (112 m^2) well-watered sod roof has a cooling potential of 1.5 million Btu (1.58 x 10^9 J) per day (22). The maximum possible solar heat gain to the ground surface (occurring on June 21) is approximately 2.7 million Btu (2.84 x 10^9 J) per day (23). Therefore, it is evident that an appreciable amount of solar heat gain may be blocked from an underground building by evapo-transpiration. In addition, research has shown that tall grass or natural ground cover provides cooler surface temperatures than short grass, although the effect on a building's thermal performance has not been determined (22).

Other methods of ground temperature modification include burning off grass cover in the fall to decrease shading effects in the winter, but beneficial effects of a still air layer trapped by the grass may outweigh the effects of burning off the grass cover. This burning-off method, however, should only be used where erosion would not be a problem. Also, covering the ground with plastic sheets may decrease the soil moisture content and increase heat gain to the soil from solar radiation in winter, although the potential for energy conservation may be outweighed by a corresponding degradation of aesthetic value. Another method may be to use a soil with different thermophysical properties for backfilling around and above the building. However, researchers at the University of Minnesota have not concluded any significant difference in thermal performance of different soil types used for backfill (2). They maintain that even with large structures buried deep into the ground, surface conditions are much more important than soil types in affecting ground temperature profiles. However, this method of ground temperature control may be investigated to determine its specific potential in a temperate to warm climatic region. Table III outlines the investigations to be performed.

Investigation #4 - Will modifying soil moisture content appreciably change the heat flow at an earth covered roof or wall?

This investigation will compare irrigation and umbrella construction to "unmodified" soil conditions (Tests 1, 2, 5, and 6; Table III).

Investigation #5 - What affect does surface treatment have on the thermal performance of underground buildings?

This test will compare ground temperature behavior associated with different surface treatments. The two most common types of ground cover are mowed grass and natural growth (Tests 1 and 2; Table III).

Investigation #6 - Does evapo-transpiration appreciably affect ground temperature during warm months?

TABLE III

GROUND TEMPERATURE CONTROL

PARAMETER	VARIATION	TEST 1	2	3	4	5	6	7	8	9	10	11
Moisture Content	Irrigation	X		X								
	No Irrigation		X		X							
	Umbrella Construction					X						
	Combination*						X					
Surface Treatment	Short Grass	X	X			X	X					
	Natural Growth			X	X							
Backfill	Sand							X				
	Clay and Topsoil								X			
	Insulative Mix									X		
	Soil Layering										X	
	Gravel Layering											X

* Umbrella construction with irrigation pipes below

Comparison of irrigated long and short ground cover to non-irrigated cover will determine the actual potential of this concept (Tests 1 through 4; Table III).

Investigation #7 - Do different soil types used in backfill produce substantially different thermal regimes surrounding underground buildings?

Comparison of various backfill soil types will determine if substantial thermal differences exist and, if so, which type produces a more desirable thermal regime for energy conservation. Consecutive investigations may include different irrigation techniques and surface treatments for the same test rooms (Tests 7 through 11; Table III).

Investigation #8 - May ground temperatures be modified in cold months to improve energy performance of underground buildings?

Grass may be burnt off or plastic sheets laid down in the fall to determine the potential of decreasing heat losses from the building to the earth. The method of burning off grass may be weighed against the beneficial effects of the still air layer trapped by long, natural grass growth (Tests 1 through 4; Table III).

Earth Coupling

In temperate to warm climates, the annual space cooling load is as important to energy conservation as the annual space heating load. Central Oklahoma has 1,882 Cooling Degree Days (base 65F), 1046 CDD (base 18.3C), compared to 3,725 Heating Degree Days (base 65F), 2069 HDD (base 18.3C), making passive cooling strategies a relevant part of total energy design (24,25). If properly designed for maximum earth coupling, earth sheltered homes may substantially reduce or even eliminate mechanical space cooling loads. In a survey of earth sheltered home owners conducted by Oklahoma State University, owner perceptions indicate that conventional mechanical systems provide from 25 to 50 percent of space cooling energy requirements, with earth contact cooling and natural ventilation systems providing the remainder (26). However, many of these homes have been found to be less effectively coupled to the natural earth heat sink than they might be if designed for passive cooling, which indicates that less mechanical cooling may be needed with proper design. Twenty percent of the owners surveyed had no mechanical cooling in their homes (1). The elimination of mechanical cooling may be feasible when one considers that the cooling load is much smaller for an underground building than for an equivalent size above-ground building. The design cooling load for a typical earth sheltered house in a temperate to warm climate has been found to be 30 to 45 percent of that for contemporary above-ground buildings (27).

In temperate to warm climates where passive cooling is beneficial, the decoupling of earth sheltered buildings from the surrounding soil occurs in several ways. The most common is the use of explicit or implicit insulation on the interior surfaces of walls and ceilings, thermally separating the structure (as well as the soil) from the building interior. The use of furred-out drywall or paneling also decouples walls from the conditioned space, and carpet may prohibit the mass under the floor from being part of the effective thermal mass of the building. Interior spatial planning can cause much of the decoupling problem because cabinets and closets are often located along exterior earth-contact walls. All of these elements can be designed to increase the coupling of the building to the surrounding earth to improve the passive cooling potential.

Interior and exterior building surface treatments will be the focus of earth coupling investigations. Test rooms may be used to determine the extent of coupling which is associated with a given assembly. Insulation placement is covered in the next section.

TABLE IV

EARTH COUPLING

PARAMETER	VARIATION	TEST 1	2	3	4	5	6	7	8	9	10
Interior Surface Treatment	Bare or Painted Conc	X									
	Plaster		X								
	Drywall on Furring			X							
	Insulation				X						
Exterior Surface Treatment	Drainage Mat					X					
	Backfill Protection Bd						X				
	No Protection Board							X			
Floor Treatment	Carpet								X		
	Vinyl Asbestos Tile									X	
	Brick or Quarry Tile										X

Investigation #9 - How does interior wall surface treatment affect earth coupling with respect to earth contact cooling and winter heat loss?

Comparison of various interior wall treatments will provide data to determine the effect of decoupling on underground buildings. Drywall on furring may be compared to plaster and painted or bare surfaces. Interior placement of insulation, discussed in the next section, may also be tested (Tests 1 through 4; Table IV).

Investigation #10 - Does the addition of insulation, waterproofing protection boards, or drainage mats substantially decouple an underground building's exterior surface from the adjacent soil?

Exterior wall treatments may be investigated to determine if they cause significant decoupling effects. Different soil types, as discussed earlier and included in ground temperature control investigations, will also be compared for optimum earth contact cooling potential, as well as corresponding heating season performance (Tests 5, 6, and 7; Table IV).

Investigation #11 - Will carpet dramatically reduce building thermal performance?

Carpet may be compared to vinyl asbestos tile and quarry tile to determine the relative effect on total building energy performance. Also, the effect of carpet over a passive solar collection mass may be investigated to determine the possible degradation in heat storage potential of the mass (Tests 8, 9, and 10; Table IV).

Insulation Types and Installations

Several types of insulation are suitable, to a greater or lesser extent, for application in underground construction. If exposed to the soil surrounding a structure, the insulation must resist moisture, maintain structural stability under high soil pressures, and maintain a high percentage of initial R-value over time. Extruded polystyrene is highly recommended for below-grade applications due to good resistance to soil moisture and the material's ability to retain a high percentage of initial R-value for at least ten years. High density expanded polystyrene (EPS), if kept dry, may be suitable for below-grade use at a lower cost than extruded polystyrene. A polyethylene sheet may provide only minimum protection from ground moisture if the integrity of the membrane is maintained. Polyurethane foam has a higher R-value per unit thickness than the polystyrenes, but lacks a resistance to moisture which results in a greater insulating value degradation over time. It also loses some insulating value due to aging. Fiberglass batt insulation, although only suitable for interior applications, is clearly the lowest price per R-value of the above-mentioned products. In temperate climates, where only the roof may warrant insulation, glass fiber batts may be considered (25).

Insulating the floor slab of an earth sheltered building decreases the effective thermal mass of the building and may actually increase the heating or cooling load for this reason. Also, only a relatively small amount of the building's total heat loss or gain occurs at the floor. Therefore, the added cost of floor insulation cannot be justified by appreciable energy savings. However, by investigating the actual energy performance associated with under-floor insulation, the extent of the degradation assumed to occur with this design may be determined. The difference in comfort effects can also be examined, especially with respect to mean radiant temperature aspects. It should be noted that the portion of the slab adjacent to exposed walls and patios should be insulated to prevent heat flow at such perimeter areas.

Aside from insulating products, substantial amounts of earth cover will provide "insulation" to the building. Although the soil itself is a poor insulator, it provides thermal stability to the building in several ways. First, daily temperature swings are damped out by earth cover so that the building does not experience as great a peak load as would an above-ground building (28). This damping effect is shown in Figure 2.

Second, seasonal phase shifts occur due to the mass and thermal capacity of the soil and increase with depth of soil. The lowest soil temperatures at a given depth may occur perhaps a few months after the lowest air temperatures, and the highest soil temperatures will occur a few months after the highest air temperatures. This offsetting of loads will tend to decrease any coincident peak seasonal loads which would otherwise be imposed on the building (28).

Finally, the soil surrounding an underground structure protects it from solar insolation and infiltration, two important contributors to a building's total thermal load. All of these factors contribute to the thermal stability of earth sheltered structures.

The depth of earth cover which will provide the most optimal performance without substantially increasing the cost of the structure must be determined for each specific site and building. However, general information concerning the amount of extra "insulation" provided by increasing depths of earth cover can be determined by experimental measurements. Many computer models assume an earth-covered roof as one homogeneous layer, but physical modeling can more closely match actual conditions. Therefore, the total depth of earth cover to be investigated may include a gravel base and nonhomogeneous layers of fill and top soil.
In Oklahoma, a minimum of 8 in. (20 cm) of earth cover is necessary to sustain good plant growth, with irrigation, so test conditions may begin at 8 in. with increasing intervals of 8 in.

Insulation may be tested using the test cells for comparison between products and placement techniques as well as absolute levels of product performance. Roof insulation may be tested to compare the performance of no insulation to various thicknesses of the different product types. Wall insulation may be tested for different thicknesses and placement techniques. Various depths of earth cover may also be tested for performance and comparison. Table V outlines the investigations to be performed.

TABLE V

INSULATION TYPES AND INSTALLATIONS

PARAMETER	VARIATION	TEST												
		1	2	3	4	5	6	7	8	9	10	11	12	13
						Roof			/			Wall		
No Insulation		X								X				
Expanded Polystyrene	1 in. (25 mm)A		X											
	2 in. (51 mm)A		X											
Extruded Polystyrene	1 in. (25 mm)A			X							X			
	B										X			
	C										X			
	D										X			
	2 in. (51 mm)A			X										
Polyurethane Foam	1 in. (25 mm)A				X							X		
	B											X		
	2 in. (51 mm)A				X									
F/G Batt	3.5 in. (89 mm)E					X							X	
Earth Cover	8 in. (20 cm)						X							
	16 in. (41 cm)							X						
	24 in. (61 cm)								X					
Under-floor insulation														X

A = Full exterior surface coverage
B = Upper 4 ft (1.2 m) exterior wall surface coverage
C = Extended 4 ft (1.2 m) horizontally into the soil
D = Extended 8 ft (2.4 m) horizontally into the soil
E = Full interior surface coverage

Investigation #12 - How does roof insulation affect the building's thermal performance?

Various types and thicknesses of insulation, including no insulation, will be compared to determine optimum design for temperate climatic regions. Eventually, the appropriateness of the different types of insulation tested may be determined by their performance over several years time (Tests 1 through 5; Table V).

Investigation #13 - What is the optimal depth of earth cover with respect to thermal performance?

Three depths of earth cover will be compared to a conventional above-ground roof to show the relative change in energy savings for each foot increase in depth or for doubling of depth. This investigation may require consecutively testing the same room by increasing the depth of cover after each testing period if three rooms cannot be used simultaneously (Tests 6, 7, and 8; Table V).

Investigation #14 - What is the optimal amount and placement location for wall insulation in temperate to warm climatic regions?

The most common types of insulation will be compared using different installation techniques to determine optimum design strategies (Tests 9 through 12; Table V).

Investigation #15 - What is the actual change in energy performance and comfort related aspects associated with the use of under-floor insulation?

This investigation will provide documentation for the assumption that under-floor insulation substantially decreases the building's winter energy performance. Some occupants may choose to accept this degradation in winter energy performance in exchange for beneficial passive cooling effects and a floor temperature closer to comfort conditions (Test 13; Table V).

Earth Shelter/Passive Solar Integration

In a recent survey, earth shelter occupants in Oklahoma identified a reduction in heating requirements as a major reason for choosing this particular building type (1). The earth and structure provide a thermal mass which decreases the effects of harsh winter temperatures and wind. This large amount of thermal mass can be used as storage to improve the performance of a passive solar space heating system. By combining passive solar concepts with earth shelter concepts, a large portion of the space heating load may be eliminated without an appreciable increase in construction costs. Therefore, the facility will be used to investigate the energy aspects of various passive solar/earth shelter integrated systems.

All passive solar designs perform three functions: collection of solar energy, transferral of this heat energy to a storage mass, and distribution of this heat to the living space. The collection area is simply the glazing area and collecting surface which accept solar energy. The storage mass depends on the type of passive system involved. For direct gain systems, the storage mass is the floor and walls of the living space. For indirect gain systems, the mass is usually a Trombe or water wall or thermal storage roof. For isolated gain systems, the mass may be located adjacent to the collector (greenhouse floor and walls), in the living space (floor and walls), or in a remote location (rock storage below the floor). The connection from the storage mass to the living space in the indirect gain and isolated gain systems may consist of either simple openings as in a Trombe wall or a ductwork system as in a rock storage bed.

No standards are available for use in determining the size of the components of passive solar systems when combined with the high thermal mass of underground structures. The rules-of-thumb which are available for above-ground buildings may be modified for earth shelters based on the relative heating requirements of the two building types.

Emery and others (29) state that earth-covered passive solar homes typically save as much as 50 to 85 percent of the heating energy requirements associated with standard wood frame homes. In comparing the predicted energy use of earth sheltered residences in Oklahoma to calculated energy use of above-ground equivalents, Bice (30) found a percentage savings of 63 percent in the design heating load of the earth sheltered residences. Grondzik (26) also feels that at least a 50 percent reduction in heating and cooling energy requirements is possible with earth sheltered buildings over comparable conventional above-ground buildings. Since heating and cooling energy costs are roughly equal in Oklahoma, it may be assumed that a 50 percent reduction in heating requirements exists between earth shelter and above-ground equivalent buildings. Using this assumption as a guideline, current rules-of-thumb may be reduced by 50 percent when combined with earth sheltering.

There are few widely accepted rules-of-thumb for use in sizing passive solar component areas (APPENDIX C) (31,32). Using these solar glazing rules-of-thumb, modified for combination with earth sheltering, glazing areas may be determined to set up investigations. Table VI outlines the possible tests that may be performed using test rooms exposed to the south.

TABLE VI

EARTH SHELTER/PASSIVE SOLAR INTEGRATION

PARAMETER	VARIATION		TEST								
			1	2	3	4	5	6	7	8	9
Direct Gain (Window)	Glazing	6% *	X								
		9		X							
		12			X						
Indirect Gain (Trombe Wall)	Glazing and Mass Wall	11				X					
		20					X				
		30						X			
Isolated Gain (Greenhouse)	Glazing	17							X		
		22								X	
		26									X

* Expressed as percent of total floor area

Investigation #16 - What is the benefit, if any, of combining earth shelter with passive solar concepts?

This investigation will be conducted to determine the possibility of a reduction in space heating energy requirements from passive solar designs. A year-round energy performance investigation of passive solar concepts may be used to determine if additional glazing results in an increase in summertime space cooling load which negates the wintertime benefits. Also, various solar shading techniques may be investigated during summer months and may, in turn, have significant bearing on the winter performance (Tests 2, 5, and 8; Table VI).

Investigation #17 - What component areas should be used for direct gain, indirect gain, and isolated gain designs in earth sheltered buildings?

The investigations of collecting surface area will be performed to develop design optimization guidelines for temperate to warm climates. The lower and upper limits of areas are determined using existing rules-of-thumb (Appendix C) modified for earth shelter designs (Tests 1 through 9; Table VI).

Investigation #18 - Is night insulation a cost effective addition to passive solar earth shelter designs?

The addition of night insulation to passive solar designs will provide data for cost analyses of various insulation designs. Insulative curtains, interior and exterior insulation boards, and loose fill beads may be tested after the above-mentioned investigations have been performed using the same passive solar test rooms. Therefore, no additional tests are outlined in Table VI, and night insulation will simply be investigated in conjunction with existing testing components.

Model Validation

Several analytical thermal models have been developed to provide technical information for the design and engineering of earth sheltered buildings. The main areas of earth shelter design requiring analytical models as design tools are optimization of building thermal design for minimal energy use and life cycle costing analysis of building design options (33).

Many of these existing models have limited or no associated validation using actual monitored buildings. For this reason, the earth shelter test facility proposed here may also be utilized to validate existing models and develop new models.

A simple model developed by Blick (34) provides an approximation for the heat transfer through earth-covered roofs. This hand-calculation method takes no account of the time-lag effect of the soil's thermal mass. A correlation between Blick's calculated values and actual monitored values might be used to validate this method as a simple design tool or further develop it to include the mass of the soil.

Speltz and Meixel (35) have also developed a model of the thermal performance of earth-covered roofs. This computer simulation takes into account the thermal mass of the soil, roof insulation, evapo-transpiration, and convective and radiative heat transfer properties. Comparisons of this thermal model with experimental results from physical data will determine its usefulness for estimating the annual thermal performance of earth-covered roofs.

An important aspect of all models is the type of soil that is being investigated and its associated thermal characteristics. A graphical design aid developed by Baggs (36) provides an assessment of soil types with respect to moisture content and phase lag intervals. Backfill materials may be chosen using this design aid to optimize building thermal performance. Therefore, the validity of this information, adapted to local climate, may be investigated using the facility.

A plan design index, developed at Oklahoma State University, provides an appraisal of the passive cooling potential of earth sheltered housing in Oklahoma (37). This index is based on the amount and configuration of earth contact surfaces and associated surface treatments, ventilation potential, and solar gain control characteristics. This plan design index was further developed by Seals (38) who included an equivalent heating season index to determine the appropriateness of a design with respect to energy performance for a given climate. The research facility may be used to determine the validity of assumptions used to develop the plan design index, such as the relative energy performance of one wall surface treatment over another.

These investigations are included in previous sections and may provide data for the validation of these existing models in addition to providing data for the development of new computer simulation models from research conducted at this facility.

CHAPTER IV

DESCRIPTION OF THE RESEARCH FACILITY

The facility must be capable of accommodating many of the investigations outlined in the preceding chapter simultaneously due to the time span of each investigation, which may require months or years for the acquisition of a sufficient data base upon which to draw conclusions. Also, due to the nature of the facility, the changing of experimental parameters would require a major effort for excavation, backfill, and settling time. Therefore, several small, independently controlled test rooms will be required to model the large number of investigations to be performed. An above ground equivalent of the earth sheltered test rooms will be needed for performance comparison as a control case. A data acquisition center will be located on the site and a weather station is required. A description of the facility follows.

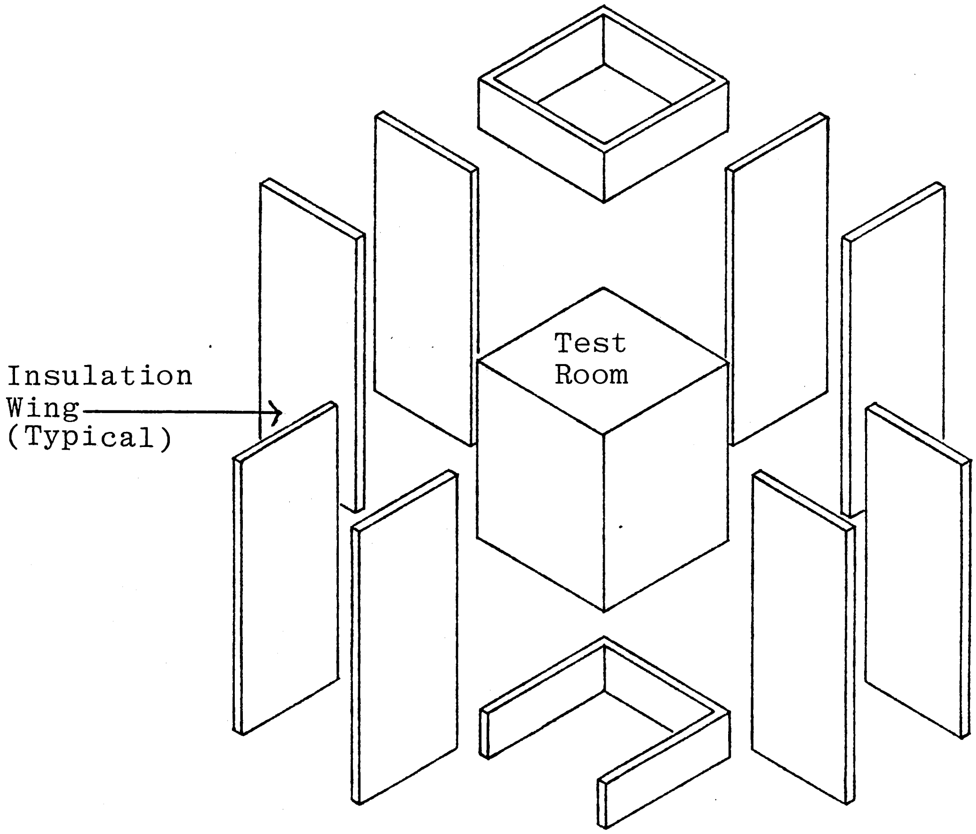
Test Room

A test room will be essentially a single-room earth sheltered building. Because of the number of test rooms needed at the facility, each should be as small as possible while maintaining the thermal characteristics which would be expected in larger structures. The floor to ceiling height will be eight to ten feet, which is the same as the actual height of a single story structure. The test room should be full scale in height because heat flow path lengths from earth covered walls cannot be properly modeled at a smaller scale. However, two-dimensional heat flow will be assumed in the soil near the wall so the width of the wall may be reduced while proper modeling is maintained.

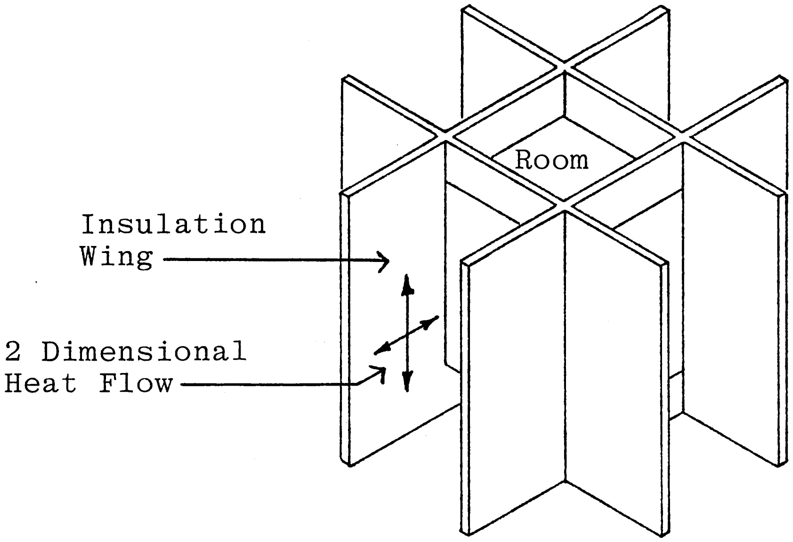
Because there is no theory behind small scale modeling of soil thermal characteristics when transient loads are applied, such as near earth sheltered buildings, a short questionnaire was circulated to experts in the earth shelter research field to reach a professionally-based opinion of the smallest test room size required for proper modeling of soil conditions near an earth sheltered wall (APPENDIX B) (10).

The floor of the test room is a concrete pad on a sand base. As outlined in Chapter III, the walls and roof of the room will be constructed of whatever material is being used for the investigations at that room; concrete, concrete block, or wood.

The two-dimensional heat flow assumed at the walls is accomplished by insulation wings which extend from the room into the soil (Figure 7). These wings prevent heat flow to soil at either side of the wall in order to simulate a wall of infinite length. Corner effects may be tested by eliminating both wings at one corner of the room. The



a.) Exploded Isometric



b.) Isometric

Figure 7. Illustration of Test Room
with Insulation Wings

insulation must extend far enough away from the test room to enclose the entire volume of soil which will be influenced by the earth sheltered wall. Using the ASHRAE (23) description of heat flow paths from basement walls, the distance from the building through which the soil is thermally influenced by the building is shown in Figure 8. This is for an uninsulated wall and would represent the most extreme case. This distance is in agreement with professional opinions (APPENDIX B) and may, therefore, be used for determining the size of the insulation wings.

An insulation wing R-value of 30 hr ft^2 F/Btu (5.28 m^2 K/W) is needed at the insulation wings to approximate an adiabatic condition (10). Table VII shows the types of insulation which are suitable for below-grade application and the thickness needed to obtain an R-value of 30 (25).

TABLE VII

INSULATION WING PROPERTIES

PRODUCT	DENSITY lb/ft^3 (kg/m^3)	INITIAL R-VALUE PER INCH (PER cm)	PROBABLE R-VALUE PER INCH WITH TIME (PER cm)	R-30 - THICKNESS INCHES (cm)
Extruded Polystyrene (blue)	2.0 (32)	5.0 (0.35)	4.5 - 4.9 (0.31 - 0.34)	7 (17)
Extruded Polystyrene (pink)	1.7 (27.2)	5.0 (0.35)	No data published	7 (17)

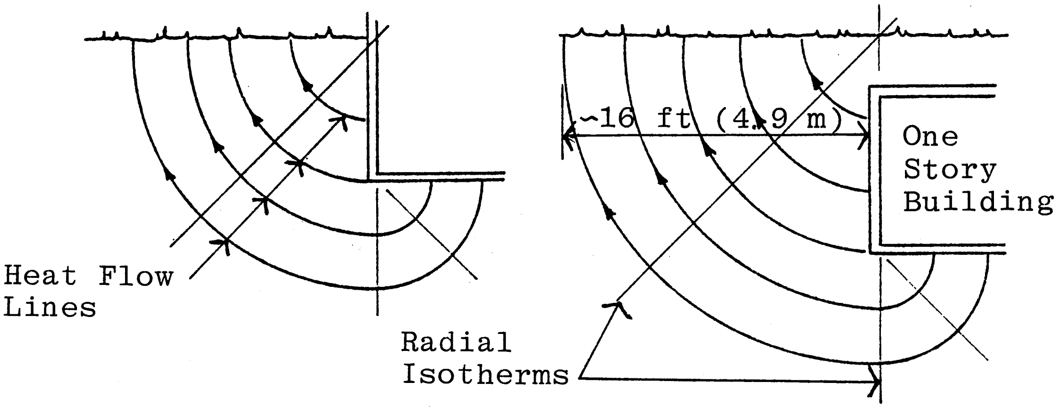
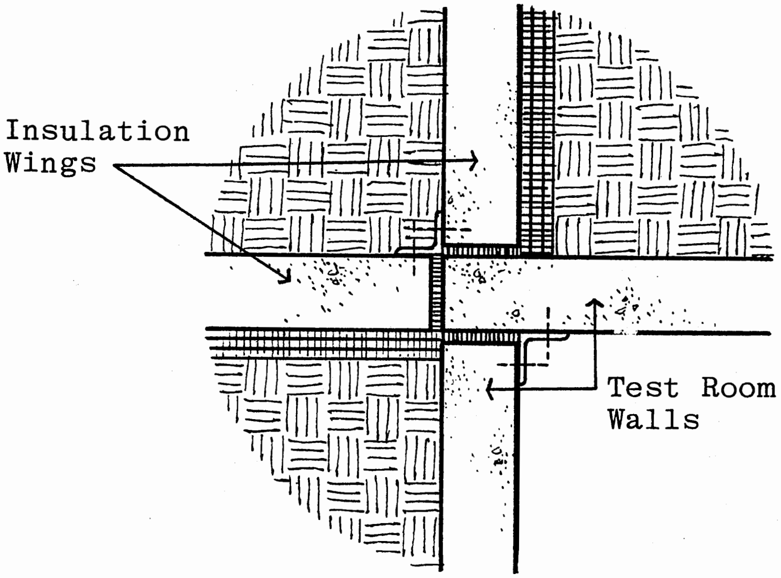


Figure 8. Area of Thermal Influence in Soil from Underground Buildings

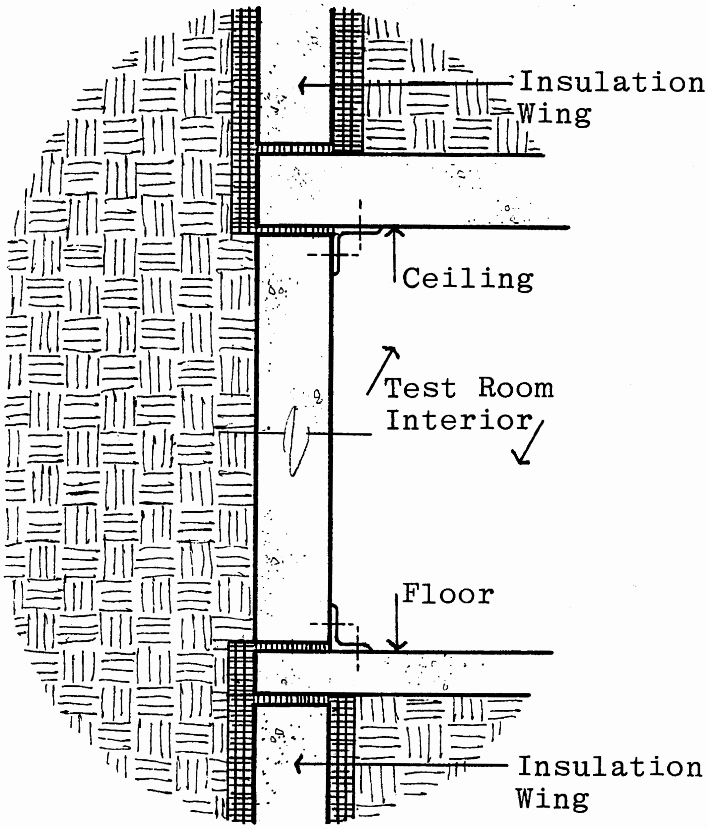
The insulation wings are supported by precast panels which will act as retaining walls to allow excavation at either side for repair or replacement of wall materials. Figure 7 shows how the insulation wings are positioned around the test room. The design of the test room/insulation wing assembly must provide thermal breaks to prevent heat migration from the test room walls to the concrete insulation wing supports. This may be accomplished using insulating board (Figure 9).

Above-Ground Control Room

A control room is needed to represent the above-ground equivalent of an earth sheltered test room. The control room will serve two purposes: to provide a comparison of the energy performance of above ground and earth shelter



a) Plan at Test Room Corner



b) Section Through Test Room

Figure 9. Details of Thermal Breaks at Test Room

applications, and; to provide consistency in the monitoring and instrumentation processes which cannot be accomplished by simulation.

The control room should be the same size as the test rooms and should be of a construction that is widely known and accepted. The "Arkansas" Well-Insulated House construction is chosen for the control room because it is well documented and has been compared to earth sheltered housing in Oklahoma for energy performance (30). It represents an insulative rather than capacitive type of construction and will provide a useful data base for energy comparisons with earth shelter construction. APPENDIX D describes the construction components of the Arkansas House (39).

Earth Sheltered Reference Room

One underground test room may be used to perform various investigations and, at the same time, be used as a "standard earth sheltered building reference from which other building designs may be compared. This control room should reflect a bare bones design such that the relative energy benefits of any particular design alternative can be weighed against this reference. The design of the reference room reflects neither good nor poor design, but represents a typical earth sheltered building.

The construction of the test room should exclude all energy-related design options which may be considered extra in terms of cost and energy benefits, such as insulation, interior surface treatments, and ground temperature control techniques. The roof and walls of the reference room should be constructed of 8 in. (0.2 m) concrete and the floor should consist of an uninsulated concrete pad on a sand base. Excavated soil from the site should be used as backfill and 24 in. (0.6 m) of soil, the minimum depth to sustain plant growth without irrigation, should cover the roof. Natural growth is appropriate for the surface treatment above the reference room because extra costs are involved in planting and maintaining short grass. The interior surfaces of the room should be left bare and only a waterproofing system should be used on the exterior surfaces.

Weather Station

Weather conditions must be monitored on the site to provide precise data for correlation with building and surrounding soil thermal properties. The weather data provided by the National Weather Service is not appropriate due to the fact that it is not site specific or time specific (real time). Also, solar insolation and precipitation must be measured on an hourly basis to closely follow dynamic soil thermal responses to these conditions. However, meteorological data from other regions may be used to determine the accuracy of correlation for other sites. Equipment required at the weather station is discussed in Chapter V.

Monitoring Center

A monitoring center is needed at the facility to house the data acquisition system. The system may be located entirely at the facility, or data may be sent to another location for processing. This center will function as a collection point for the sensors from the entire facility. If the data acquisition system is located in the monitoring center, the control of all mechanical equipment will be performed from the center. Therefore, it will become an office for the researcher in charge of facility operations. If data acquisition is located away from the facility; for example, at the Oklahoma State University School of Architecture, then the monitoring center will simply collect and transfer data, and may occupy very little space.

Mechanical Equipment

Each test room must be conditioned to simulate comfort conditions in an occupied earth sheltered building. Space heating, space cooling, and humidity control must be provided. Each space requires independent control in order to maintain specified conditions. Each test room will gain or lose heat depending on weather conditions and envelope characteristics. As heat is transferred to or from a test room the mechanical equipment will maintain the conditions defined for the given investigation being performed.

It may be beneficial to determine the effects on interior conditions from a power outage which will discontinue any mechanical space conditioning. Also, a simulation of fully passive conditions may be investigated with respect to test room performance. Independent control of each test room will permit these investigations without interrupting investigations in other rooms.

Due to the relatively large distances between test rooms, each room may require a separate conditioning unit. Thermocouple sensors which monitor interior conditions will act as thermostats to control each unit through the data acquisition system. In this manner, each test room and corresponding mechanical system may be monitored and controlled from a central location; either at the monitoring center or at another location remote from the facility.

Site Planning

There are five basic configurations which could be adapted for the facility; linear, radial, concentric, grid, and consolidated. The functions included in the facility include a monitoring center, test spaces, weather data, and control house. The monitoring center is where all information from monitored points is brought to be recorded or delivered to a data acquisition system, if it is not located at the facility. Test spaces include underground rooms, passive solar rooms and the control house. Weather data will be measured at the site.

The linear scheme allows excavation of each cell for changing experimental elements and repair without disturbing other areas, but instrument wire runs may become excessive. Figure 10 shows a possible solution using a linear configuration. The monitoring center is located between rows of test rooms which allows easy access and viewing into each room. Passive solar modules extend beyond the conditioned monitoring center to accommodate southern exposures. The facility is well suited to phase type construction. The monitoring center and northern test rooms may be constructed, later adding passive solar rooms, and finally, rooms to the south of the monitoring center. Future expansion can be readily added to the west end of the facility, although expansion is limited in the linear direction and another layout may be more appropriate.

The radial layout (Figure 11) will require shorter wire runs from individual rooms to the monitoring center than the linear scheme. The major disadvantage of this design is that excavation of interior test rooms will be difficult without disturbing other rooms. A greater distance would have to exist between the inner ring and the outer ring of test rooms to reduce this problem. Tunnels made of culvert pipe connect underground test rooms to the monitoring center allowing access and sensor wire runs. The tunnels run horizontally under the floor level and up into the test rooms. The advantage of having rooms located totally underground with access from below is that all four walls may be used for various investigations, while the floor is of somewhat less importance.

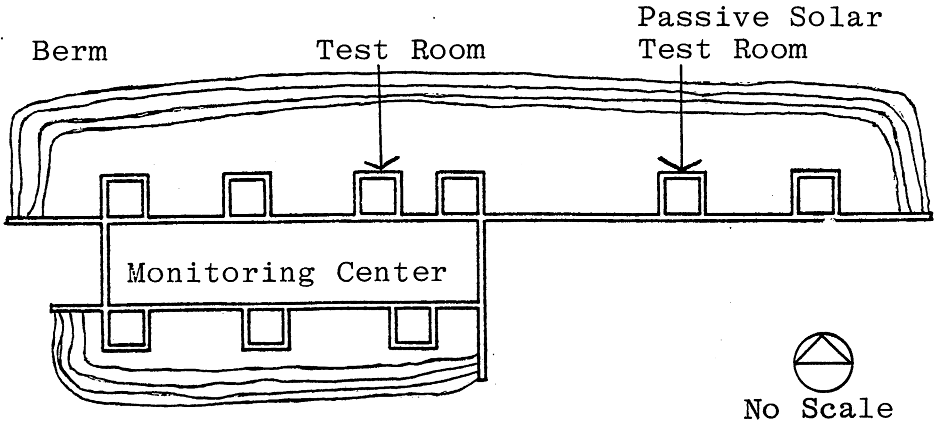


Figure 10. Test Facility Layout - Linear Configuration

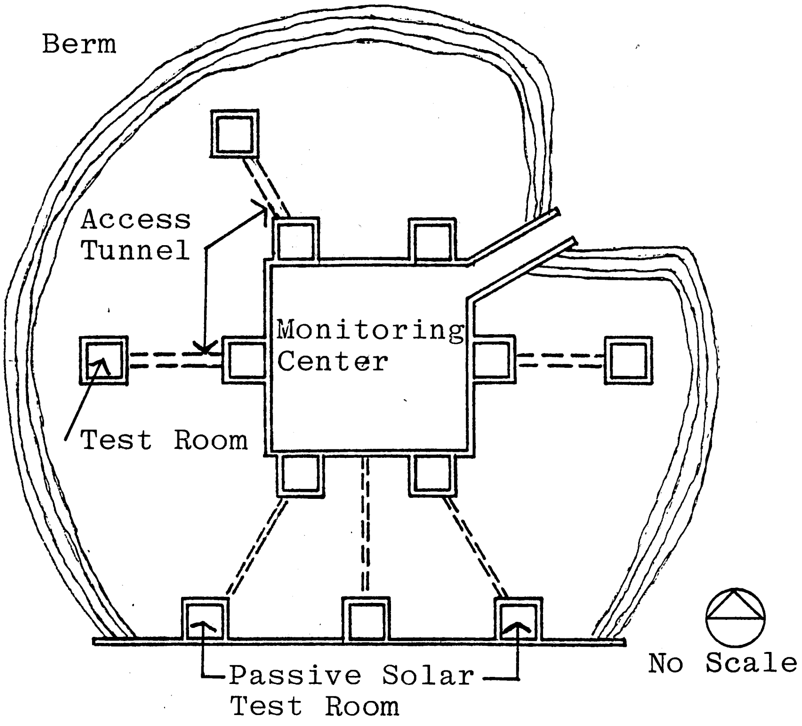


Figure 11. Test Facility Layout - Radial Configuration

The concentric design is similar to the radial except the lines of communication from the sensors to the collection point follow a circular path (Figure 12). The monitoring center is treated like a test room and may, in fact, be monitored as a test room. The same disadvantages apply to this arrangement as to the radial scheme in that excavation may be difficult without disturbing other areas. However, this may be seen to be the case in all but the linear arrangement. Also, only three walls of each cell are available for earth-backed wall investigations.

With the grid design, the facility can be arranged to take full advantage of a small site by placing all rooms in a grid pattern where no gaps are present between areas of influence (Figure 13). Also, more investigations are possible using fewer test rooms due to the fact that most are totally underground.

The consolidated plan includes a long, segmented building with insulated dividing walls forming individual test rooms (Figure 14). The building is oriented along the north-south axis with greater depths of earth cover to the north to eliminate retaining walls which might shade adjacent roofs. This plan allows the use of a single space conditioning system with individual test room control, and requires the smallest land area and shortest wire runs of the design possibilities mentioned. The passive solar test rooms may be designed in a similar manner, oriented along

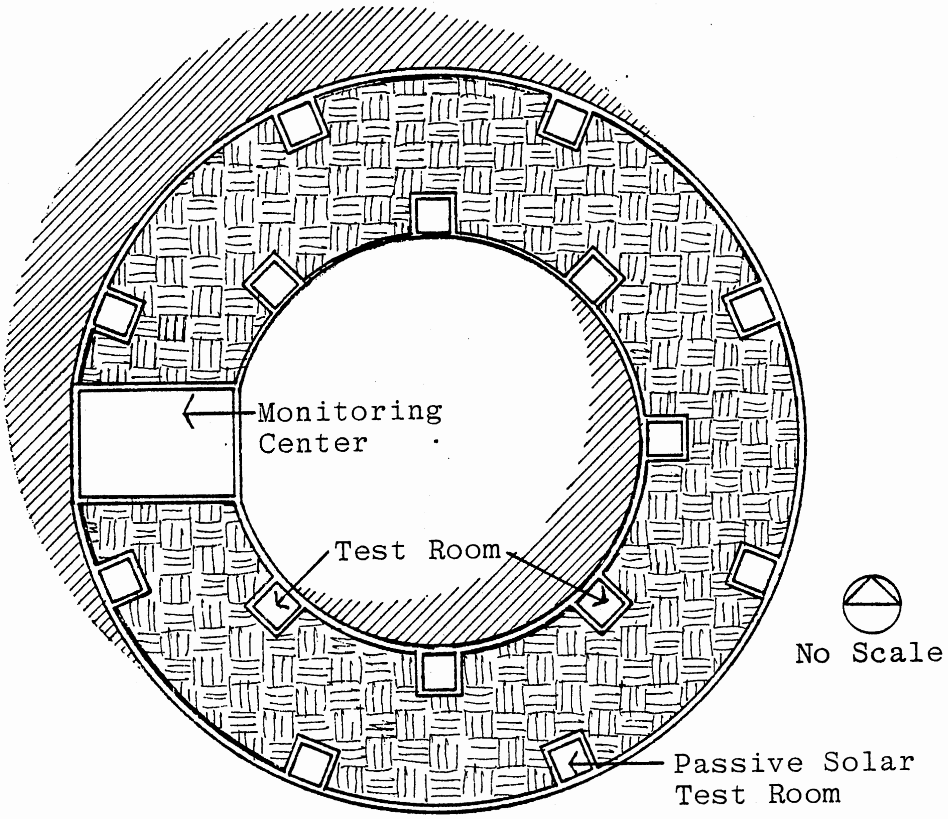


Figure 12. Test Facility Layout - Concentric Configuration

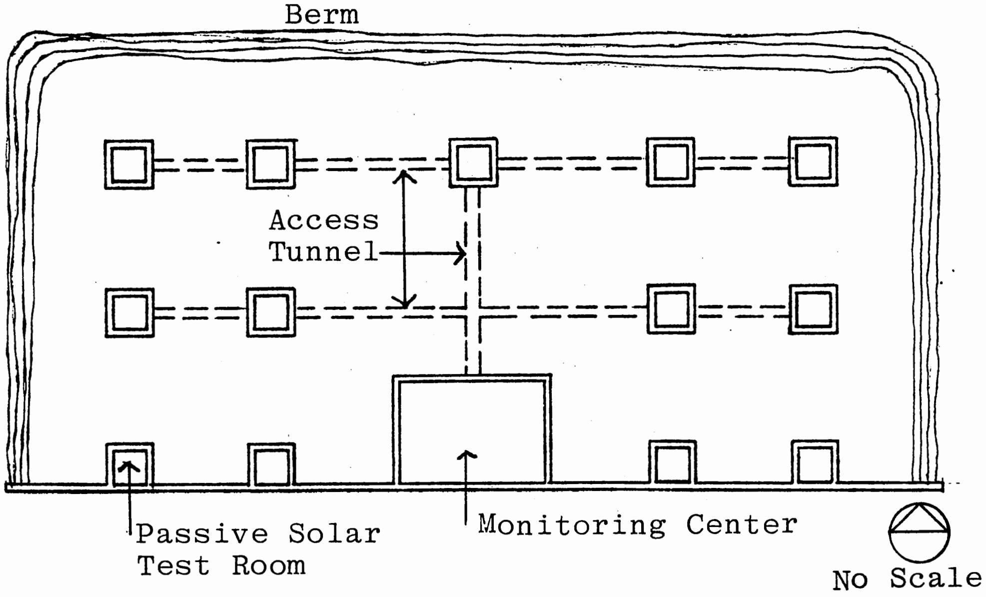
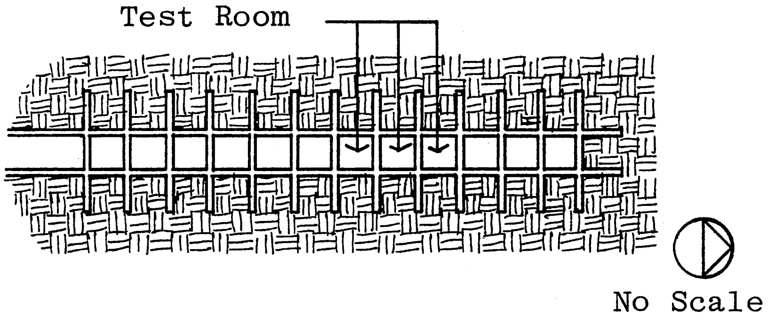
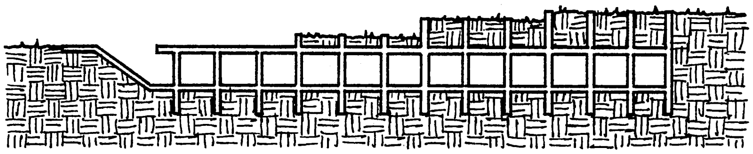


Figure 13. Test Facility Layout - Grid Configuration

the east-west axis with the southern wall exposed to accept direct, indirect, and isolated gain passive solar designs.



a) Plan



b) Section

Figure 14. Test Facility Layout - Consolidated Configuration

CHAPTER V

INVESTIGATION METHODS AND PROCEDURES

Instrumentation

Experimental investigations of the thermal performance of individual test room components, as well as overall assessment of earth shelter/passive solar modules, requires monitoring with a very large number of sensors. These sensors will measure weather conditions, interior conditions, structural thermal behavior, and soil conditions over relatively large areas. The data collection from these sensors must be continued for months or years, depending on the nature of the investigation, resulting in a vast amount of data. Therefore, an automatic data acquisition and reduction system may be necessary. The system must be capable of data collection, processing, storage, and retrieval. The success of the research conducted using the facility depends greatly on receiving relevant data using an appropriate data acquisition system.

Weather Conditions

Ambient outside temperature will be measured using a thermocouple mounted in a small instrument shelter located away from any heat producing equipment and parking areas. Ventilation must be provided and a reflective covering will mitigate radiation effects. Because humidity is also a factor in heat transfer, it will be monitored using a solid state relative humidity probe located in the small instrument shelter. This sensing element will probably need calibration if long leads are used (40).

Precipitation at the site can be measured in 0.01 in. (0.25 mm) intervals using a tipping bucket rain gauge. It can be coupled to the data acquisition system for making long-term documented measurements (40).

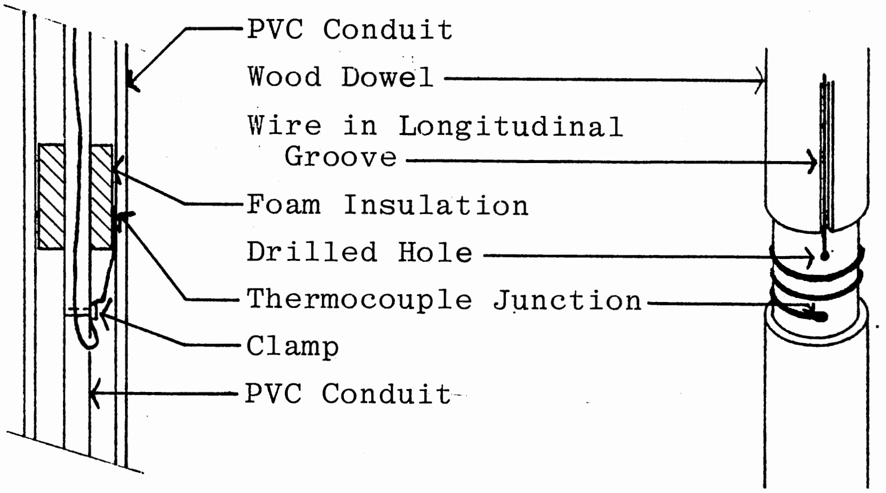
Wind affects heat transfer at exposed building and ground surfaces as well as evapo-transpiration from vegetation. Wind velocity is measured by a cup anemometer to an accuracy of ±1% or 0.15 mph (0.07 m/s). Wind direction is measured by an airfoil vane. Both the anemometer and the vane may be heated to reduce icing problems (40).

Solar radiation must also be measured at the site to determine the insolation incident on the vertical building surfaces and the ground surface. A vertically-oriented pyranometer will measure the radiation striking the vertical glazing of passive solar test rooms and a horizontally-oriented pyranonmeter will measure the radiation striking the ground surface.

Soil Conditions

Soil temperature and moisture content will be monitored extensively throughout the facility, providing a large amount of data needed for the determination of thermal regimes surrounding conditioned buildings. Soil temperatures will almost universally be measured using probes running from the ground surface vertically to a depth deemed necessary by the characteristics of each experimental application. Several temperature probes have been designed in the past to study soil thermal properties and heat transfer in basements and underground buildings. McBride (4) and others used temperature probes consisting of copper constantan thermocouples soldered to copper tubing to investigate heat loss from basements. Szydlowski (5) used PVC conduit temperature wells with thermocouples held in position by foam insulation (Figure 15a) to measure soil temperatures surrounding an earth shelter test facility. This method is similar to the one used in monitoring at Williamson Hall, an underground bookstore at the University of Minnesota (41).

A thermocouple rod designed for the measurement of subsurface temperatures in Canada provides ease of installation and control of position (42). A wooden dowel rod with a circular groove at the desired depth of measurement allows a thermocouple to be wrapped around the rod to reduce heat conduction along the thermocouple wire close to the junction (Figure 15b). A longitudinal groove accepts the wire run to the surface. The junctions and exposed areas of thermocouple wire are coated with epoxy resin to delay oxidation of the copper wire. For insertion of the rod, a hole is bored using a drill, after which the thermocouple rod is hammered into the hole. Although this system could not be used directly for the larger depths necessary for the earth shelter test rooms, it may be adapted for such use.



a) PVC Conduit Temperature Probe

b) Wood Dowel Temperature Probe

Figure 15. Thermocouple Assemblies

Soil moisture will be measured for several probe groups in each area of influence depending on the nature of the experiment. A method used in the monitoring of Williamson

Hall may be suitable for the needs of the Oklahoma facility. A Troxler nuclear moisture meter is inserted into thin aluminum tubes which are positioned vertically in the ground. The meter contains a small radioactive source emitting neutrons which measure the back scatter produced by hydrogen atoms in the soil. Thus, the water content of the soil may be measured at various depths (41).

Interior Conditions

As mentioned earlier, each test room must be conditioned independently to provide total control for various investigations. In order to determine the energy performance of a given test room, the amount of energy input in the form of conditioned air must be known. Therefore, several aspects of the air flow entering the test room from the mechanical conditioning system will be monitored. These include air flow rate, temperature, and humidity. Also, the mechanical equipment will be monitored for energy use.

The air temperature and relative humidity will be monitored in each test room. For the purposes of heat loss/gain calculations, it is sufficient to determine a single value for interior air temperature. However, the facility's use may be expanded to include the investigation of interior comfort conditions and a sensor tree should be used to monitor air temperature at various heights in the room. This would also provide information concerning temperature stratification which may or may not be important in heat transfer investigations.

Surface temperatures will be monitored on the interior and exterior surface of the walls, roof/ceiling, and floor of each test room. If a furred wall or suspended ceiling is used, the temperature at both the interior surface and the structural surface will be monitored. Heat flow meters should also be used at the center of the ceiling, floor, and each wall to monitor continuous heat flow rates at these surfaces for comparison with calculated heat flow rates found using interior and exterior surface temperatures.

Solar radiation entering each passive solar test room will be monitored to determine the heat gain admitted through various glazing and shading devices. This value should be monitored in each space to insure that the actual heat gain is known. Numerous variables might affect an assumption of interior heat gain based solely on exterior insolation levels. These include cleanliness of glazing, assumed versus measured properties of each type of glass, and diffuse radiation input when the glazing is shaded.

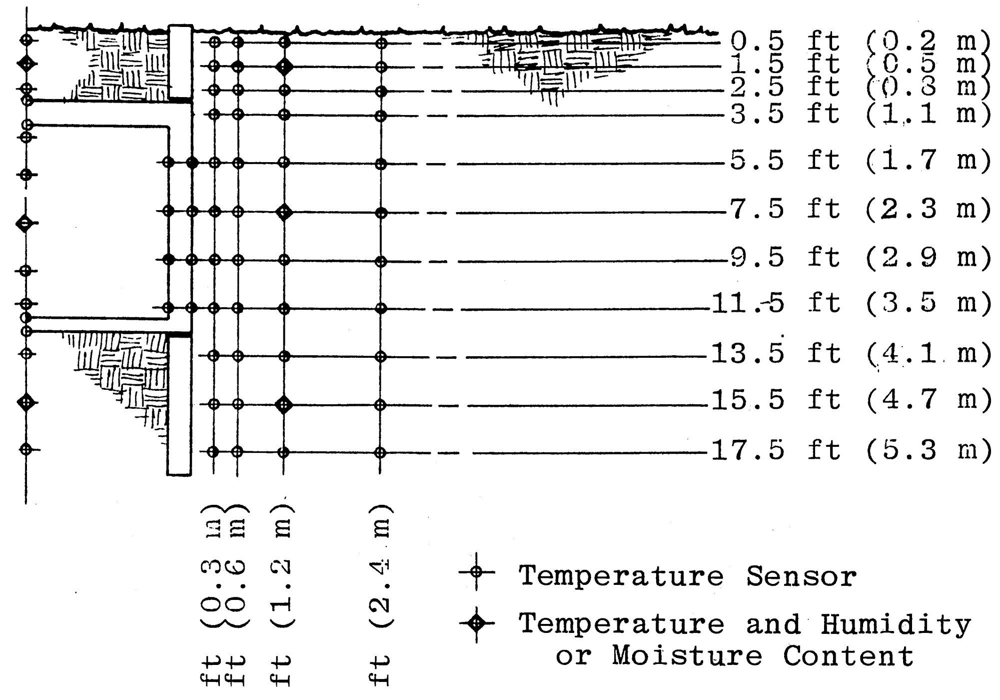
Event sensors may be needed in the passive solar test rooms if moveable insulation is investigated. Also, event sensors may be used with the lighting system in all test spaces to determine the heat gain from lights and when doors are opened and closed.

Instrumentation Placement

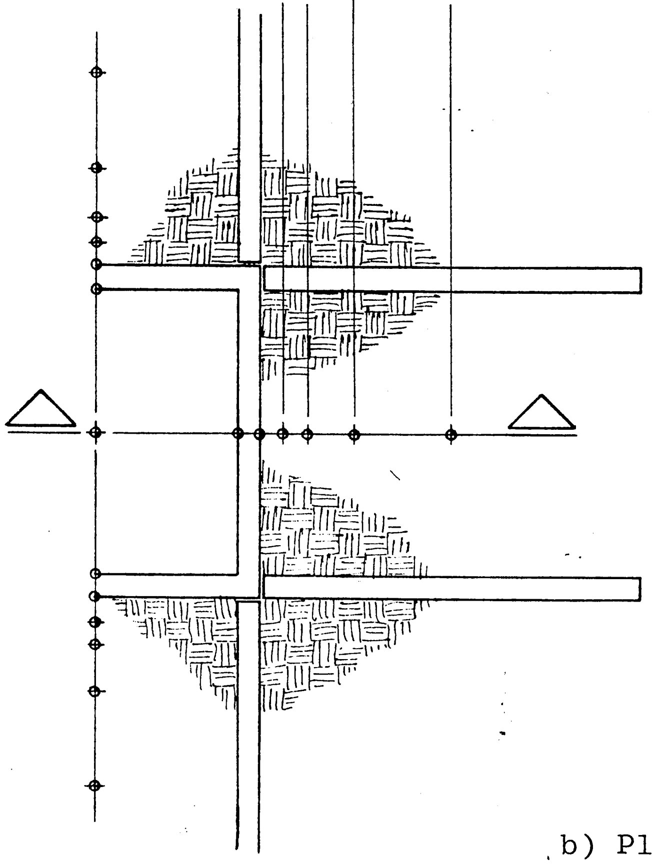
The instrumentation needed to monitor individual test rooms includes soil temperature sensors, surface sensors, interior sensor trees, and event sensors. The location of these sensors will be determined by the nature of each investigation being performed at a given test room. A general layout of sensor location is shown in Figure 16.

Soil temperature sensors are located at horizontal intervals from the test room wall such that soil temperatures may be obtained for each doubling of distance from the wall. Also, this sensor layout will provide a more detailed thermal profile near the test room wall where greater temperature gradients are expected to occur. The vertical spacing of soil temperature sensors is 2 ft (0.6 m) except near the ground surface where, again, greater temperature gradients are expected. A vertical column of sensors is also located above the test room ceiling and below the floor to monitor the thermal behavior of the soil at those locations. Because the floor and ceiling are modeled to exhibit one-dimensional heat transfer characteristics, soil temperatures are only monitored at the center of these areas.

Test room surface temperature sensors are located on both the interior and exterior ceiling, wall, and floor surfaces as shown in Figure 16. An extra surface-mounted sensor and corresponding vertical column of soil temperature sensors may be located near the corner of the ceiling and



a) Section



b) Plan

Figure 16. Test Room Instrumentation Placement

floor area to validate the modeling of one-dimensional heat flow above and below the test room.

Also, sensors may be used to validate the modeling assumptions used in the design of test room insulation wings. For instance, several pairs of insulation wing surface temperature sensors may be used to insure that the insulation's resistive properties do not diminish over time or by soil moisture impingement. Soil temperatures may be monitored just beyond the assumed area of thermal influence of the test room to insure that an appreciable amount of heat is not flowing beyond the controlled area enclosed by the insulation wings.

The sensor locations shown in Figure 16 are for general cases. Additional sensors may be required for each specific investigation. For instance, if layered soils are used in backfill, additional sensors may be required at soil layer interfaces. However, in general, a consistent spacing of sensors should be maintained to provide proper correlation between different investigations.

The interior conditions will be monitored using a sensor tree, located at the center of each test room, which monitor temperature gradients in the room. The sensor points will be located as shown in Figure 16. The relative humidity will be measured four feet above the floor on the sensor tree.

The control room will be monitored to provide data for accurate calculation of actual heat transfer through all surfaces. Surface temperatures will be monitored at each wall, floor, ceiling and roof and at doors and windows on both interior and exterior surfaces. In this way, differences between temperatures may be inserted into heat gain or heat loss calculations described by ASHRAE (23) to determine the energy performance of the control room.

Interior conditions must also be monitored in the control room. A sensor tree will be located at the center of the room, similar in fashion to earth sheltered test room sensor trees, to provide interior temperature and relative humidity data. Event sensors will monitor the opening of doors and windows, and the heat gain to the room from electric lighting. Event sensors will be located in earth shelter test rooms for the same purposes and, in addition, to monitor use of night insulation in the passive solar test rooms.

Data Collection

The collection of data at the facility must be accomplished using a data acquisition system because of the large number of sensors to be monitored and the length of investigations which may continue for years. Although the design of the data acquisition system itself is beyond the scope of this thesis, identification of the number of collection points and measurement intervals required would be useful for future sizing and selection of such a system. The determination of an approximate number of collection points requires the development of a test room schedule which leads to the number of rooms required at the facility.

The number of test rooms required at the facility is determined by combining all of the previously mentioned investigations into a room schedule to determine the number of individual elements of each room required to test all investigations. Table VIII indicates that nine test rooms, as described later, are needed at the facility to perform the investigations outlined in this thesis. These nine test rooms handle all of the investigations on a continuous basis with no test materials or assemblies requiring replacement for consecutive tests. However, the facility must be totally flexible to allow replacement or repair of building elements in the future. Thus, if a particular test is found to be relatively unimportant for the investigation of total building energy performance, it may be discontinued and replaced by new ideas which continue to emerge from researchers and designers in the field of earth sheltering.

From Figure 16, an estimated 54 data collection points are needed at each earth-backed wall. Seven points are needed at each roof, five points are needed at each floor, and six points are needed for monitoring interior conditions. Combining these requirements with the number of roofs, walls, and floors in Table VIII results in a base estimate of 2260 data collection points for the total test room facility. Adding ten percent for model validations and specific design features results in approximately 2500 points required for the test rooms.

TABLE VIII

TEST ROOM SCHEDULE

INVESTIGATION	TEST ROOM REQUIREMENTS ROOFS	 WALLS	 FLOORS
#1	4		
2,3		4	
4,5,6,8	4	4	
7		5	
9		4	
10		3	
11			3
12	8		
13	3		
14		9	
15			1
16,17,18		9*	
TOTAL	19	38	4

* Above-ground walls

Other elements of the facility which are monitored include the control room, mechanical equipment, and weather measuring devices. The control room will require an estimated 60 points for surface temperature, interior space temperature and event sensors. Mechanical units serving each of the nine test rooms and the control room require one sensor each to measure the air supply temperature, humidity, and air flow rate, return air temperature, and the energy used by each unit. Fifty collection points are needed for these measurements. The weather station at the site requires six sensors to monitor air temperature and humidity, precipitation, wind velocity and direction, and solar radiation. From these estimates, an approximation of the total data collection points required at the facility is 2600 points.

The interval at which data collection must occur at a specific sensor depends upon the thermal time response at the point being measured. Thermal time responses of soil temperatures at greater depths tend to be relatively long, while air temperatures and solar radiation can vary rapidly. Table IX gives proposed monitoring intervals for each type of sensor at the facility. Event sensors are used to record the occurrence of a particular event, such as turning on lights or opening doors and, therefore, do not operate at predetermined intervals. The intervals given will be useful in the future design of the data acquisition system..

TABLE IX

SENSOR MONITORING INTERVALS

SENSOR TYPE		INTERVAL
Weather Conditions		
Outside Air Temperature		15 min
Humidity		4 hr
Precipitation		continuous
Wind Velocity		continuous
Wind Direction		continuous
Solar Radiation		5 min
Soil Conditions		
Soil Temperature	Above 2 ft depth	1 hr
	Below 2 ft depth	4 hr
Moisture Content		4 hr
Interior Conditions		
Air Temperature		15 min
Humidity		4 hr
Surface Temperatures		1 hr
Solar Radiation		5 min
Event Sensors		continuous

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

Summary of Procedure

An earth shelter research facility has been proposed which will be used to investigate energy-related aspects of earth sheltered building components and arrangements. The climate of the proposed site, near Stillwater, Oklahoma, was examined to determine the feasibility and usefulness of particular investigations. Several areas of design were then identified and further developed to provide a program for the design of the facility.

Test rooms were designed to allow isolated investigations to be performed on each earth-backed wall. Insulation wings were designed to isolate each wall thermally and to model two-dimensional heat flow in the soil adjacent to each wall. The roof and floor of each test room were also designed for thermal isolation and to model one-dimensional heat flow at those areas.

Other elements of the facility were described which include the control room, weather station, monitoring center, and mechanical equipment. These elements were then used to develop possible site configurations for the facility.

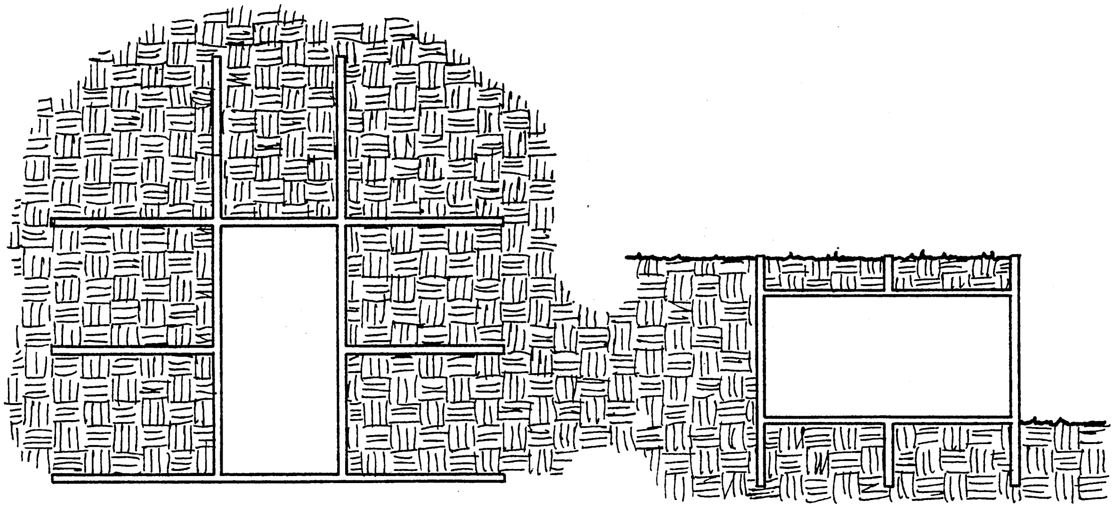
The instrumentation needed to monitor the thermal characteristics of various parameters was described and possible methods of implementing the measurement of soil properties were explored. The location of sensor points for the test rooms and control room was provided and sensor quantities lead to an estimate of the requirements for a data acquisition system. Sensor monitoring intervals were also determined to aid the future selection of a data acquisition system.

Recommendations

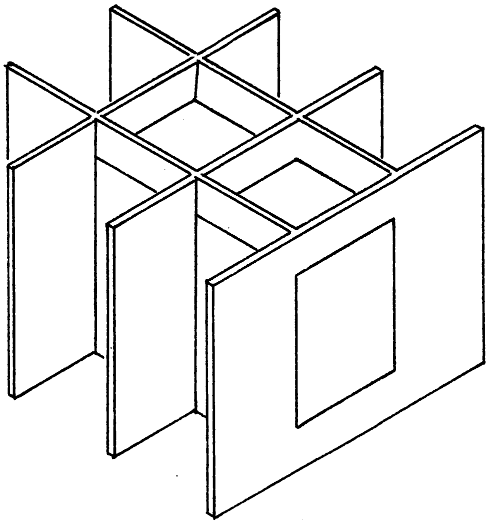
It was determined in Chapter V that nine test rooms are required in order to perform all of the investigations simultaneously. By performing investigations simultaneously, useful data may be collected from all tests immediately upon the completion of the facility. Consecutive testing would result in data collection from some tests being delayed, possibly several years, until a first group of investigations is completed. The design of these rooms must be somewhat modified from the simple design given in Figure 7 to accomplish all of the needed tasks. This is due to the fact that 19 thermally independent roofs are needed, compared to only 38 walls. If simple test rooms such as that shown in Figure 7 were used, ten of the 19 rooms would only provide data concerning the roofs while the walls would not necessarily be used. Therefore, if a larger test room were designed which could include more than one roof assembly, this problem would be eliminated. It is recommended that the test rooms be designed to allow for the investigation of more than six independent surfaces. This approach is shown in Figure 17. This design also provides extra wall sections for more investigations. For instance, the insulation wings may be removed at one corner of a room to investigate corner effects without requiring additional test rooms. Test rooms may also be divided into two adjacent rooms by constructing a highly insulated wall to form a small passive solar space and a totally underground space. This would allow the investigation of a totally passive room or investigation of thermal performance during a power outage.

The layout of the facility must be somewhat linear due to the fact that each test room includes a south-facing, exposed wall for passive solar investigation. However, a grid layout is recommended for shorter wire runs from each room to the monitoring center which may be located in one of the test rooms. The rooms in each row must be either raised in elevation or separated by a considerable distance to allow a view of the sky to the horizon for passive solar investigations. The south-facing slope of a hill would provide the most compact site layout as shown in Figure 18. The land would need a slope of only 15 degrees to accommodate this design without excessive berming.

As with any large research facility, it is very likely that funding and construction of the earth shelter research facility would occur in phases. Therefore, it is necessary to determine which investigations should hold precedence over the others.



a) Plan b) Section



c) Isometric

Figure 17. Recommended Test Room Design

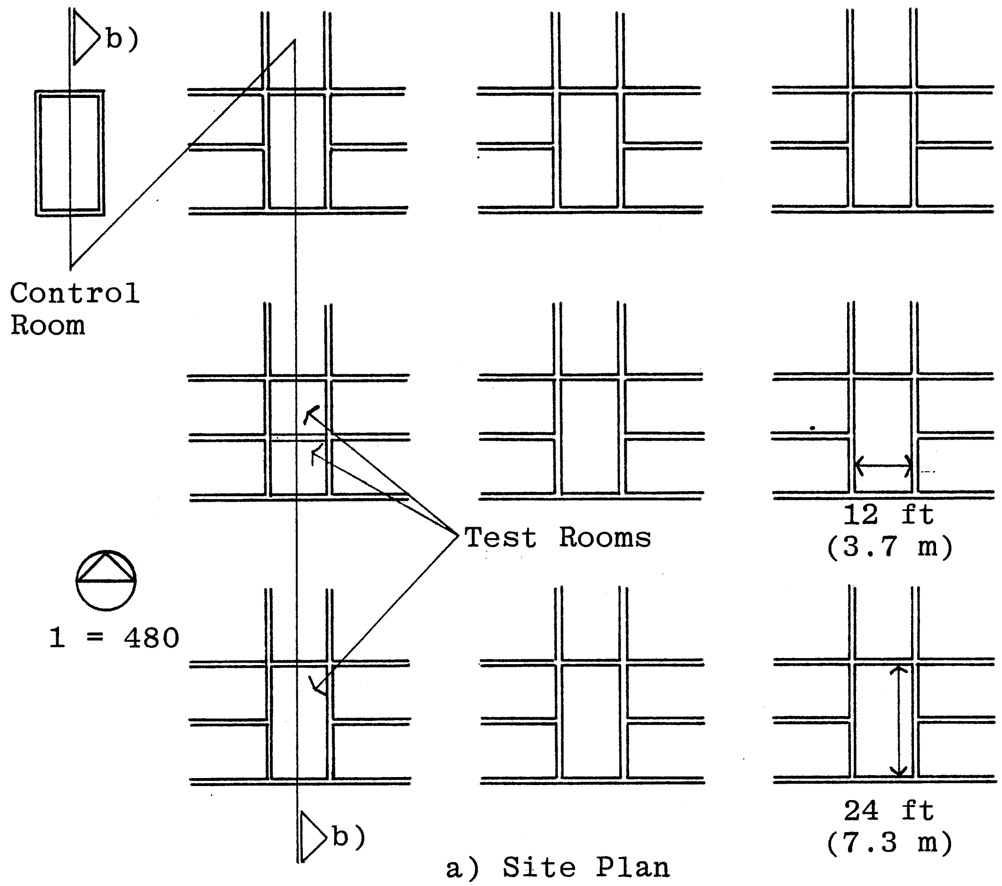
The investigations of most importance are those which lead to a quantification of heat transfer phenomenon at earth sheltered walls and roofs. By focusing attention in this area, conclusions may be drawn as to the actual and relative thermal performance of earth sheltered buildings compared to above-ground buildings in a similar climate. Only after realistic load calculation methods are developed for earth sheltered buildings may designers propose this design alternative with the definitive cost analyses insisted upon by most clients.

After earth sheltering becomes more established as a feasible building alternative, design optimization investigations will become more important. Therefore, the performance tests of most commonly used design elements may be considered second in importance and may be added to the facility as a later phase.

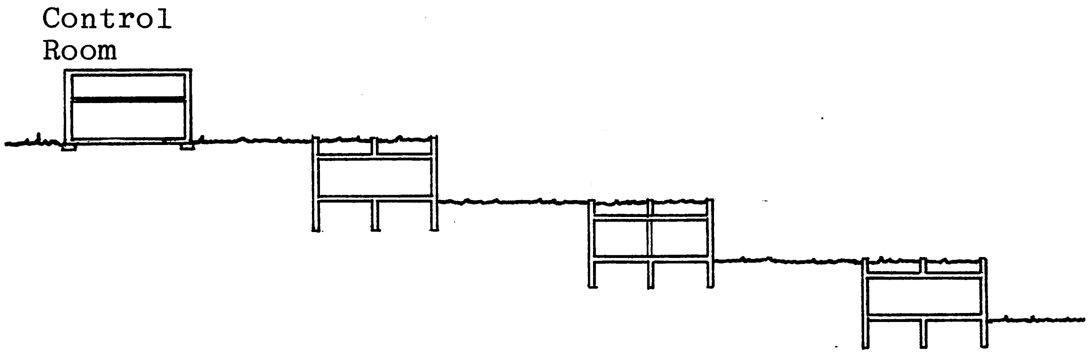
Finally, additional design alternatives may be investigated to "fine tune" earth sheltered designs with respect to energy performance. Also, the relative importance of various design alternatives with respect to energy performance may be determined. Design decisions should reflect this relative importance rather than unquantified energy-related benefits of one alternative over another.

Future Applications

The possibility of expanding the facility to include the investigation of earth shelter interior conditions including visual, acoustical, and thermal comfort should be considered when determining the size of each test room. Professional opinions indicate that the walls should be at least 8 ft (2.4 m) wide for proper modeling and, more importantly, that the opposing walls of the room should be separated by at least 12 ft (3.7 m) (Appendix B). This would result in 12 ft (3.7 m) by 24 ft (7.3 m) rooms containing 288 ft^2 (13.4 m^2) of floor area, an adequate size to handle daylighting, acoustic and interior thermal investigations. The design of larger rooms for expanded use of the facility will add substantial cost as opposed to smaller rooms. However, the facility should be considered a long-term investment and additional types of investigations would be worth considering in the initial design.



a) Site Plan



b) Site Section

Figure 18. Recommended Facility Layout

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APPENDICES

APPENDIX A

QUESTIONS CONCERNING ENERGY ASPECTS OF EARTH SHELTERED BUILDINGS

In order to develop a program for the design of an earth shelter research facility, a list of questions concerning energy-related concepts must be established. The questions listed here are developed by the author with the added assistance of professionals in the field of earth sheltering (Appendix B). Questions are arranged to correspond to areas of investigation in Chapter III.

Materials of Construction

What is the comparative performance of concrete versus wood earth sheltered structures?

What is the effect of reinforcing steel on vertical and horizontal conduction?

Ground Temperature Control

Is it possible to appreciably improve the energy performance of underground buildings by ground temperature modification?

Soil Moisture Content

How will modifying soil moisture content affect the heat flow at an earth covered wall or roof?

Does a regular irrigation schedule during summer months affect the heat gain to the building through an earth covered roof?

Can a black or clear plastic sheet placed on the ground decrease soil moisture and increase solar insolation during winter months?

How does umbrella-type construction (roof insulation extending horizontally beyond the structure into the soil) affect the soil moisture content surrounding earth sheltered buildings?

What depth of earth is needed over conditioned spaces to sustain given types of planting?

Ground Surface Treatment

What effect does ground surface treatment have on the thermal performance of underground buildings?

Does evapo-transpiration appreciably affect the soil temperature during warm months?

What are the surface shading effects associated with different types of ground cover and what affects do these have on building energy performance?

Can the ground temperature be raised in winter by burning off grass to expose the ground surface to solar energy?

Soil Type and Backfill

Does the use of different soil types for backfill produce substantially different thermal regimes surrounding underground buildings?

Can a better thermal regime be produced by layering different soil types in backfill according to their thermal characteristics?

Can an additive such as vermiculite be used to decrease the weight of the soil and affect thermal performance of earth sheltered buildings?

What is the effect of drainage tile - gravel placement on heat transfer surrounding underground buildings?

What is the effect of flat versus sloping roofs on moisture-heat transfer phenomena?

What are the corner effects associated with heat transfer from underground buildings?

Earth Coupling

Does a passive cooling potential using earth coupling techniques exist in a temperate to warm climate as found in Stillwater, Oklahoma?

What is the effect of decoupling of earth-backed walls on space cooling requirements in temperate climates?

What trade-off exists when designing for earth-contact cooling; i.e., what is the effect on a building's heating load?

Interior Surface Treatment

How does interior wall surface treatment affect earth coupling with respect to effective thermal mass and earth contact cooling?

How does a suspended ceiling affect the thermal stability of the space?

Will carpet dramatically reduce a building's effective thermal mass, degrading thermal performance?

Exterior Surface Treatment

Does the addition of backfill protection boards or drainage mats to the exterior of an underground structure decouple the structure from the adjacent soil?

Insulation Types and Installations

How much degradation in initial R-value is experienced over the life of an insulation material and how does this affect cost analysis?

When comparing 1 in. (2.5 cm) of insulation to 2 in. (5 cm), can tests be made on one product and translated to others; for instance, if EPS is doubled in thickness and the energy savings is 50% more, can we say that polyurethane foam, if doubled, will exhibit the same increase in percent savings?

Is condensation affected by insulation thickness or placement?

Roof Insulation

What is the optimum type and thickness of roof insulation for underground buildings for a given depth of earth cover and climate?

Will extending roof insulation horizontally beyond exterior walls (umbrella-type construction) increase the effective thermal mass of a building?

Does a degradation in building thermal performance occur when roof insulation is placed on the interior of the structure?

What is the optimal depth of earth cover with respect to thermal performance?

What is the relative increase in energy savings for each foot increase in depth or for doubling of depth?

Wall Insulation

What is the optimal amount and placement of wall insulation in temperate climatic regions for a given depth of earth cover?

How much degradation in thermal performance results from placing the insulation on the interior surface of the wall?

Floor Insulation

How and to what extent does under-floor insulation affect an earth sheltered building's energy performance?

Earth Shelter/Passive Solar Integration

How great is the added benefit with respect to energy performance, if any, of combining earth shelter with passive solar concepts?

What is the optimum size of passive solar design components in relationship to the size and effective mass of an earth-sheltered building?

Modeling Concepts

How large must a test wall or roof be to properly model an actual condition?

What physical shape of test room will best reflect the investigations to be performed?

Should internal loads be produced in the test room or may their effect be calculated by conventional methods?

What is the actual or relative impact of a given test on the total energy performance of a building?

How flexible should the earth-backed wall design be for changing experiments?

Are there thermal modeling problems involved with drainage at footings?

Will the insulation wings tend to create a cumulative heat effect by interfering with the infinite thermal sink of the soil?

APPENDIX B

QUESTIONNAIRE RESPONSES AND FREQUENCIES

There are no hard and fast rules for modeling the heat transfer characteristics of earth shelters. In addition, very little literature regarding this topic exists. In order to get a feel for current thinking on the subject, a brief questionnaire was sent by the author to selected experts in the field of earth shelters. Although some questions may currently be impossible to answer definitively, professional opinions may be very useful in developing reasonable models to investigate energy-related aspects of earth sheltered buildings. Therefore, the design of test rooms described in Chapter IV is based in part on the questionnaire responses received.

Q1. For proper modeling of the heat flow through an earth sheltered wall, assuming two-dimensional heat flow, the wall width (A) should be a minimum of ______.

Answer ft	(m)	Absolute Freq (%)	Relative Freq (%)	Adjusted Freq (%)	Cumulative Freq (%)
2	(0.6)	1	9	10	10
6	(1.8)	3	27	30	40
8	(2.4)	4	36	40	80
10	(3.0)	2	18	20	100
No Answer		1	9		
Total		11	100	100	

Q2. The zone of influence with respect to heat flow in the earth surrounding the test rooms should not overlap. Therefore, the distance between rooms (B) should be at least _____.

Answer ft (m)	Absolute Freq (%)	Relative Freq (%)	Adjusted Freq (%)	Cumulative Freq (%)
10 (3.0)	4	36	40	40
20 (6.1)	4	36	40	80
30 (9.1)	1	9	10	90
40 (12.2)	1	9	10	100
No Answer	1	9		
Total	11	100	100	

Q3. The vertical insulation wings should extend at least _____ beyond the structure (C).

Answer ft (m)	Absolute Freq (%)	Relative Freq (%)	Adjusted Freq (%)	Cumulative Freq (%)
4 (1.2)	3	27	38	38
6 (1.8)	1	9	12	50
8 (2.4)	2	18	25	75
16 (4.9)	2	18	25	100
No Answer	3	27		
Total	11	100	100	

Q4. To approach an adiabatic condition, the minimum R-value for the vertical insulation wings should be _____.

Answer $\frac{\text{hr ft}^2\text{ F}}{\text{Btu}}$ $(\frac{\text{m}^2\text{ K}}{\text{W}})$	Absolute Freq (%)	Relative Freq (%)	Adjusted Freq (%)	Cumulative Freq (%)
R-5 (0.88)	1	9	10	10
R-10 (1.76)	1	9	10	20
R-15 (2.64)	2	18	20	40
R-20 (3.52)	2	18	20	60
R-30 (5.28)	4	36	40	100
No Answer	1	10		
Total	11	100	100	

Q5. If the insulation wings are eliminated at one corner of a test cell to investigate corner effects, then the adjacent walls of the cell should be at least _____ wide to include a reasonable length of the wall which is influenced by a corner.

Answer ft (m)	Absolute Freq (%)	Relative Freq (%)	Adjusted Freq (%)	Cumulative Freq (%)
6 (1.8)	2	18	20	20
8 (2.4)	5	45	50	70
10 (3.0)	2	18	20	90
12 (3.6)	1	9	10	100
No Answer	1	9		
Total	11	100	100	

Q6. In order to prevent opposing and adjacent walls from exchanging more radiant energy than would be experienced in actual buildings, the opposing walls should be separated by at least _____ (dimension A).

Answer ft (m)	Absolute Freq (%)	Relative Freq (%)	Adjusted Freq (%)	Cumulative Freq (%)
6 (1.8)	1	9	12.5	12.5
8 (2.4)	1	9	12.5	25
10 (3.0)	1	9	12.5	37.5
12 (3.6)	5	45	62.5	100
No Answer	3	27		
Total	11	100	100	

Q7. List five characteristics of earth sheltered walls that warrant investigation (example: insulation placement).

Answers:

Thickness of wall.

Transient versus steady-state losses.

Detailed analysis of performance of actual walls in summer and winter.

Energy storage patterns in masonry walls during steady state and fluctuating interior and ambient thermal conditions.

Effect of soil moisture--soil type on heat transfer.

Vertical temperature profile.

Vertical heat flow profile.

Interior conditioning effect on earth temperatures.

Overall effects of furred wall treatments with respect to heat transfer and comfort.

Identify outside air temperatures and times (duration) necessary to cause indoor condensation.

The effect of insulation placement on condensation formation on interior surfaces.

Condensation potential when varying thicknesses of insulation are graduated top to bottom (thickest at top).

Inside versus outside insulation.

The effect of using different types of insulation on heat transfer.

Heat flow paths of walls insulated on exterior (losses to outside).

Cold flow paths of walls insulated on exterior (gains to interior a result) (Hot external climate).

Identify actual measurement of heat losses/gains to walls uninsulated, but with roof plane insulation in ground to "isolate" mass of surrounding earth.

Empirical analysis of various insulation strategies on a seasonal and annual basis.

Insulation moisture resistance.

Effects of drainage materials such as Enkadrain or gravel.

Heating or cooling effect of air flow through porous backfill adjacent to embanked wall.

Effect of porous backfill on thermal energy transfer between soil and structure.

Thermal conductivity of wet and dry soil.

Potential of changing soil conductivity.

Heat transfer coefficients on inside of walls.

Effect of soil diffusivity at various depths.

Effect on termite mobility (to above-grade wood).

Thermal performance as a function of orientation of wall.

Cost of structure to resist earth loads.

Corner effects.

Effect of reinforced steel on vertical and horizontal conduction.

Q8. List five characteristics of earth-covered roofs that warrant investigation (example: depth of earth cover).

Answers:

Influence of ground cover on temperature profiles above a conditioned space.

Effect of plant shading (low and high foliage).

Effect of shade and ground cover on soil energy absorptions.

Effect of evaporation on heat transfer.

Varying rates of moisture available at the ground surface (quantify cooling benefits available by evapotranspiration).

Empirical analysis of various soil depths with respect to energy performance.

Influence of various irrigation approaches.

Effect of water (rain or irrigation) on energy storage and heat transfer.

Effect of irrigation (sprays versus trickles).

Effect of soil types (dry and wet).

Empirical analysis of various insulation schemes.

Investigation of soil temperature modification techniques.

Energy storage patterns under varying climatic conditions.

Cost of system for different support spacings and earth fill depths.

Compare resistive and capacitive insulation (earth cover versus superinsulated roof).

The effect of sloping versus flat roofs on moisture - heat transfer phenomena.

The effect of sloping landscape surface on heat transfer.

Waterproofing longevity.

Difficulty of repair of waterproofing.

Waterproofing resistance to puncture by plant roots.

Q9. List five special areas of earth sheltering that warrant investigation (example: drainage).

Answers:

Indoor air quality.

Differential costs, especially with respect to roofs.

Two-dimensional effects and three-dimensional effects.

Passive cooling potentials.

Aesthetics.

Entrance design aspects.

Heat transfer to soil.

Energy storage and release in structures.

Thermal performance of earth sheltered structures with penetrational windows versus one-side exposed structures.

The effects of carpeting versus tile floor coverings on thermal perfromance.

Effects of freezing in insulation.

Moisture control (humidity and condensation).

Condensation control in humid climates.

Pipe/duct/chimney penetration effects.

Thermal break design effectiveness.

Durability of waterproofings.

Earth tubes - around, under and over.

The comparative performance of concrete versus wood earth sheltered structures.

Practical tradeoffs involved in different berm heights.

Effect of backfill compaction.

Rodent damage to exterior insulation.

Detailed life cycle cost comparison of interior versus exterior insulation in dry and in humid climates.

Daylightng performance.

Access and lighting to underground spaces.

Acceptability of underground housing in communities.

Human comfort.

Hybrid systems (passive solar, ventilation strategies incorporated into earth sheltered buildings).

Efficient structural designs to make earth-covered roofs more competitive with conventional roofs.

Zoning characteristics of large earth sheltered buildings - optimizing zone placement to minimize space cooling/heating requirements.

List of Respondents

Sydney A. Baggs
The University of New
South Wales
Australia

Lester L. Boyer
Oklahoma State University
Stillwater, Oklahoma

Joseph A. Carroll
Energy Science Laboratories
San Diego, California

Richard Cottrell
College of the Sequoias
Visalia, California

R. R. Gilpin
University of Alberta
Edmonton, Alberta Canada

Walter Grondzik
Oklahoma State University
Stillwater, Oklahoma

T. Kusuda
National Bureau of Standards
Washington, D.C.

Fuller Moore
Miami University
Oxford, Ohio

Jerry O. Newman
U.S. Department of
Agriculture
Clemson, South Carolina

J. Ramsey
University of Minnesota
Minneapolis, Minnesota

Jerome Speltz
Setter, Leach & Lindstrom
Minneapolis, Minnesota

APPENDIX C

PASSIVE SOLAR RULES-OF-THUMB

Mazria (31) developed the following rules-of-thumb for passive solar designs. These values may be modified, as discussed in Chapter III, for earth shelters and used to develop earth shelter/passive solar investigations.

Solar Windows

In temperate climates (average winter temperatures 35 to 45F (1.7 to 7.2C)), provide 0.11 to 0.25 ft^2 (m^2) of south-facing glass for each ft^2 (m^2) of floor area.

Heat Storage

The surface area of concrete exposed to direct sunlight over the day is 1.5 times the area of the glazing, resulting in temperature fluctuations of about 40F (22.2C) over the day.

The surface area of concrete exposed is 3 times the area of the glazing, resulting in temperature fluctuations of 26F (14.4C).

The surface area is 9 times the area of the glazing, resulting in temperature fluctuations of 13F (7.2C).

These results show that for a space to remain comfortable during the day, each square foot of direct sunlight striking a concrete surface must be diffused over at least 9 ft^2 (0.8 m^2) of masonry surface.

Thermal Walls

Surface of container should be a dark color, at least 60% solar absorption, and use about 1 ft^3 or 7.5 gallons of water for each ft^2 (306 l of water for each m^2) of solar window.

In temperate climates (average winter temperatures 35 to 45F (1.7 C to 7.2C)), use between 0.22 and 0.6 ft^2 (m^2) of thermal wall (0.16 and 0.43 ft^2 (m^2) for a water wall) for each ft^2 (m^2) of floor area.

Recommended thicknesses of thermal storage walls.

Adobe	8-12 in.	(20 - 31 cm)
Brick (common)	10-14 in.	(25 - 36 cm)
Concrete (dense)	12-18 in.	(31 - 46 cm)
Water	6 or more in.	(15 or more cm)

In temperate climates, use 0.33 to 0.9 ft^2 (m^2) of greenhouse glass for each ft^2 (m^2) of building floor area.

Sizing the Attached Greenhouse for Climatic Conditions

	Avg Winter Temp (degree days/mo)		Unit Area of Greenhouse Glass for each unit of floor area	
	F	C	Masonry	Water Wall
	20(1350)	6.7(750)	0.9 - 1.5	0.68 - 1.27
Cold	25(1200)	3.9(667)	0.78 - 1.3	0.57 - 1.05
	30(1050)	1.1(583)	0.65 - 1.17	0.47 - 0.82
	35(900)	1.7(500)	0.53 - 0.90	0.38 - 0.65
Temp	40(750)	4.4(417)	0.42 - 0.69	0.30 - 0.51
	45(600)	7.2(333)	0.33 - 0.53	0.24 - 0.38

For combining systems, for the same amount of heating, each ft^2 (m^2) of direct gain glazing equals 2 ft^2 (m^2) of thermal storage wall or equals 3 ft^2 (m^2) of greenhouse common wall area.

To provide heat storage for one or two cloudy days, increase the collector area by 10 to 20 percent.

Projection of overhang:

32 latitude	F factor = 4.0 - 6.3
36 latitude	3.0 - 4.5

$$\text{F factor} = \frac{\text{window opening (height)}}{\text{projection}}$$

The following rules-of-thumb are from the U.S. Department of Energy (32).

Solar Collection Area

A solar collection area of R1% to R2% of the floor area can be expected to reduce the annual heating load of a building in (location) by S1% to S2%, or, if R-9 hr ft^2 F/Btu (R-1.584 m^2 K/W) night insulation is used, by S3% to S4%.

	R1	R2	S1	S2	S3	S4
Oklahoma City	11	22	25	41	41	67
Tulsa	11	22	24	38	40	65

Orientation

The orientation of the solar glazing should lie between 20 degrees east and 32 degrees west of true south.

Note that this rule-of-thumb is based on sensitivity calculations done for Trombe walls and water walls. Some designers prefer to use some direct gain oriented slightly east of true south to "wake up" the building early in the morning. Another important consideration in selecting orientation is summer performance. Summer solar gains are very sensitive to orientation, especially at more southerly latitudes, and east or west orientations are to be avoided as much to prevent summer overheating as to maximize winter performance.

APPENDIX D

THE "ARKANSAS" WELL-INSULATED HOUSE

The building envelope design of the "Arkansas" Well-Insulated House is used as a guide in the design of the above-ground equivalent of the earth sheltered test rooms. Figure 19 illustrates the features of the house as described below (38).

Roof Construction

Roof Truss 24 in. (0.6 m) on center.
12 in. (0.3 m) Friction Fit batts.
Polyethylene vapor barrier completely covering both studs and insulation on interior side of ceiling.
Controlled ventilation of attic space.

Wall Construction

6 in. (0.15 m) stud walls, 24 in. (0.6 m) on center.
6 in. fiber glass insulation.
Polyethylene vapor barrier completely covering both studs and insulation on interior side of wall.
Single pane windows with storm windows.
Therma-Tru doors, R-13.8 hr ft^2 F/Btu (R - 2.4 m^2 k/w).
Total window area restricted to 8 percent of living area.

Floor Slab Construction

Concrete slab reinforced with welded wire mesh.

Polyethylene vapor barrier below slab.

1.5 in. (3.8 cm) urethane insulation around the perimeter of the slab.

Sand base.

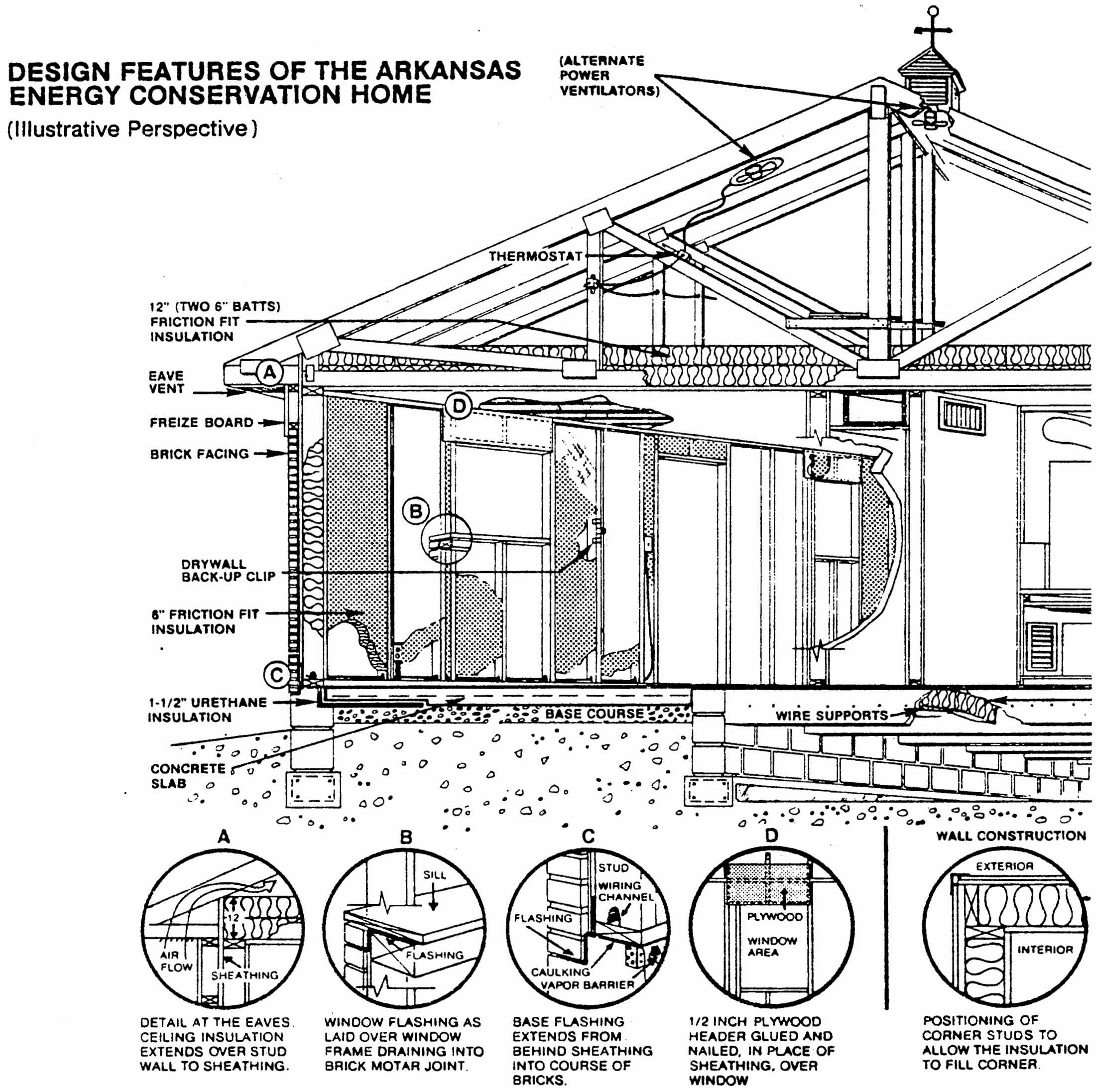

Figure 19. Details of the "Arkansas" Well-Insulated House

VITA

Joseph Henry Hackney

Candidate for the Degree of

Master of Architectural Engineering

Thesis: EARTH SHELTER TEST FACILITY AT OKLAHOMA STATE UNIVERSITY FOR ENERGY-RELATED INVESTIGATIONS: PROGRAM AND CONCEPT DESIGN

Major Field: Architectural Engineering

Biographical:

Personal Data: Born in Oklahoma City, Oklahoma, October 26, 1957, the son of Mr. and Mrs. C. J. Hackney.

Education: Graduated from Drummond High School, Drummond, Oklahoma, in May, 1975; received Bachelor of Architectural Studies from Oklahoma State University in 1981; completed requirements for the Master of Architectural Engineering in December, 1983.

Professional Experience: Part-time draftsman for Kenneth L. Sain and Associates, P.E., Enid, Oklahoma, 1976-81; job superintendent's assistant for P. C. Davis and Sons Construction Company, Enid, Oklahoma, 1978-79; graduate teaching and research assistant, School of Architecture, Oklahoma State University, 1981-83.

Professional Organizations: Charter Member, National Society of Architectural Engineers, 1982-83; American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1981-83; Construction Specifications Institute, 1981-83.