ANALYSIS OF THE THERMAL PERFORMANCE OF EARTH COVERED ROOFS BASED UPON A FORMULATED INTERACTIVE COMPUTER DESIGN AID

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PREFACE

This study is concerned with diurnal heat transfer through earth covered roofs. The primary goals of this thesis are: 1) to gain an understanding of current empirical data and methodologies for calculating heat transfer through earth covered roofs or methodologies that may be applied to this area; 2) to formulate an interactive computer design and analysis aid; and 3) to formulate design guidelines and a quick estimation method for calculating peak diurnal heat transfer.

The author wishes to express his appreciation to his major adviser, Professor Lester Boyer, for his guidance and assistance in this study. Special appreciation is also expressed to Professor Walter Grondzik for his guidance, assistance and continual nudging. Appreciation is also expressed to the other committee members, Professor Alan Brunken and Professor George Chamberlain.

A note of thanks is given to Professor Faye C. McQuiston for his assistance in accessing the transfer function program in Oklahoma State University's IBM mainframe computer. Appreciation is also given to the School of Architecture; I shall never forget the endless studio hours spent there.

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LIST OF SYMBOLS

A - Apparent solar irradiation (Btu/hr-ft^2)

a - Effective absorption coefficient of the surface

a_c - Effective absorption coefficient of the topping

a_s - Effective absorption coefficient of the soil

B - Atmosphere extinction coefficient

b_n - Transfer function coefficient (Btu/hr-ft^2-^oF)

b - Solar Altitude angle from horizontal (degrees)

C - Diffuse radiation factor

CF - Coupling factor

c_n - Transfer function coefficient (Btu/hr-ft^2-^oF)

D - Density (lb_{mass}/ft^3)

DR - Average daily temperature range (^oF)

DRP_t - Percentage of daily range at time t

d_n - Transfer function coefficient (unitless)

dT - Incremental change in temperature (^oF)

dy - Incremental change in depth (ft)

e - Effective emittance coefficient of the surface

e_c - Effective emittance coefficient of the topping

e_s - Effective emittance coefficient of the soil

F_{ss} - Angle factor between surface and sky

G - Solar declination

H - Hour angle

h_o - Coefficient of heat transfer by long wave radiation and convection (Btu/hr-ft^2-^{o}F)

I_{ds} - Diffuse solar radiation (Btu/ft^2-hr)

I_{dn} - Direct solar radiation (Btu/ft^2-hr)

I_n - Different between the long wave radiation incident on the surface from the sky and surroundings, and the radiation emitted by a black body at outdoor air temperature (Btu/hr-ft^2)

I_t - Total solar radiation (Btu/hr-ft^2)

i - Number of increments

k - Thermal conductivity (Btu/hr-ft-^{o}F)

L - Local latitude (degrees N)

MC - Moisture content by weight (percent)

n - Summation index

q - Heat flux per unit area (Btu/hr-ft^2)

q_e - Estimated delayed peak heat flux (Btu/hr-ft^2)

q_i - Instantaneous peak heat flux (Btu/hr-ft^2)

q_n - New delayed peak heat flux (Btu/hr-ft^2)

q_s - Delayed peak heat flux through high mass roof (Btu/hr-ft^2)

q_t - Heat flux per unit area at time t (Btu/hr-ft^2)

R - Thermal resistance (^{o}F-ft^2-hr/Btu)

R_e - Thermal resistance of the soil (^{o}F-ft^2-hr/Btu)

R* - Thermal resistance of composite roof minus soil (^{o}F-ft^2-hr/Btu)

S - Specific heat (Btu/lb$_{mass}$-^{o}F)

S_1 - Storage load factor

S_{mc} - Specific heat at moisture content MC(Btu/lb_{mass}-^{o}F)

S_s - Specific heat of soil (Btu/lb_{mass}-^{o}F)

S_t - Storage time factor

SC - Shading coefficient

T_i - Indoor temperature (^{o}F)

T_m - Average daily maximum temperature (^{o}F)

T_o - Outdoor temperature (^{o}F)

T_{rc} - Constant indoor room temperature (^{o}F)

T_{t-n} - Sol-air temperature at time t-n (^{o}F)

t - Time (hr)

t_a - Estimated time of delayed peak load (hr)

t_e - Hourly sol-air temperature (^{o}F)

t_i - Hour in which q_i occurs

t_o - Hourly outdoor temperature (^{o}F)

t_s - Hour in which q_s occurs

V - Variance factor

θ - Angle of incidence between incoming radiation and a line normal to the surface (degrees)

CHAPTER I

INTRODUCTION

Background

The energy waste that developed during this century as a result of the abuse of the world's finite supply of fossil fuels has been well established. The United States is the greatest per capita energy user in the world.[1]

All sectors of society are affected by energy. Architecture is no exception to this fact. Residential and commercial sectors together consumed 35 percent of the total energy consumed in the United States.[2] Proper building design can increase the efficient use of energy in architecture. Architects and engineers before 1973 had little regard for efficient use of energy in buildings. Building designers of that era were applying the design freedom afforded them by the combination of modern mechanical systems and abundant cheap energy.

Space heating and cooling are responsible for the largest proportion of energy use in residential and commercial buildings. In the residential sector alone, space heating and cooling account for almost 70 percent of all residential energy use and 16 percent of the United States' total raw energy use.[3]

There is an ever-increasing array of design strategies available for use in reaching energy conservation goals. The National Energy Plan II (NEP-II), a federal energy program, advocates energy conservation and the authors hope that this will provide valuable time to develop new technologies, new energy sources and new energy facilities.[4]

Earth Sheltering

One building design solution that has gained much attention since the energy squeeze is the concept of earth sheltering. "Underground space is a resource of great potential benefit which has been exploited in different parts of the world for thousands of years."[5] Malcolm Wells, probably the earliest and most adamant contemporary proponent of earth sheltering, believes the major benefit of earth sheltering is minimal environmental impact. Nearly 20 years ago, he maintained "that there just isn't any building as beautiful or as appropriate, or as important, as the bit of forest it replaces."[6]

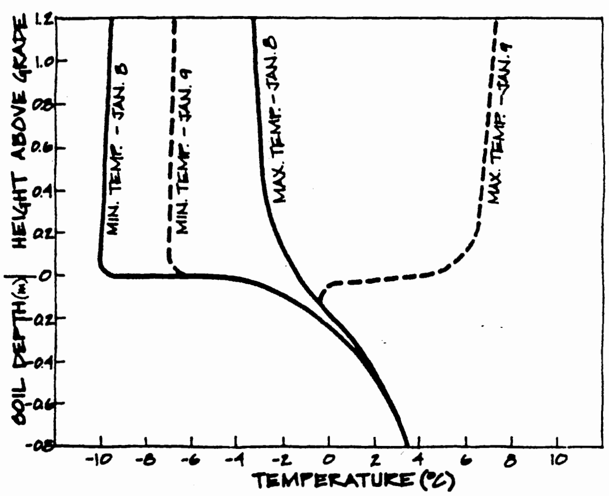
There are many advantages to earth sheltering. These advantages include storm protection, increased security, earthquake protection, reduced environmental noise, double use of land, reduced exterior maintenance, and reduced energy consumption. In many areas, energy conservation is the primary and most recognized of these advantages. An Oklahoma State University study of contemporary earth sheltered residences in Oklahoma singled out the desire for reduced heating and cooling requirements as the primary reason for building underground.[7]

The thermal environment ultimately responsible for the reduced heating and cooling requirements of an earth sheltered residence is much different from its above-ground counterpart. This different thermal environment is the primary reason for potential energy savings in earth sheltered residences.

Earth's Thermal Environment

The transfer of heat from any structure is a function of two principal factors: the air infiltration and ventilation load and heat transmission through the building envelope. In an earth sheltered home, there is a large reduction in air infiltration due to earth covering.[8] Although the infiltration load is reduced, it's magnitude may still account for a large portion of the total building load. Heat transfer through the building envelope is a function of the insulative quality (thermal transmission coefficient) of the envelope and the temperature difference between the inside air and outside air.

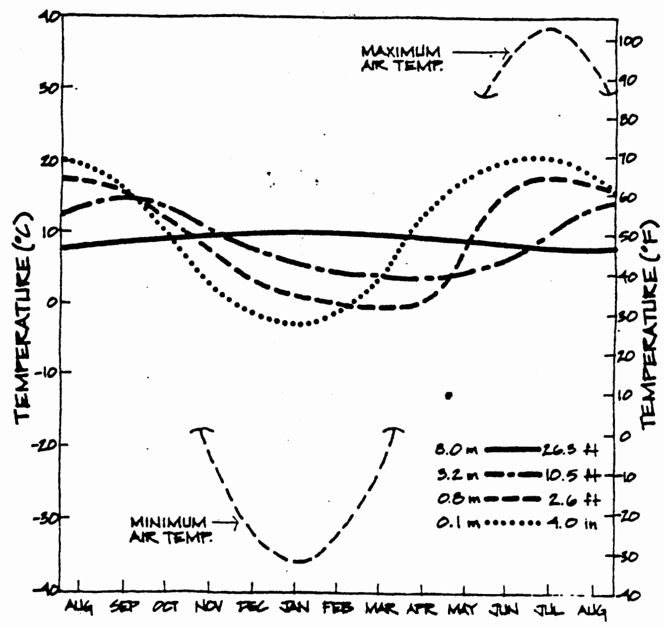
The earth's large soil mass has a climatic dampening effect by smoothing out diurnal and seasonal temperature fluctuations. Figure 1 demonstrates the negligible effect of hourly or daily temperature fluctuations below about eight inches (0.2 meters). The elimination of these diurnal fluctuations demonstrates the thermal advantage of an earth-covered roof even with a shallow earth cover of only an eight inch depth.[9] At greater depths, soil temperatures respond to seasonal changes after a time lag. The soil temperature distribution for one year in the Minneapolis- St. Paul area (Figure 2) shows the dampening effect at various depths.[10]



Source: Underground Space Center, University of Minnesota Earth Sheltered Housing Design (New York: Van Nostrand Reinhold, 1979), p. 53.

Figure 1. Tautochrone

Heat is transferred through the soil at varying rates. The rate of heat transfer is a function of depth of earth cover and the temperature distribution or gradient in the soil, which generally changes with depth. Figure 3 schematically shows the pattern of heat loss from a buried, uninsulated structure for nearly steady-state, mid-winter conditions. The rate of heat transfer is indicated by the closeness of the solid lines.[11] Note that the greatest rate of transfer is from the roof while the lowest is from the floor slab. The reason for this difference is the temperature variation between the two depths and the difference in lengths of the heat transmission paths.



Source: Underground Space Center, University of Minnesota <u>Earth Sheltered Housing Design</u> (New York: Van Nostrand Reinhold, 1979), p. 53.

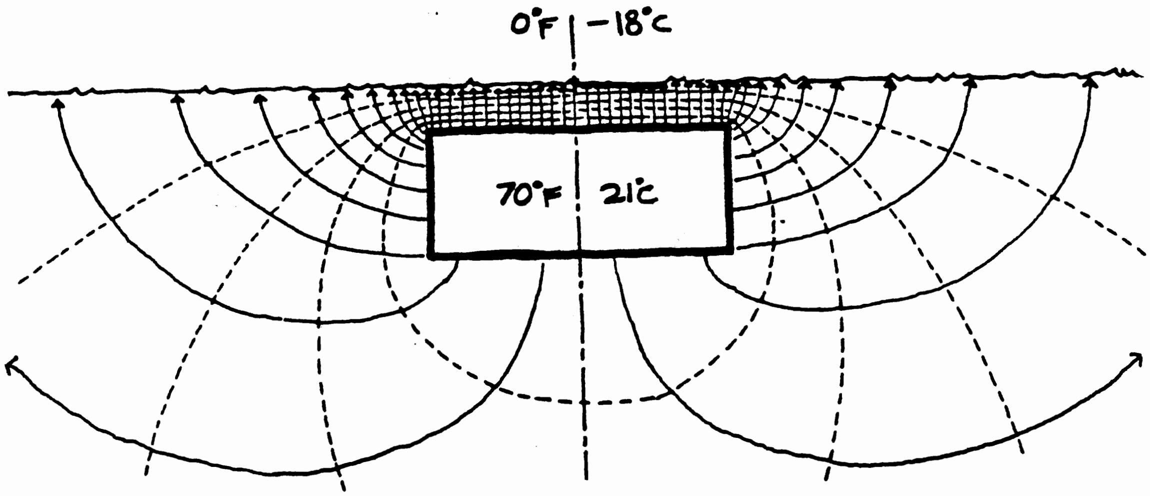
Figure 2. Soil Temperature Distribution

The Roof System

There is a controversy over the relative thermal benefits of an earth covered roof (high mass) and a thermal roof (well insulated, conventional).[12] It is beyond the scope of this thesis to closely scrutinize this issue, but this controversy does reflect the uncertainty of the relative degree of thermal benefit of earth covered roofs.

The relatively large rate of heat transfer, as shown in Figure 3, of an uninsulated earth covered roof as compared to floor and walls, demonstrates the importance of considering the earth covered roof in thermal design. The relative thermal benefits of the roof as compared to wall/floor surfaces are less, but the thermal characteristics of earth covered roofs are nevertheless important because of the roof's closeness to the relatively harsh above ground environment. "Evidence suggests that cooling benefits associated with earth-covered roofs are certainly of a lower magnitude than the benefits associated with earth contact wall and floor surfaces;" however, "it is clear that earth covered roofs can provide both heating and cooling season thermal benefits."[13]

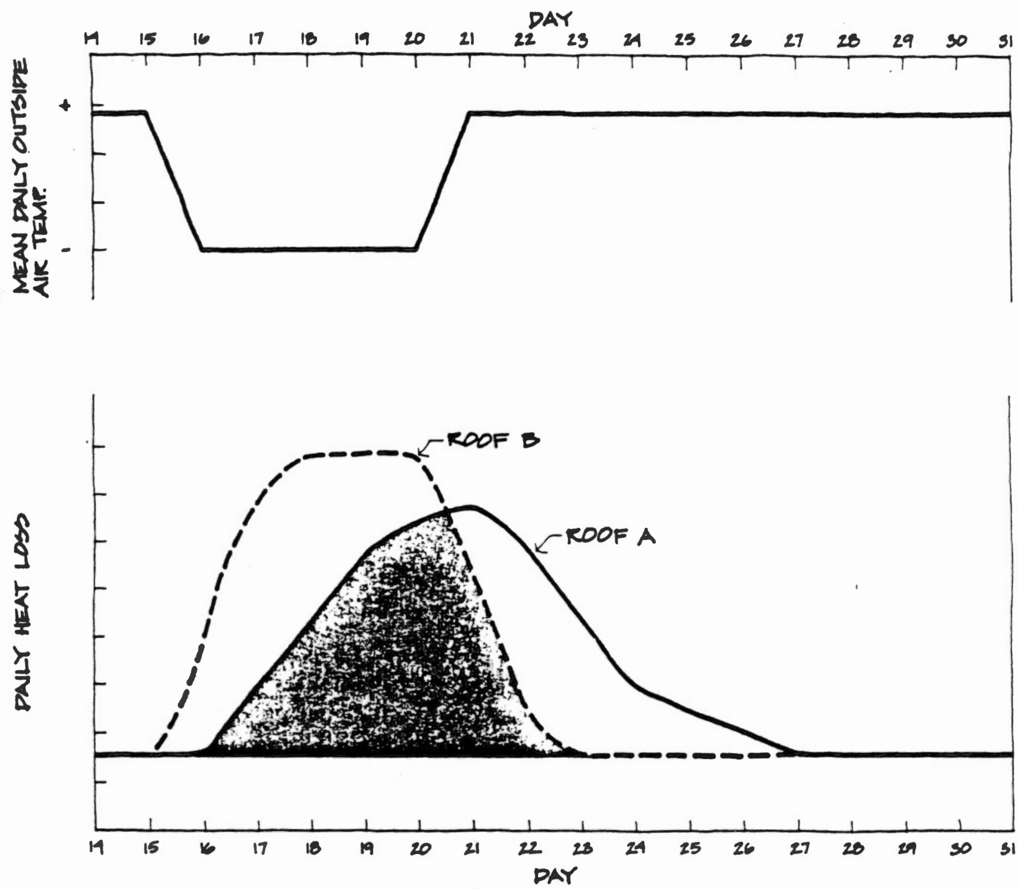
The thermal resistance (R-value) of soil is not a major factor in roof design because of soil's large thermal conductivity as compared to that of insulating materials.[14] Three primary factors influencing thermal performance of an earth covered roof are the heat capacity or thermal mass of the roof system, roof insulation and surface boundary conditions.[15]



Source: U.S. Department of Energy, Insulation Principles, Earth Sheltered Structures Fact Sheet No. 5, ORNL/SUB-7849/05 (May, 1981), p. 1.

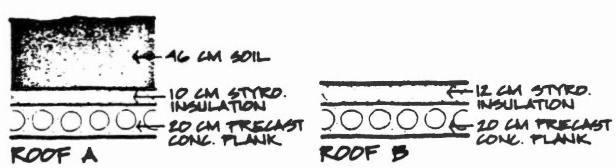
Figure 3. Schematic Section Illustrating Heat Flow From Buried Uninsulated Structure

A study at the University of Minnesota[16] showed that a high mass roof is less sensitive to changing climatic conditions compared to a roof with insulation and shallower earth cover. A high mass roof also results in a reduction of peak load. These advantages are shown in Figure 4, where roof A represents an installation with 9.8 feet (3.0 meters) of soil cover with no insulation, and roof B represents an installation with 1.5 feet (0.46 meters) of soil with



Source: Underground Space Center, University of Minnesota Earth Sheltered Housing Design (New York: Van Nostrand Reinhold, 1979), p. 57.

Figure 4. Thermal Mass Effect in Two Roof Structures



Source: -Underground Space Center, University of Minnesota Earth Sheltered Housing Design (New York: Van Nostrand Reinhold, 1979), p. 57.

Figure 5. Roof Section Comparison

insulation. Both roof designs had nearly identical R-values and were subjected to identical weather conditions (by computer simulation) resulting in nearly the same heat loss. Even with thermal benefits, there is a major trade-off involved due to increased structural costs to support large soil depths. This trade-off warrants future investigation.

The surface boundary is important to the thermal performance of earth covered roofs. The rate at which heat is transferred to or from the soil is influenced by the soil-air interface.[17] Vegetation influences heat transfer by shading, evaporation, improved insulation due to air pockets in the vegetation, absorption and reflection of solar heat gain, and water retention.

Kusuda and Baggs have investigated the influence of ground cover on earth temperature. Kusuda compared asphalt, bare ground and grass surfaces.

> The temperature in the earth is affected by the nature of the ground surface cover. The annual variation as well as the average temperature under the high heat absorbing surface (black asphalt) is higher than the lower heat absorbing (grass covered) surfaces.[18]

Baggs found that shading effects of vegetation had more direct results in affecting earth temperature than did changes in earth cover depth or changes in soil thermal diffusivity.[19]

The earth covered roof system is important to the thermal design of an earth covered building. The earth covered roof deserves close scrutiny due to greater climatic sensitivity, as compared to the walls and floor. This makes the earth covered roof the thermally weakest earth backed surface. By understanding earth covered roofs and designing them to meet thermal performance goals, the roof system can help make earth covered buildings an energy conservation alternative with even greater potential.

ENDNOTES

[1]T. P. Bligh, "Energy Conservation by Building Underground," Underground Space (May/June, 1976), 1(1) p. 21.

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[8]Underground Space Center, University of Minnesota, Earth Sheltered Housing Design (New York: Van Nostrand Reinhold, 1979), p. 53.

[9]Ibid.

[10]Ibid.

[11]U.S. Department of Energy, Insulation Principles, Earth Sheltered Structures Fact Sheet No. 5, ORNL/SUB-7849/05 (May, 1981), p. 1.

[12]M. R. Lunde, "Efficiency Compared: Earth Covered and Thermal Roof," Earth Shelter Digest and Energy Report (May/June, 1981), No. 15, p. 26.

[13]W. T. Grondzik, L. L. Boyer and T. L. Johnston, "Earth Coupled Cooling Techniques," Proc. 6th National Passive Solar Conf., Portland, AS/ISES (September, 1981), p. 841.

[14]T. P. Bligh, Paul Shipp and George Meixel, "Energy Comparisons and Where to Insulate Earth-Sheltered Buildings and Basements," Energy (September, 1980), Vol. V, p. 457.

[15]Ibid.

[16]Underground Space Center, University of Minnesota, Earth Sheltered Housing Design (New York: Van Nostrand Reinhold, 1979), p. 53.

[17]T. P. Bligh, Paul Shipp and George Meixel, "Energy Comparisons and Where to Insulate Earth-Sheltered Buildings and Basements," Energy (September, 1980), Vol. V, p. 459.

[18]T. Kusuda, "The Effect of Ground Cover on Earth Temperature," Alternatives in Energy Conservation: The Use of Earth Covered Buildings, F. Moreland (ed.), (Washington: National Science Foundation) NSF-RA 760006, p. 281.

[19]S. A. Baggs, "Effects of Vegetation Upon Earth-Cooling Potential," Proc. Earth Shelter Performance and Evaluation Conf., L. L. Boyer (ed.), Oklahoma State University, Stillwater, Oklahoma (October, 1981), p. 87.

CHAPTER II

PROBLEM DEFINITION

General Statement

Reduction of heat transfer from the floor slab and earth-backed walls of an earth sheltered building, due to earth sheltering, causes the earth covered roof system to be the most critical area of thermal transfer next to the typically encountered air-exposed facade. The ability to predict thermal performance of this climatically sensitive earth sheltered surface will allow an overall improvement in thermal design of earth sheltered residences.

Goals and Objectives

> Only since the mid-1970's has the subject of an accurate analysis of underground heat transfer from buildings under normal operating conditions for human comfort become a subject of intensive research.[1]

Before that time, most research was in the areas of soil temperature analysis for agricultural and climatic purposes, thermal behavior of occupied underground civil defense shelters and heat loss from house basements.[2] Due to the relatively young research effort into underground heat transfer, with respect to human comfort, existing published methods of analysis leave much to be desired as a design tool for earth sheltered buildings.

Most methods of evaluation are simplified and restricted in their use or are extremely complex and costly to use. A hand method for determining the maximum design heat loss from earth backed basement walls is outlined in the 1981 ASHRAE Fundamentals[3] and is based on research by Boileau and Latta.[4] This method makes several simplifying assumptions and is restricted to only mid-winter conditions. It does not consider earth covered roofs.

Several computer models of earth contact heat transfer have been developed. These programs are complicated and non-design oriented. Each requires a good understanding of the model in order for it to be used correctly. These models have been developed by Speltz,[5] Shipp,[6] Syzdlowski,[7] Davies,[8] McBride,[9] and others. A major drawback to these models is that they do not permit direct and isolated study of earth covered roof systems. They also require generalized assumptions or neglect the variability of such things as soil thermal conductivity, surface radiation, moisture content of the soil, and vegetation effects. These parameters are of primary concern in this thesis.

The primary goal of this study is to provide an interactive design aid that will allow designers to more accurately and easily attain the thermal design goals desired for an earth covered roof system. There are many secondary objectives involved in the above-stated goal. These specific objectives are outlined as follow:

1. Identify those parameters which influence heat transfer through earth covered roofs and define their influence.
2. Identify existing and potential strategies for analysis of heat flow through earth covered roofs.
3. Model an interactive computer design aid based on the synthesis of methodologies identified in specific objective 2.
4. Validate the model using data from a model with similar capability.
5. Formulate general design guidelines for maximizing the passive cooling and heating potential of earth covered roofs.

Procedure

The procedure involved in reaching the previously stated goal is made of up of five procedural steps. These steps are outlined as follows:

1. Identification of those factors which influence heat transfer through earth covered roofs is based on research and existing literature on the subject of heat transfer through an earth sheltered roof system. Each factor, such as moisture content, is then associated with the parameter it most directly affects; i.e., thermal conductivity (k) in the case

of moisture content. The general effect of these factors and parameters on heat transfer through earth covered roofs is discussed based on past research on the subject.

2. Identification of strategies for analysis of heat flow through earth covered roofs is based on research of existing literature.
3. A methodology will be formulated into an interactive computer design aid. Formulation of the methodology includes synthesizing previously identified strategies based on their representation of previously identified parameters.
4. The model will be validated by comparing "test case" results from the model formulated and Blick's method, which is described in Chapter IV. The model will be validated for a specific parametric configuration for an entire year.
5. General design guidelines for maximizing passive cooling and heating potential of earth covered roofs are based on studies of a base test case evaluated under differing environmental and parametric conditions using the computer design aid.

Scope and Limitations

The scope of this thesis is limited to earth covered roofs and is further limited in that it does not consider heat transfer through the roof by means of exhaust air, structural thermal bleeds or infiltration/exfiltration, but only by means of a structure-soil system with a uniform soil depth and its air/soil interface.

One method discussed in this thesis is a simple method formulated by Blick which is directly applicable to roofs.[10] This method does not consider the soil's mass effects, but only conduction heat transfer through the soil-structure system, which limits calculation of heat gain in the summer due to lack of consideration of radiation and ground cover effects. A second method is the transfer function approach.[11] This technique is restrictive due to the need to recalculate transfer function coefficients for any changes in roof materials or depth of cover. Generation of all transfer function coefficients for even the most simple roof system and its incremental variations in layer thicknesses, etc., is a huge task. For this reason, only transfer functioncoefficients for a reference roof system with several soil depths is evaluated. Although only extreme conditions of this basic earth covered roof system are evaluated, the methodology and computer program developed herein have the capability to evaluate the thermal performance of any earth covered roof system.

The methodology formulated in this thesis is further limited in that it considers only horizontal earth covered roof systems. Calculations are based on average conditions typical of each month, except for incident solar radiation which is specifically characteristic of the 21st day of each month. Evaporation and transpiration effects of vegetation are not considered.

Empirical data and rational predictive methods for many key parameters under differing conditions are scarce and, thus, limit the present potential of the methodology formulated. Examples of these parameters include the insulative values of various earth toppings, thermal conductivity for various soil types and moisture contents, and the solar absorption characteristics of soil and earth toppings. These variables are also difficult to predict due to the non-homogeneous and thermally dynamic nature of actual earth covered roof systems.

Heat transfer is calculated for a typical day of any month; therefore, the effects of mass on heat transfer are limited to a diurnal time frame. Effects of mass in a yearly time frame would mean calculating heat transfer for consecutive hours for at least one year and is beyond the scope of this thesis.

ENDNOTES

[1]R. L. Sterling and G. D. Meixel, "Review of Underground Heat Transfer Research," Proc. Earth Shelter Performance and Evaluation Conf., L. L. Boyer (ed.), Oklahoma State University, Stillwater, Oklahoma (October,1981), p. 69.

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[9]M. F. McBride, R. S. Blancett, C. F. Sepsy and C. D. Jones, "Measurement of Subgrade Temperatures for Prediction of Heat Loss in Basements," ASHRAE Transactions, 1979, pp. 642-655.

[10]E. F. Blick, "A Simple Method for Determining Heat Flow Through Earth Covered Roofs," Proc. of Earth Sheltered Building Design Innovations Conf., L. L. Boyer (ed.), Oklahoma State University, Stillwater, Oklahoma (April, 1980), pp. III-117 to III-123.

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CHAPTER III

PARAMETER DEFINITION

Basic Thermal Principles

Basic Heat Transfer Processes

The three basic modes by which sensible heat is transferred are: conduction, convection and radiation. In a given earth covered roof system under specific conditions, the proportion of each mode involved in heat transfer and the rate at which heat is transferred are dependent upon several parameters and factors to be discussed in this chapter.

Conduction generally accounts for the largest proportion of heat transmission to and from an underground structure. Thermal conduction is a

> process of heat transfer through a material medium in which kinetic energy is transmitted by the particles of the material from particle to particle without gross displacement of the particles.[1]

In the case of earth covered roofs, conduction occurs between the ground surface and air, between soil particles (for dry soils) and between soil and roof structure.

Convection is "heat transfer by movement of a fluid."[2] Heat is accepted at one location and rejected at another location by movement of a fluid. Convection primarily occurs at the ground surface in the process of heat transfer to the air. Convection can also occur in wet soils which results in a faster rate of heat transfer than would be expected of dry soil conduction.

Radiation is the "transmission of heat through a space by wave motion; passage of heat from one object to another without warming the space between."[3] Radiation at the ground surface occurs in one of two modes: ground radiation to the night sky and solar radiation to the ground during daylight hours.

Surface Heat Transfer Processes

The primary mechanisms by which the ground is heated and cooled are thermal conduction to the air, solar radiation, evaporative cooling, and longwave radiation exchange with a cold sky.[4]

Solar radiation can have a significant impact on ground surface temperature and, thus, heat transfer. This impact is dependent upon two primary factors: incident solar radiation and surface conditions. The incident solar radiation varies seasonally due to the sun's changing seasonal position in the sky. Solar radiation varies daily due to sky conditions and time of day. Ground surface conditions affect the impact of solar radiation by determining how much incident radiation is absorbed or reflected by the ground surface. Kusuda found that during the summer months a blacktop surface with high absorption became 15°F warmer than the average air temperature while a more reflective grass surface stayed consistently below ambient conditions by 1 to 7°F.

Generally, both direct and diffuse solar radiation components should be considered for earth covered roofs. For horizontal surfaces, there is usually no reflected component. Further discussion on how to calculate incident solar radiation can be found in Chapter IV.

Conduction heat transfer between the air and soil surface is the primary mechanism which drives the surface temperature toward the air temperature.[6] Heat transfer per unit area is equal to the temperature difference between surface and air multiplied by the surface conductance. Surface conductance is important in this process because it can be controlled by the type of ground cover.

Evaporation of moisture from the ground is governed by the temperature of the surface during the daytime and by the vapor pressure of the air at night. Vapor pressure at the surface is dependent upon soil topping and soil cover.[7] The significance of evaporation can be demonstrated by the fact that one pound mass (454 grams) of evaporated water removes approximately 106 Btu's (267860 calories) of heat from the soil.

Heat rejection at the surface due to transpiration effects of vegetation can also contribute to summer cooling.

Soil Characteristics

Soil characteristics that impact heat flow are: type, compaction, moisture content, and composition. For soils with non-homogeneous or discontinuous characteristics, the thermal parameters vary in a very complex way. Therefore, it is necessary to assume that soil conditions are continuous and homogeneous. These soil characteristics are defined and quantified by the following parameters:

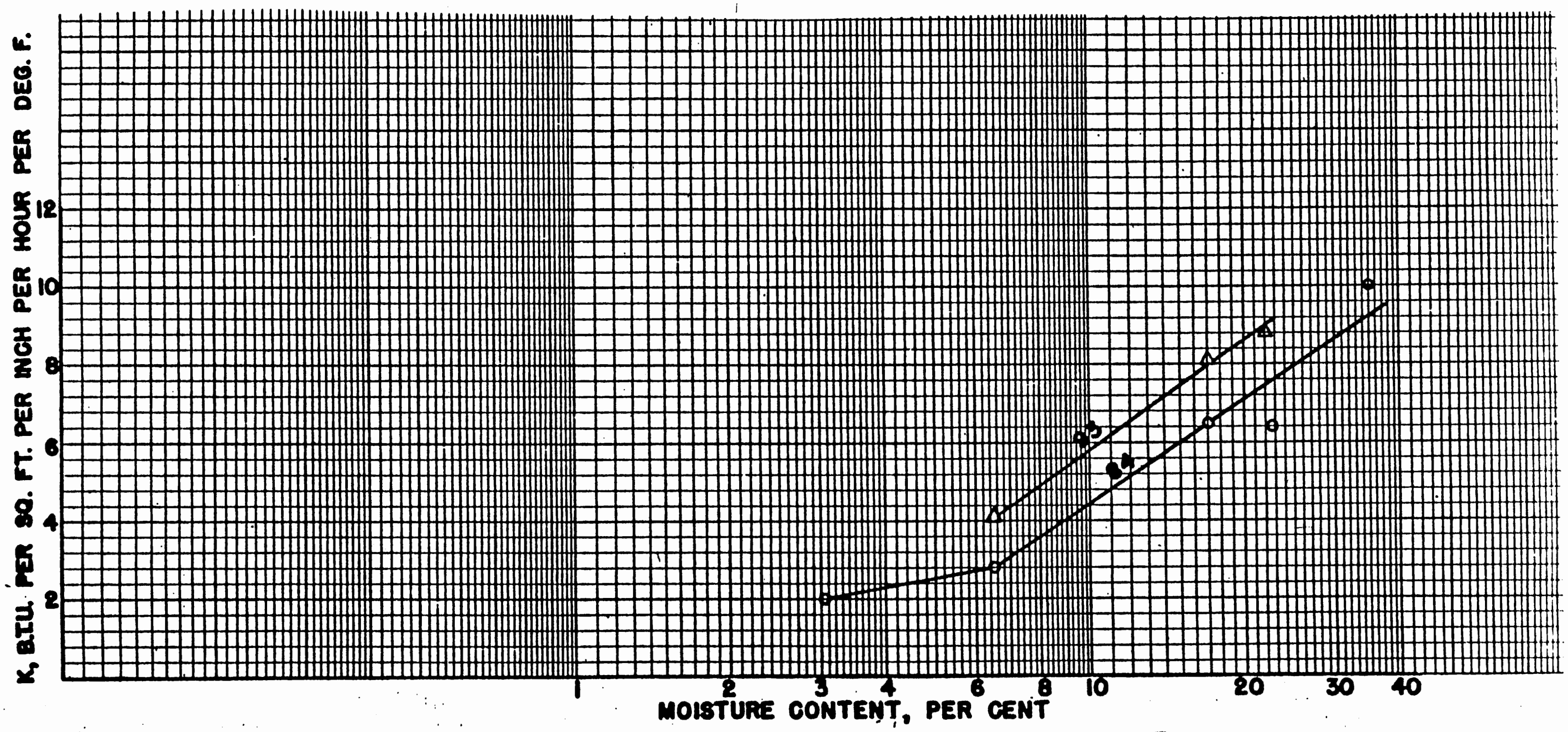
1. Thermal Conductivity (k) (Btu/hr-ft-^{o}F or Btu/hr-ft^{2}-^{o}F/in) is a property of a material which reflects the rate of heat transfer (Btu/hr) through an area of surface for each unit of thickness, for each degree of temperature difference between two sides of a material.[8]
2. Specific Heat (S) (Btu/lb-^{o}F) is the ratio of the amount of heat required to raise the temperature of a given mass of any substance one degree to the amount required to raise the temperature of an equal mass of a standard substance one degree (water at 59^{o} F).[9]
3. Thermal Diffusivity (α) (ft^{2}/hr) is the ratio of the ability of a material to conduct heat to its ability to store heat.[10]

Moisture Content

Water content is considered the most important thermal characteristic of soils. The specific moisture content of a soil is largely a function of the micro-climate for any given location and is extremely difficult to predict. The impact of moisture content is reflected in all three previously defined thermal parameters. Moisture content can be expressed as a percentage of weight or volume. For this thesis, moisture content is defined as the ratio of the weight of water to the weight of dry soil, expressed as a percentage.

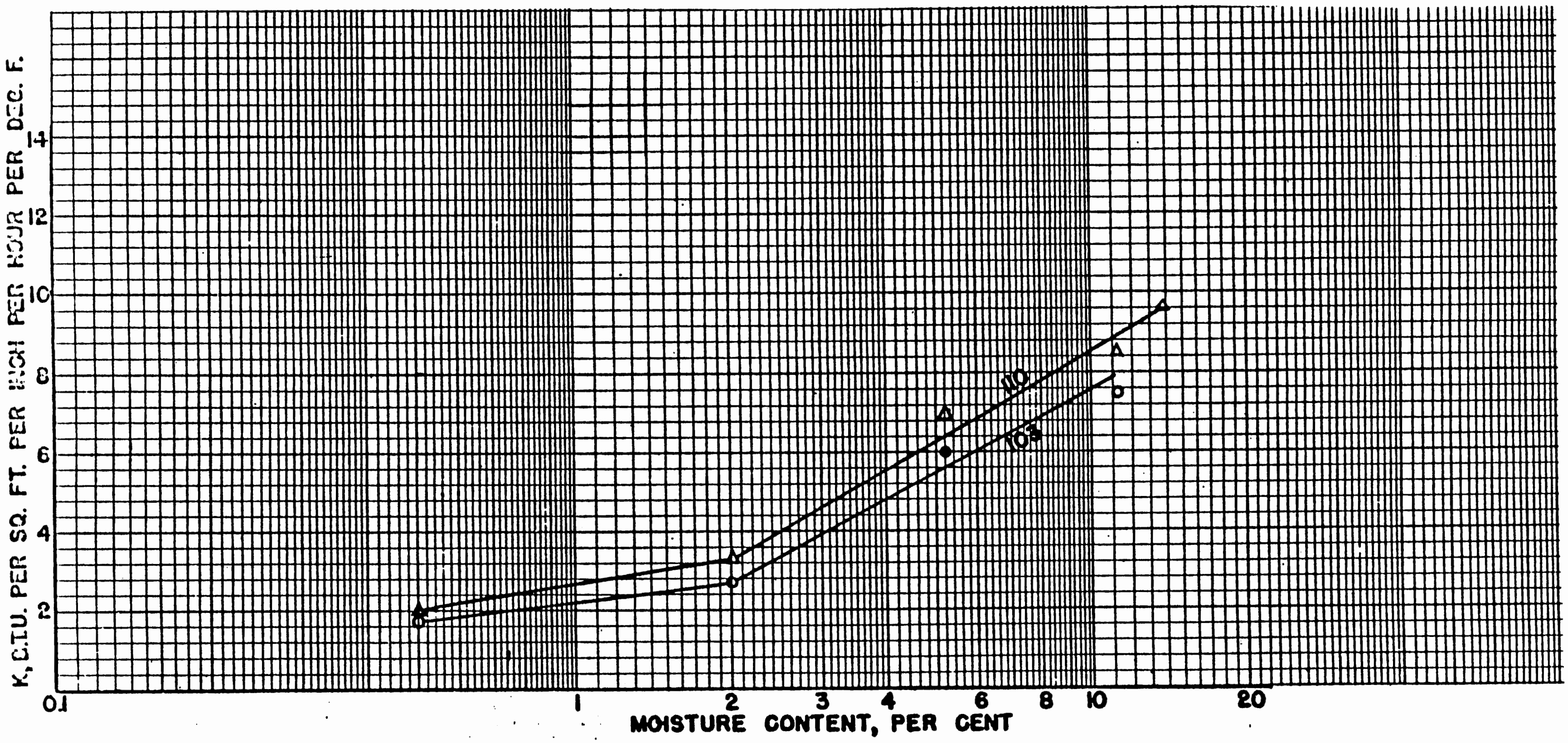
All authors researched agree that, with all other factors constant, all three thermal parameters increase with increasing moisture content.[11, 12, 13, 14] Kersten[15] found that at moisture contents less than 10%, the thermal conductivity for sands and clays increased 30 to 40 percent for every doubling of moisture content. At higher moisture contents, the increase in thermal conductivity was less extreme. Figures 6, 7 and 8 show how thermal conductivity varies with moisture content in samples of clay, fine sand and coarse sand.

Gupalo[16] found that thermal diffusivity for a particular soil increases as moisture content increases to a point where plant growth is inhibited. Thermal diffusivity is greatest at this point. As moisture content increases beyond this point, the diffusivity decreases. Gupalo found that this maximum thermal diffusivity occurs at different



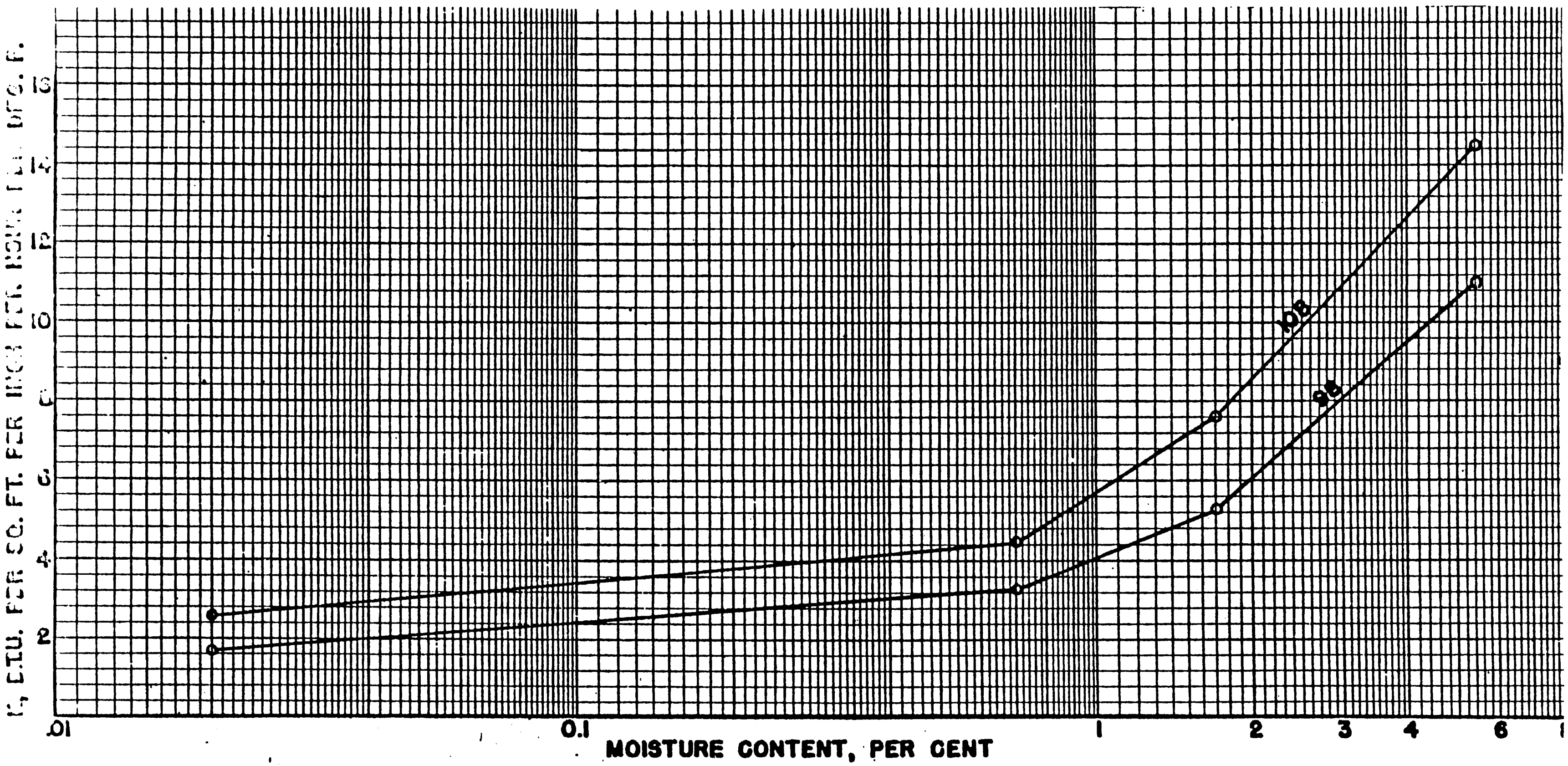
Source: M. S. Kersten, "The Thermal Properties of Soil," Bulletin of the University of Minnesota, Engineering Experiment Station Bulletin, No. 28, Volume LII, No. 21, June 1, 1949, p. 183.

Figure 6. Variation of Thermal Conductivity With Moisture Content at 40^{O}F for Clay Soil at Two Densities (lb/ft^3)



Source: M. S. Kersten, "The Thermal Properties of Soil," Bulletin of the University of Minnesota, Engineering Experiment Station Bulletin, No. 28, Volume LII, No. 21, June 1, 1949, pg. 177.

Figure 7. Variation of Thermal Conductivity with Moisture Content at 40°F for Fine Sand at Two Densities (lb/ft^3)



Source: M. S. Kersten, "The Thermal Properties of Soil," Bulletin of the University of Minnesota, Engineering Experiment Station Bulletin, No. 28, Volume LII, No. 21, June 1, 1949, pg. 173.

Figure 8. Variation of Thermal Conductivity with Moisture Content at 40°F for Coarse Sand at Two Densities (lb/ft^3)

moisture contents depending upon soil type: 5 to 8% for large-grained sand; 8 to 10% for fine-grained sand; and 24 to 28% for clays.

Specific heat also increases with increasing moisture content. When specific heats of dry soils are compared to specific heats of "wet" soils, with moisture contents ranging between 2% and 99%, there is a corresponding increase of 10% to 70% in the specific heats. Specific heats for "wet" soils can be calculated according to the proportion by weight of soil and water and their respective specific heats.[17]

Thermal conductivity acts differently in frozen and unfrozen soils. In frozen soils, there is little change in thermal conductivity at low moisture contents; but for moisture contents greater than 5%, there is an increase in thermal conductivity for a decrease in temperature.[18] Thermal conductivity of soils above freezing increases slightly with an increase in mean soil temperature. Conductivities at 70°F average approximately 4% more than those at 40°F.

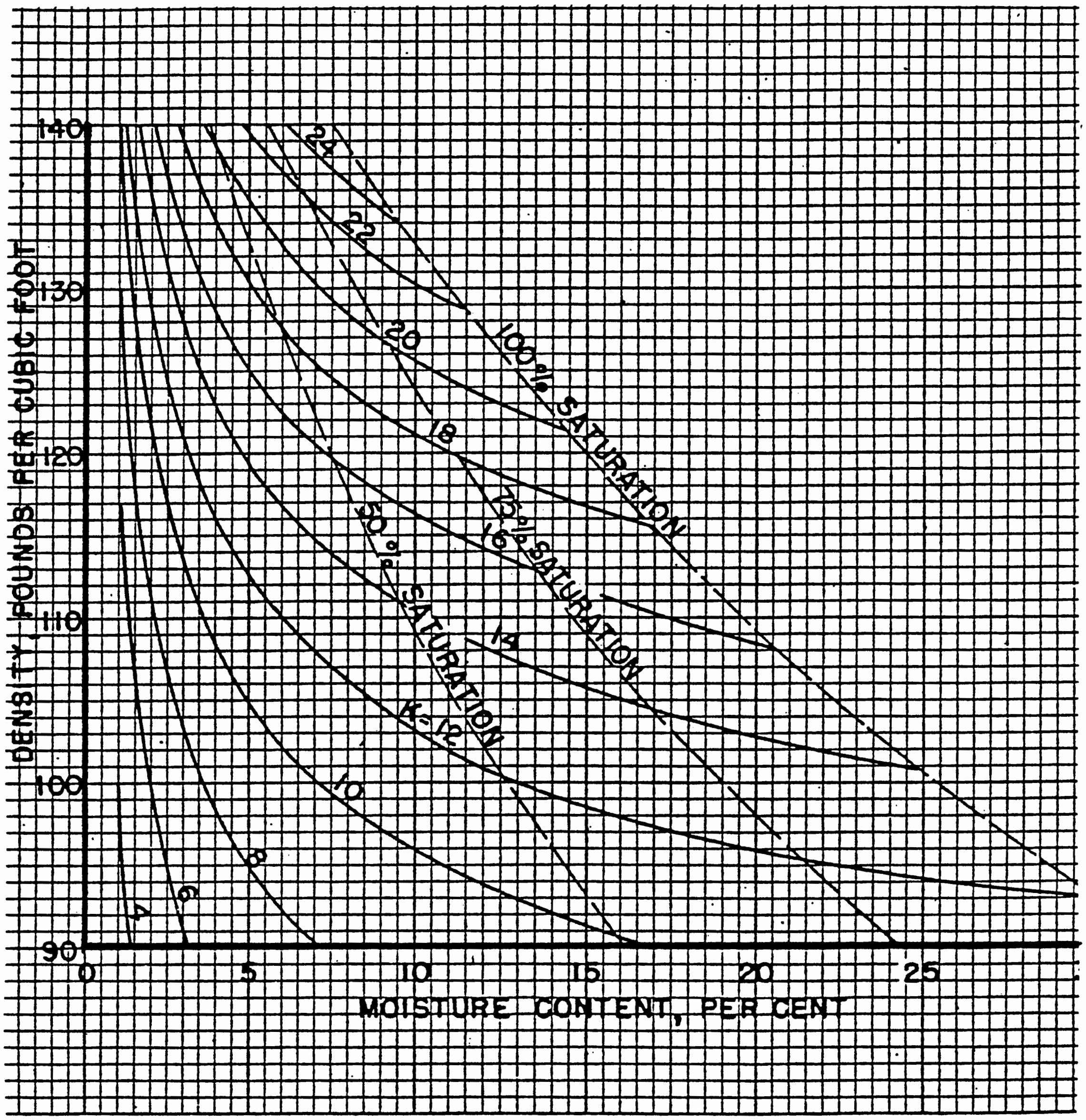
Compaction

Soil compaction is defined in terms of density. Density is the mass of material in a given volume of space. An increase in density results in an increase in thermal conductivity.[19,20] The rate of increase of thermal conductivity with an increase in density is approximately the same for frozen soils, unfrozen soils and most moisture contents. Kersten found the average increase in thermal conductivity for each additional one pound mass of soil per cubic foot is 2.8% for unfrozen soils; 3.0% for frozen.[21]

Gupalo found thermal conductivity increases linearly as density increases for soils with a moisture content of 10%.[22] In dry soils, the rate of increase was greater for small densities and lesser for large densities. Figure 9 shows how thermal conductivity varies with density and moisture content. This figure also shows the relationship of water saturation in the soil to density, moisture content and thermal conductivity. Water saturation is the ratio of a specific moisture content to the moisture content at which all the voids in a soil are water filled or saturated. There is only a slight increase in thermal diffusivity with increases in density.[23]

Type and Composition

Soil consists of particles of various sizes with inclusions of air and water. Soil mostly contains particles that are mineral in composition; but, in addition, contain varying amounts of organic matter. The size distribution of the particles defines the soil texture.[24] Soils have been classified into two major divisions based on texture: coarse grained soils such as sand or gravel and fine grained soils such as silt and clay.[25] See Figure 10 for a chart



Source: M. S. Kersten, "The Thermal Properties of Soil," Bulletin of the University of Minnesota, Engineering Experiment Station Bulletin, No. 28, Volume LII, No. 21, June 1, 1949, p. 87.

Figure 9. Variation of Thermal Conductivity with Density and Moisture Content by Weight for Sandy Soils at 40°F (Btu/hr-ft^2-°F/inch)

outlining soil classifications. Thermal conductivity varies with soil type as defined by texture. For a given soil density and moisture content, thermal conductivity is highest for coarse textured materials (sand and gravel) and lowest for fine grained materials (silt and clay). These differences are not as valid under natural conditions where fine textured soils such as clay exist at higher moisture contents and, therefore, higher thermal conductivities.

(Values of specific heat differ only slightly (about 0.01 Btu/lb-°F) for a wide variety of soils. Kersten found the average values for specific heat range from 0.16 Btu/lb-°F at 0°F to 0.19 Btu/lb-°F at 140°F. Specific heats within that range may be linearly interpolated.[26]

Site Parameters

Surface Conditions

The surface boundary condition of an earth covered roof can play a significant role in the heat exchange between earth and the exterior environment. Soil temperature profiles are a direct result of this heat exchange. Vegetation has been found to improve the thermal efficiency of an earth covered roof system in several ways: shading effects, improved insulation due to air trapped in the foliage and transpiration (the cooling of vegetation by release of moisture).

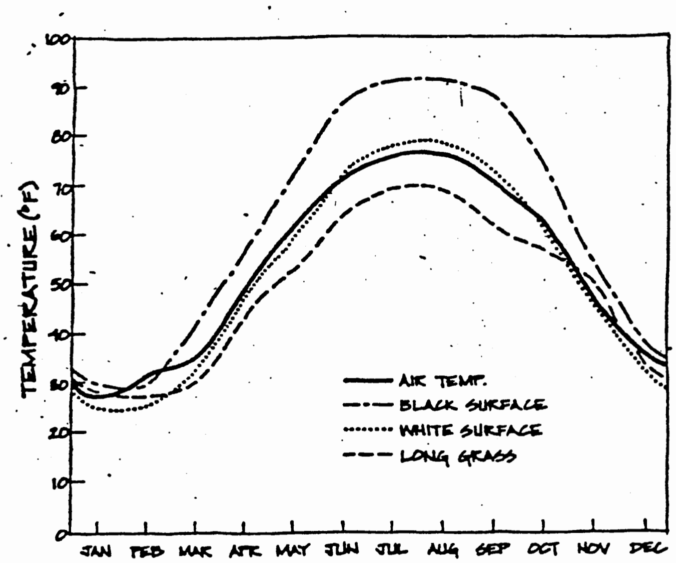
major divisions			letter symbol	typical descriptions
coarse grained soils more than 50% of material is larger than no. 200 sieve size	gravel and gravelly soils more than 50% of coarse fraction retained on no. 4 sieve	clean gravels (little or no fines)	GW	well-graded gravels, gravel-sand mixtures, little or no fines
			GP	poorly-graded gravels, gravel-sand mixtures, little or no fines
		gravels with fines (appreciable amount of fines)	GM	silty gravels, gravel-sand-silt mixtures
			GC	clayey gravels, gravel-sand-clay mixtures
	sand and sandy soils more than 50% of coarse fraction passing no. 4 sieve	clean sand (little or no fines)	SW	well-graded sands, gravelly sands, little or no fines
			SP	poorly-graded sands, gravelly sands, little or no fines
		sands with fines (appreciable amount of fines)	SM	silty sands, sand-silt mixtures
			SC	clayey sands, sand-clay mixtures
fine grained soils more than 50% of material is smaller than no. 200 sieve size	silts and clays	liquid limit less than 50	ML	inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity
			CL	inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			OL	organic silts and organic silty clays of low plasticity
	silts and clays	liquid limit greater than 50	MH	inorganic silts, micaceous or diatomaceous fine sand or silty soils
			CH	inorganic clays of high plasticity, fat clays
			OH	organic clays of medium to high plasticity, organic silts
highly organic soils			PT	peat, humus, swamp soils with high organic contents

Source: M. S. Kersten, "The Thermal Properties of Soil," Bulletin of the University of Minnesota, Engineering Experiment Station Bulletin, No. 28, Volume LII, No. 21, June 1, 1949, p. 227.

Figure 10. Soil Classification Chart

> The principal cause of the variation of the temperature at the soil surface is the changing intensity of short-wave radiation. Absorption of both short- and long-wave radiation takes place in a full layer of a fraction of a millimeter thickness . . . The temperature in the upper layers fluctuates in the course of time corresponding to alternating intervals of heat storage and release of heat."[27]

Kusuda investigated the effects on earth temperature of five types of earth covering with different radiation absorbing characteristics.[28] These surfaces were: five inches of asphalt, five inches of asphalt painted white, bare soil, grass maintained at a height of four inches, and unmowed grass. Figure 11 shows the surface temperatures for three of these conditions for a period of one year. It can be seen from this figure that solar radiation during the winter months has little effect on earth temperature, probably due to the sun's low altitude. The largest temperature variations occurred during the summer. Kusuda concluded that earth temperature is affected by the nature of the ground surface cover. The annual variation, as well as the average temperature under the high heat absorbing surface (black asphalt), was higher than for the lower heat absorbing (grass covered) surface. The ground temperature became lower than the ambient air temperature during summer nights with a clear sky for all coverings except for the black asphalt surface, which soaked up too much heat during the previous daytime hours to be sufficiently cooled. At a depth of four feet (1.2 meters), soil temperatures varied as much as 20°F, depending upon surface conditions.



Source: T. Kusuda, "The Effect of Ground Cover on Earth Temperature," Alternatives in Energy Conservation: The Use of Earth Covered Buildings, F. Moreland (Ed.), (Washington: National Science Foundation) NSF-RA-760006, p. 57.

Figure 11. Monthly Average Surface Temperatures for Five Surface Conditions

Grondzik[29] compared temperature profiles from two monitored earth covered residences in Oklahoma. The temperature profiles for each residence were for four day periods of similar summer weather conditions. The primary differences in the two cases were in extent and location of roof insulation and treatment of the surface boundary. The first case had 1.67 feet (0.5 meters) of earth cover, one inch of rigid insulation on the exterior roof structure surface, and 50% vegetation coverage density on the surface. The second case had 1.3 feet (0.4 meters) of earth cover, no roof structure insulation and 100% vegetation coverage density. There was substantial heat gain reduction in both cases due to the earth covered roofs. Temperatures recorded at the interior surface of the structures were virtually equal, but one residence maintained this profile by using exterior insulation while the other maintained this profile by roof cover management.

Baggs formulated an equation to estimate the effect of solar radiation shading by vegetation on ground temperatures in Australia.[30] He compared the effects of changes in earth cover depth, vegetation coverage and thermal diffusivity of the soil on the amplitude of the ground temperature wave. He found that an increase in overall vegetation shading coverage produced more direct results in damping the amplitude of the ground temperature wave than did changes in earth cover depth beyond 39.4 inches (1.0 meter) or soil thermal diffusivity.

At 79 inches (2.0 meters) in depth, vegetation with 60% overall shading coverage was as effective in damping the ground temperature wave as an extra 3.28 feet (1 meter) of soil. This shading coverage was also found to be more effective in amplitude damping than a change in soil thermal diffusivity from 0.2 to 0.8 ft^2 per day.[31]

Based on all three of the above studies it can be concluded that shading of solar radiation by vegetation can significantly alter soil temperature profiles and, thus, reduce heat gain through earth covered roofs as effectively as changes in soil depth, insulation or thermal diffusivity.

> If the soil is covered with a dense vegetation, the upper leaves form a surface where a considerable fraction of the incoming radiation is absorbed. The remaining part is absorbed in the lower regions of the vegetation and at the soil surface. The transfer of the heat absorbed at the surface into the soil occurs in the same manner as with a bare surface. Under equal meteorological conditions, the daily maximum temperature of the covered surface will be lower than that of the bare surface owing to the shading effect of the vegetation.[32]

In addition to shading benefits, a vegetation cover also affects conduction heat transfer between the air and surface by influencing the surface conductance or convection heat transfer coefficient. Soil/surface conditions and weather conditions such as surface and ambient temperatures, wind speed, surface textures, and depth of coverings, influence this variable.[33,34] Vegetation cover provides additional insulation due to still air trapped by the vegetation at the surface. Differences in the thermal resistance of still air are due to direction of heat flow. In the presence of air movement, thermal resistance decreases and direction of heat flow becomes less important.

The surface roughness influences air movement. A rough surface has a lower thermal resistance due to increased turbulent air flow. The presence of vegetation at the surface of an earth covered roof eliminates air movement at the soil surface and this increases thermal resistance due to increased trapped air pockets.

Depth of Earth Cover

Selection of an earth cover depth can have a substantial effect on an earth sheltered building's thermal performance. Two thermal qualities that are affected by depth of earth cover are thermal capacitance (time lag) and thermal resistance. Although a discussion of the economic trade-off between energy savings and structural costs due to added earth cover is beyond the scope of this thesis, it is a very important consideration in selecting an earth cover depth.

The thermal resistance of a material is defined by its R-value ($^{o}F\text{-}ft^2\text{-}hr/Btu$). Thermal resistance is equal to material thickness divided by thermal conductivity. Therefore, as the soil depth increases, so does its thermal resistance. The insulative quality of soil is poor compared to standard insulating materials. The depth of earth cover should not be selected on the basis of its insulative quality. The insulative quality of the soil is highest in the top few inches when there is a vegetation earth covering.[33] The roots of this vegetation create a root layer where the soil is less dense and more aerated, resulting in increased insulation.

Daily outside air temperature variations are damped out in the first few inches of the soil. At greater depths, soil temperatures respond only to seasonal changes and this change occurs after a time delay. Figure 2 in Chapter I shows how the amplitude of the mean soil temperature wave decreases with depth. This reduction in amplitude produces a phase lag so that peak conduction losses do not occur at the same time as peak loads due to ventilation and infiltration air. This thermal time lag is the greatest advantage of increased earth cover depth.

The limiting factor of increasing depth of earth cover is the physical structure required to support such a cover. Insulation is often used to increase the thermal resistance of the roof once the load limit of a lighter structure is reached. Generally, insulation of the roof structure is recommended to reduce heat loss during the winter, especially in the northern United States.[34] Insulation may be left out in some climates where summer temperatures at the soil side of the roof structure are less than the indoor temperature, in order to promote earth coupled cooling. This condition may also be created by modification of the soil's thermal environment. The modification of the soil's thermal environment to promote earth coupled cooling or to simply reduce heat transfer is discussed later in this thesis.

ENDNOTES

[1]American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 33.4.

[2]Ibid.

[3]Ibid., p. 33.1.

[4]R. G. Geiger, The Climate Near the Ground, tr. M. N. Stewart. (Massachussetts, Harvard University Press), 1950, p. 9.

[5]T. Kusuda, "The Effect of Ground Cover on Earth Temperature," Alternatives in Energy Conservation: The Use of Earth Covered Buildings, F. Moreland (Ed.), (Washington: National Science Foundation) NSF-RA-760006, pp. 279-303.

[6]S. J. Raff, "Ground Temperature Control," Underground Space, (1978), 3(1), p. 36.

[7]R. G. Geiger, The Climate Near the Ground, tr. M. N. Stewart (Massachussetts, Harvard University Press), 1950, p. 249.

[8]American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 33.8.

[9]Ibid., p. 33.4.

[10]Ibid., p. 33.8.

[11]R. G. Geiger, The Climate Near the Ground, tr. M. N. Stewart. (Massachussetts, Harvard University Press), 1950, p. 167.

[12]A. I. Gupalo, Thermal Properties of the Soil as a Function of its Moisture Content and Compactness, NASA Tech Translation, NASA TTF 14.364, p. 5.

[13]A. B. Algren, "Ground Temperature As Affected by Weather Conditions," ASHRAE Transactions, Vol. 55, 1949 p. 647.

[14]M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 84.

[15]Ibid.

[16]A. I. Gupalo, Thermal Properties of the Soil as a Function of its Moisture Content and Compactness, NASA Tech Translation, NASA TTF 14.364, p. 5.

[17]M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 73.

[18]Ibid., p. 83.

[19]Ibid., p. 39.

[20]A. I. Gupalo, Thermal Properties of the Soil as a Function of its Moisture Content and Compactness, NASA Tech Translation, NASA TTF 14.364, 1962, p. 8.

[21]M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 84.

[22]A. I. Gupalo, Thermal Properties of the Soil as a Function of its Moisture Content and Compactness, NASA Tech Translation, NASA TTF 14.364, p. 8.

[23]M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 92.

[24]W. R. Van Wijk, D. A. De Vries, Physics of the Plant Environment, (Amsterdam: North Holland Publ. Co), 1966, Chapter 4, "Periodic Temperature Variations in a Homogenous Soil," p. 48.

[25]M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 227.

[26]Ibid., p. 59.

[27]W. R. Van Wijk, D. A. De Vries, Physics of the Plant Environment, (Amsterdam: North Holland Publ. Co), 1966, Chapter 4, "Periodic Temperature Variations in a Homogenous Soil," p. 102.

[28]T. Kusuda, "The Effect of Ground Cover on Earth Temperature," Alternatives in Energy Conservation: The Use of Earth Covered Buildings, F. Moreland (ed.), (Washington: National Science Foundation) NSF-RA-760006, 1978, pp. 279-303.

[29]W. T. Grondzik, L. L. Boyer, and T. L. Johnston, "Variations in Earth Covered Roof Temperature Profiles," Proc. International Passive and Hybrid Cooling Conference, Miami Beach, AS/ISES (November, 1981), pp. 146-150.

[30]S. A. Baggs, "Vegetation Effects on Earth Cooling Potential," Proc Earth Shelter Performance and Evaluation Conf., L. L. Boyer (ed.) Oklahoma State University, Stillwater (1981), p. 87.

[31]Ibid.

[32]W. R. Van Wijk, D. A. De Vries, "Periodic Temperature Variations in a Homogenous Soil," Physics of the Plant Environment, (Amsterdam: North Holland Publ. Co), 1966, Chapter 4, p. 102.

[33]G. D. Meixel, P. H. Shipp and T. P. Bligh, "The Impact of Insulation Placement on the Seasonal Heat Loss Through Basement and Earth Sheltered Walls," Underground Space, 1980, Vol. 5, pp. 41-47.

[34]J. J. Speltz and G. D. Meixel, "A Computer Simulation of the Thermal Performance of Earth Covered Roofs," Proc of the Underground Space Conference and Expo, Kansas City, MO (June 1981), pp. 97-98.

[35]R. L. Roy, "Earth Roof Thickness: The Tradeoff," Earth Shelter Digest (January-February, 1981), No. 13, p. 17.

[36]U.S. Department of Energy, "Insulation Principles," Earth Sheltered Structures Fact Sheet 05, ORNL/Sub-7849/05, 1981, p. 5.

CHAPTER IV

FORMULATION OF METHODOLOGY

Introduction to Methods Studied

Two techniques for determining heat flow through earth covered roofs are discussed in this study. The first method was developed by Edward F. Blick at the University of Oklahoma. Blick's method correlates well to a computer solution, defined later, and will be used to validate the second model formulated in this thesis.[1] The second technique is based on transfer function coefficients.[2] The primary differences between the two methods are the consideration of vegetation and radiation effects on the surface and mass effects. Techniques for estimating parameters such as solar radiation and thermal conductivity will also be discussed in this chapter.

Blick's Method

A major complicating factor in determining heat flow through the earth is the transient nature of soil temperatures or the variance of soil temperatures with time. Another complicating factor is the thermal mass of the earth. Due to this mass earth creating a thermal time lag, heat transfer through the earth is not instantaneous as is assumed in calculations of above-ground heat transfer. Blick formulated a simple equation to predict instantaneous heat flow through earth covered roofs and compared the solution to a computer solution. This equation neglects time lag.

Diurnal and seasonal temperature variations in the soil are responsible for the heat flow through the soil being non-steady state or transient in nature. The use of the steady state equation below for conduction would create a large error in the estimation of heat flow due to the large thermal mass of the earth. The equation is[3]:

$$q = \frac{T_o - T_i}{R} \tag{1}$$

where:

q = Heat flux per unit area (Btu/hr-ft^2)

T_o = Outdoor temperature (^{o}F)

T_i = Indoor temperature (^{o}F)

R = Thermal resistance (^{o}F-ft^2-hr/Btu)

The error created by seasonal variations in soil temperature is virtually eliminated by calculating heat flow on a monthly basis. By further assuming the diurnal surface temperature fluctuations are primarily absorbed in the first 6 to 8 inches of soil, Blick could ignore those diurnal oscillations and use an average air temperature, creating a steady state condition. Under these assumptions, Blick's equation for determining the earth's heat flow is:[4]

$$q = \frac{T_o - T_i}{R_e} \tag{2}$$

where:

T_o = Mean monthly air temperature (°F)

R_e = Thermal resistance of the soil (°F-ft²-hr/Btu)

and:

$$Re = L/k \tag{3}$$

where:

L = Depth of soil (ft)

k = Thermal conductivity of soil (Btu/hr-ft-°F)

Using the Fourier conduction equation,[5]

$$q = \frac{-k\ dT}{dy} \tag{4}$$

where:

dT = Incremental change in temperature (°F)

dy = Incremental change in depth (ft),

The exact heat transfer rate (based on Equation 4) for twelve months was computed and compared to heat flow calculated by Blick's method. Figure 12 demonstrates the correlation of these two methods. Blick's method over-estimated January heat flux by 3.75% and under-estimated July heat flux by 8.5%.[6]

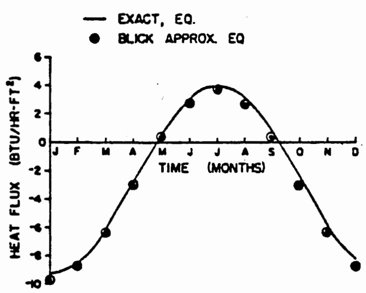
In order to consider the entire earth covered roof system, the method was expanded to include additional layers of structure, insulation, etc. The equation for determining heat flow through an earth covered composite roof is:

$$q = \frac{T_o - T_i}{R_e + R^*} \tag{5}$$

where:

To = Mean monthly air temperature (^oF)

R* = Thermal resistance of composite roof minus the resistance of the soil.



Source: E. F. Blick, "A Simple Method for Determining Heat Flow through Earth Covered Roofs," Proc. Earth Sheltered Building Design Innovations Conf. L. L. Boyer (Ed.) Oklahoma State University, Stillwater, OK 1981, p. III-21.

Figure 12. Monthly Variation of Heat Flux Through Two Feet of Soil

The use of this method should be limited to small commercial and residential scale structures. Earth covered roofs with more than three feet (0.9 meters) of earth cover should not be candidates for Blick's method. It should be noted that Blick's method does not include effects of radiation, shading, evaporation, or transpiration. Procedures for calculating thermal conductivity and determining R-values and air temperatures will be discussed later in this chapter.

Transfer Function Method

The transfer function method for determining conduction heat flow through a barrier was first introduced by Mitalas and Stevenson[7] as a simplification to the calculation procedure for determining "exact" heat gain through a barrier. This method is documented by ASHRAE for conventional above-ground barriers.[8] The mathematical derivation of the calculation procedure to determine the transfer function coefficients is documented by Mitalas and Stevenson[9] and M. J. Pawelski.[10]

Speltz and Meixel developed a transient one-dimensional heat flow model using a transfer function approach.[11] The primary difference between the Speltz-Meixel methodology and the methodology presented in this thesis is how a roof surface is defined. The Speltz-Meixel model defines the roof surface in terms of surface covering. In work done by Givoni, the effects of vegetation and other coverings is characterized by defining the roof surface as the soil surface regardless of covering.[12] The model presented in this thesis also defines the roof surface as the soil surface, regardless of covering. By doing this, the effects of earth coverings such as concrete or grass can be isolated and more clearly investigated. The Speltz-Meixel model cannot directly investigate the effects of various earth coverings on the soil's thermal environment. An excellent example of this is the cooling caused by shading the soil surface with vegetation. This concept is further discussed later.

Calculation of heat flow by the transfer function method can be divided into two parts: calculation of transfer function coefficients and calculation of heat transmission.

Transfer Function Coefficients

A transfer function is a set of coefficients which relates an output function at some specific time to the value of one or more driving functions at that time and to previous values of both the input and output functions. Calculation of these coefficients is complex and time consuming. The reader is referred to the above-mentioned references for details concerning the mathematics of deriving transfer function coefficients. Mitalas and Arseneault[13] have developed a FORTRAN program which calculates these coefficients and is quite easy to use.

In order to calculate the transfer function coefficients (TFC), the construction in question must be divided into layers. Each layer is defined by changes in material or homogeneity. When the homogeneity or materials changes so do the thermal properties. Outside/inside surface resistances are considered layers. Up to 30 different layers may be combined when using the FORTRAN program. For each layer, the following five parameters must be determined in order to calculate TFC:

1. Thickness or Depth (d) (feet)
2. Thermal Conductivity (k)(Btu/hr-ft-^{o}F)
3. Density (D)(lb_{mass}/ft^3)
4. Specific Heat (S)(Btu/lb_{mass}-^{o}F)
5. Thermal Resistance (R)(hr-ft^2-^{o}F/Btu)

The thermal resistance is used only for those layers that have negligible heat storage such as air spaces and surface air films. Once the transfer function coefficients are calculated for each layer, they are used to calculate heat flow as described in the following section. Estimation of the above parameters for soils is discussed in following sections.

Heat Transmission

Calculation of heat transfer based on steady state conditions ignores heat storage effects of building materials. The transfer function approach considers non-steady state or transient conditions and is thus applicable to earth covered roofs in that the earth's thermal mass is considered.

The primary inputs for calculating heat flow are the b, d, and c transfer coefficients and sol-air temperature.

The sol-air temperature is that temperature of the outdoor air which, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air. The use of sol-air temperatures allows the consideration of radiation effects at the surface of earth covered roofs without complicated radiation exchange balancing. Thermal resistances for each layer are assumed to be constant. Heat flow is calculated using the following equation:[14]

$$q_t=[\sum_{n=0} b_n(T_{t-ni})-\sum_{n=1} d_n(q_{t-ni})-T_{rc}\sum_{n=0} c_n] \qquad (6)$$

where:

q_t = Heat flux per unit area at time t (Btu/hr-ft^2)

t = Time (hours)

i = Time interval

n = Summation index (each summation has as many terms as there are non-negligible values of the coefficients)

T_{t-n} = Sol-air temperature at time t-n (^{o}F)

T_{rc} = Constant indoor room temperature (^{o}F)

b_n, c_n = Transfer function coefficients (Btu/ft^2-hr-^{o}F)

d_n = Transfer function coefficients (unitless)

Methodology Procedure

Introduction

The following procedure is based on the transfer function model previously described and is used to calculate the heat transfer through an earth covered roof system. Each procedural step is discussed in the following text. There are four basic parts to this procedure and they are outlined below. Parts C and D are part of a interactive program in BASIC computer language. This program is called "ECROOF." Parts A and B are performed independently of "ECROOF," although part B (transfer function coefficients) is included in the program as default values based on data described in Chapter V.

See Appendix A for a flow chart of the process. The procedural outline for calculation of heat transfer through an earth covered roof system follows:

A. Formulation of Problem

1. Number of months
2. Location
3. Roof construction and materials
4. Type of surface covering

B. Calculation of Transfer Function Coefficients

1. Soil cover
    a. Moisture content and density
    b. Soil type
    c. k, d, D and S
2. D, d, S and k for each construction material
3. R for each air film and air space layer
4. Calculate TFC's

C. Calculation of sol-air temperature

1. h_o for surface
2. e and a for surface
3. Solar radiation incident on ground surface for each month
4. Average daily maximum outdoor temperature and mean daily range

D. Calculate heat transfer

Formulation of Problem

The first step is to formulate the problem by identifying the earth covered roof construction, materials and location. Based on the location of the site, climatic information can be determined such as solar radiation, outdoor temperatures, moisture content of soil, and soil type. Based on the roof construction and materials, the number of layers and their corresponding thermal characteristics can be determined.

Heat transfer is calculated for a typical day in each month. Up to 12 months can be handled. The calculations could be made for any other period within a year such as seasons or quarters, based on a typical day for that period. Estimation of parameter values must be made for each month or period to be considered, although many of the parameter values are the same for many months.

Type of surface covering must be determined so that its shading and radiant characteristics can be estimated. Consideration must be given to how these characteristics change from month to month so that seasonal changes in the earth covering can be considered.

Calculation of TFC's

The calculation of the monthly transfer function coefficients for a given earth covered roof system involves evaluation of the thermal characteristics for each component material or layer. It must be remembered that the transfer function coefficients for a specific roof system change for any parametric change in that roof system. Once all parameter values are estimated, the transfer function coefficients can be calculated by the FORTRAN program "TRANSF" which is on the Oklahoma State University's IBM computer system. Information on the program is contained in Appendix B of this thesis.

Table I can be used to determine thickness, thermal conductivity, density, specific heat and thermal resistance of materials other than soils. The materials in this table include insulation, concrete, wood, and ceiling materials. It should be noted that for precast concrete structural roofs, lightweight (l.w.) concrete should be assumed; for cast-in-place concrete roofs, heavy weight (h.w.) concrete should be assumed.

Thermal conductivity per foot of soil can be calculated using the following charts or equations.[15] These equations and charts estimate the thermal conductivity based on soil type, dry soil density (lb_m/ft^3), moisture content as percent of dry soil weight, and soil condition.

TABLE I

THERMAL PROPERTIES OF TYPICAL ROOF CONSTRUCTION MATERIALS

Material Description	Thickness/Thermal Properties*				
	d	k	D	S	R
Outside surface resistance					0.333
Finish	0.0417	0.24	78	0.26	0.174
Air space resistance					0.91
1 inch insulation	0.083	0.025	2.0	0.2	3.32
2 inch insulation	0.167	0.025	2.0	0.2	6.68
3 inch insulation	0.25	0.025	2.0	0.2	10.0
1 inch insulation	0.0833	0.025	5.7	0.2	3.33
2 inch insulation	0.167	0.025	5.7	0.2	6.68
1 inch wood	0.0833	0.07	37.0	0.6	1.19
2.5 inch wood	0.2083	0.07	37.0	0.6	2.98
4 inch wood	0.333	0.07	37.0	0.6	4.76
2 inch wood	0.167	0.07	37.0	0.6	2.39
3 inch wood	0.25	0.07	37.0	0.6	3.58
3 inch insulation	0.25	0.025	5.7	0.2	10.0
4 inch H.W. concrete	0.333	1.0	140	0.2	0.333
8 inch H.W. concrete	0.667	1.0	140	0.2	0.667
2 inch H.W. concrete	1.0	1.0	140	0.2	1.00
2 inch H.W. concrete	0.167	1.0	140	0.2	0.167
6 inch H.W. concrete	0.5	1.0	140	0.2	0.50
4 inch L.W. concrete	0.333	0.1	40	0.2	3.33
6 inch L.W. concrete	0.5	0.1	40	0.2	5.0
8 inch L.W. concrete	0.667	0.1	40	0.2	6.67
Inside surface resistance					0.685
0.75 inch plaster	0.0625	0.42	100	0.2	0.149
Ceiling air space					1.0
Acoustic tile	0.0625	0.035	30	0.2	1.786

* d = feet; k = Btu/hr-ft-^{o}F; D = lb/ft^3; S = Btu/lb-^{o}F; R = hr-ft^2-^{o}F/Btu

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook 1977 Fundamentals, p. 25.10.

The soil type and conditions are:

1. Silt and clay soils -- frozen
2. Sandy soils -- frozen
3. Silt and clay soils -- unfrozen
4. Sandy soils -- unfrozen.

If a soil has 50 percent or more clay or silt, condition 1 or 3 should be used; conditions 2 or 4 should be used if a soil has 50 percent or more sand. The equations for k are for a mean temperature of 40°F (4.4° C) (unfrozen) and 25°F (-3.8° C) (frozen). The accuracy of these charts and equations is plus or minus 25%. The equations follow:

1. For silt and clay soil, unfrozen with moisture content greater than 7%, use equation 7 or Figure 13.

$$k = [0.9 \log(MC) - 0.2]\, 10^{0.01d} \tag{7}$$

2. For sandy soils, unfrozen with moisture contents greater than 1.0%, use equation 8 or Figure 14.

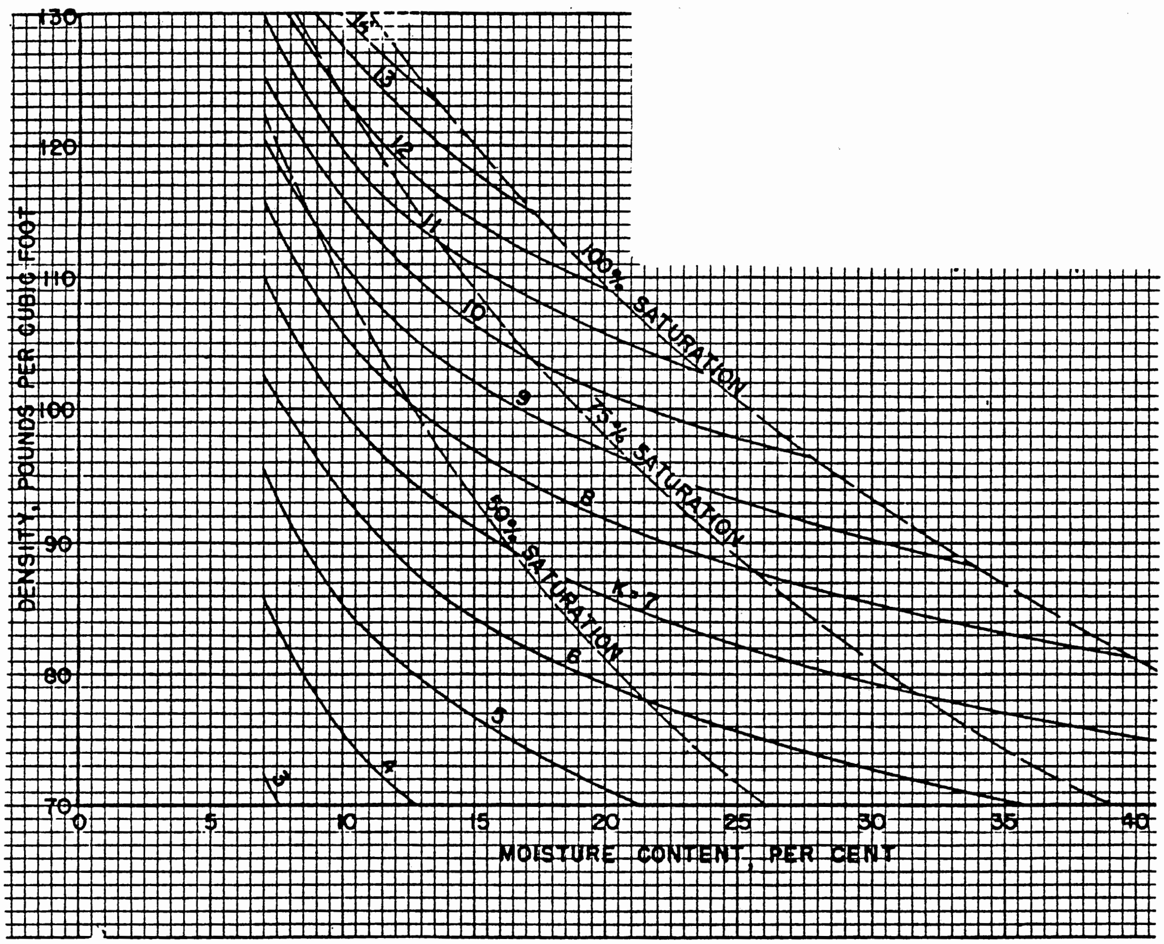
$$k = [0.7 \log(MC) + 0.4]\, 10^{0.01d} \tag{8}$$

3. For clay and silt soil, frozen with moisture contents greater than 7%, use equation 9 or Figure 15.

$$k = 0.01(10)^{0.022d} + 0.085(10)^{0.008d}(MC) \tag{9}$$

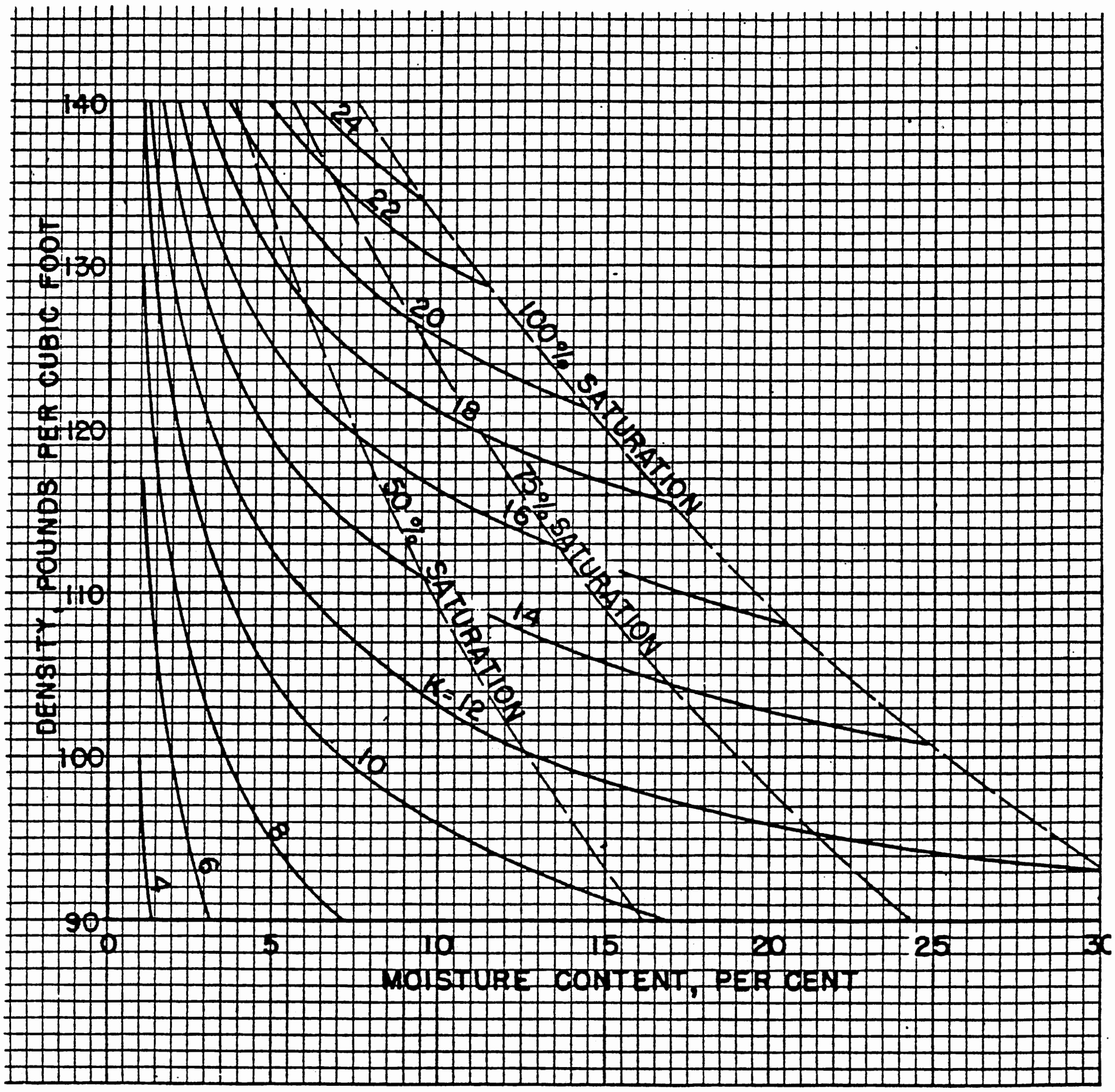
4. For sandy soil, frozen with moisture contents greater than 1.0%, use equation 10 or Figure 16.

$$k = 0.076\,(10)^{0.013d} + 0.032(10)^{0.0146d}(MC) \tag{10}$$



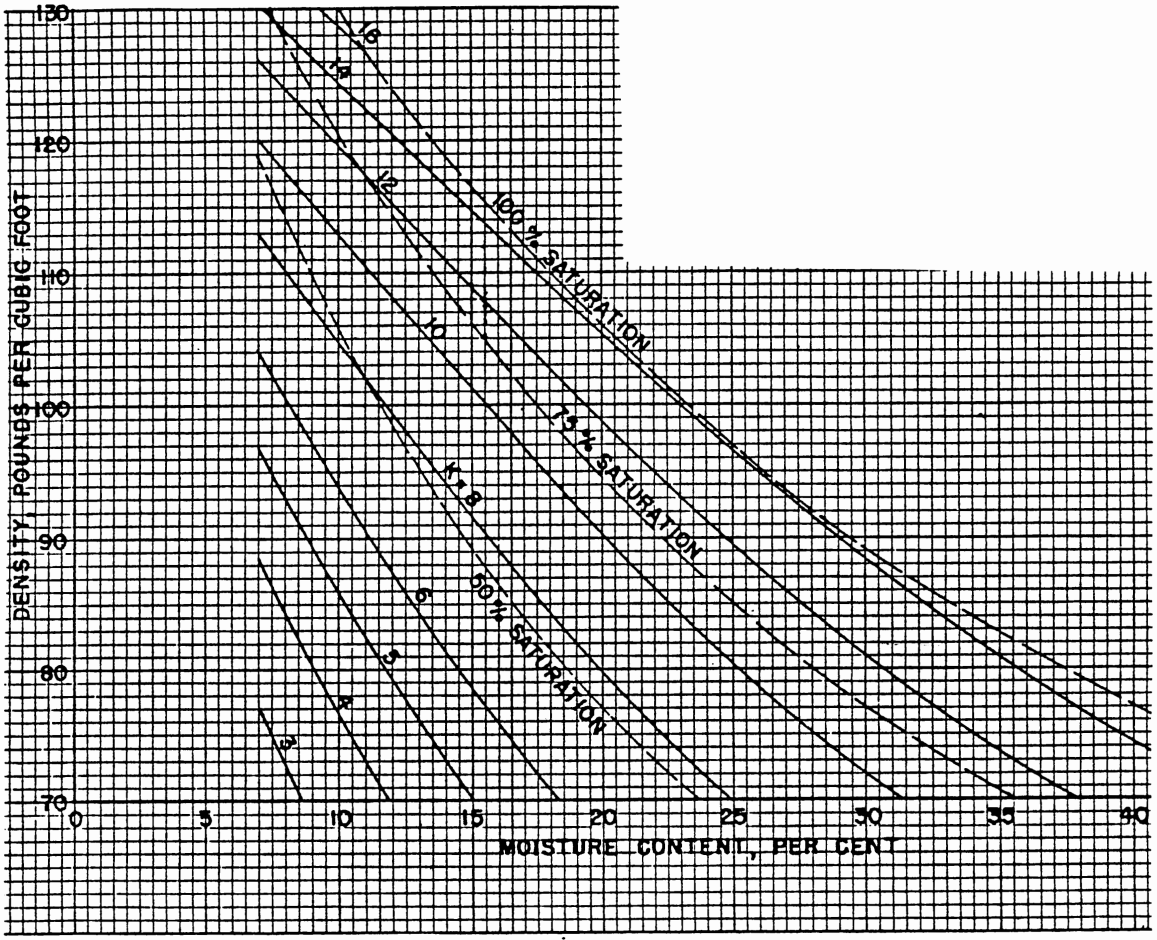
Source: M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 86.

Figure 13. Thermal Conductivity for Unfrozen Silt and Clay Soils



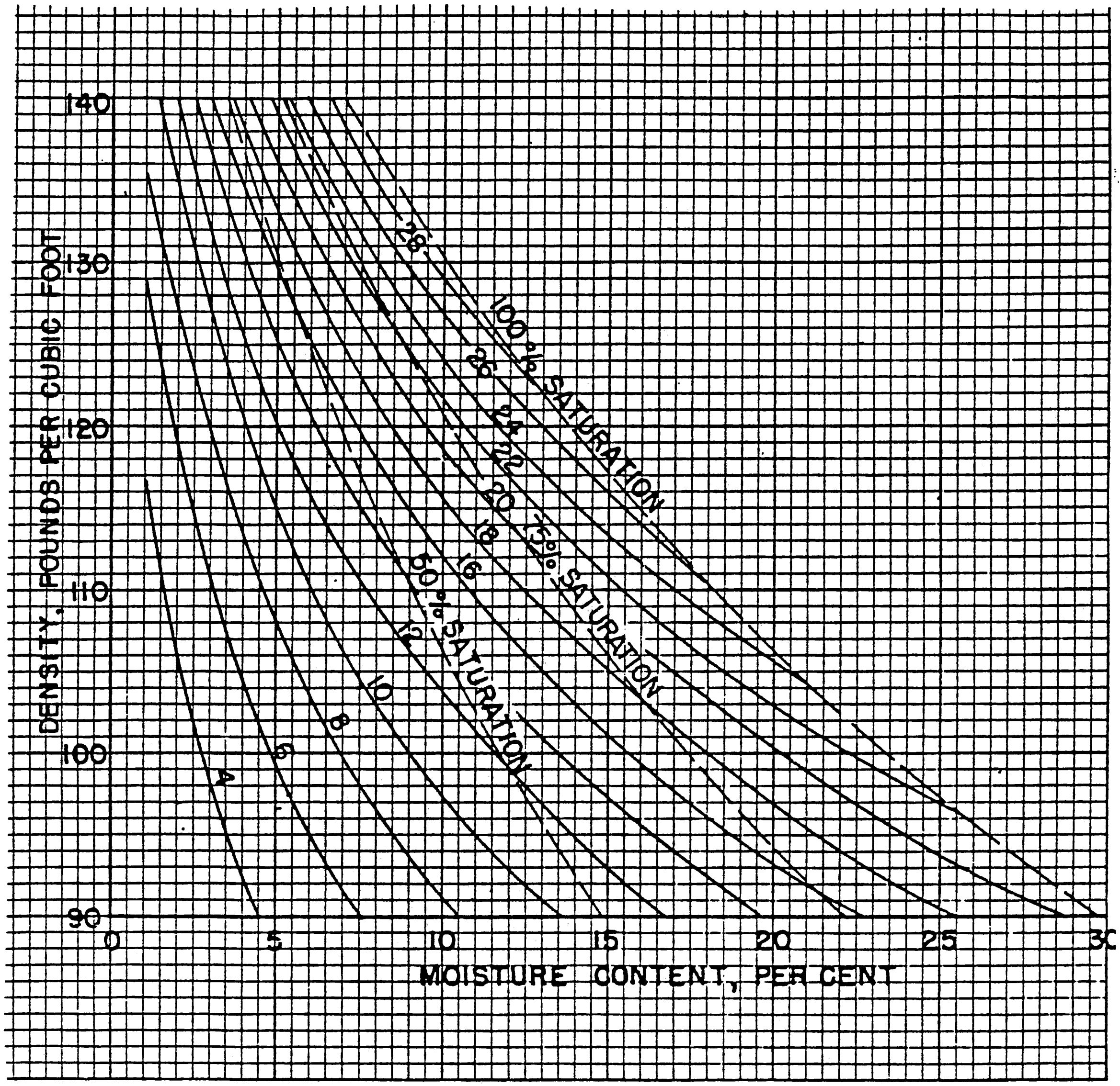
Source: M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 87.

Figure 14. Thermal Conductivity for Unfrozen Sandy Soils



Source: M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 88.

Figure 15. Thermal Conductivity for Frozen Silt and Clay Soils



Source: M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21 (June 1, 1949), p. 90.

Figure 16. Thermal Conductivity for Frozen Sandy Soils

where:

MC = Percent moisture content by weight (%)

D = Density (lb_{mass}/ft^3)

To convert units from Btu/^{o}F-inch-ft^2-hr to Btu/^{o}F-ft-ft^2-hr, divide value of computed k by 12.

As discussed in Chapter III, thermal conductivity does not vary significantly with temperature above or below freezing; therefore, temperature is not considered. There is little or no available information for predicting or determining moisture content of soils. The best way to determine the moisture content of a soil is to measure it directly by determining the loss of weight of a soil sample after drying.[16]

The moisture content of a soil may vary as a function of soil depth, site conditions and time. Therefore, the estimated moisture content must be considered an average for each month and earth cover depth. If only the relative impact of moisture content on heat transfer is of concern, then it is only necessary to accurately estimate the relative moisture content for each month. The relative moisture content for each month can be estimated from the average monthly precipitation for a location. This information is tabulated for several cities in the United States in Table II. The maximum moisture content for a soil can be estimated as a function of density from Figures 13 and 14.

TABLE II

MEAN MONTHLY PRECIPITATION FOR NINE SELECTED UNITED STATES CITIES (INCHES)

CITY	MONTH											
	J	F	M	A	M	J	J	A	S	O	N	D
Atlanta, GA	4.8	4.7	5.6	4.0	3.6	3.8	4.8	4.0	3.1	2.6	3.1	4.6
Oklahoma City, OK	1.3	1.2	2.1	3.3	5.0	3.9	2.8	2.7	3.3	2.8	1.9	1.5
San Antonio, TX	1.6	1.7	1.6	2.9	3.4	2.8	2.0	2.4	3.2	2.4	1.8	1.7
Albuquerque, NM	0.4	0.4	0.4	0.6	0.6	1.5	1.3	0.9	0.8	0.4	0.6	0.6
Los Angeles, CA	3.0	3.0	2.5	1.0	0.3	0.1	0.0	0.0	0.2	0.5	1.4	2.6
Columbus, OH	2.9	2.5	4.1	3.2	3.7	3.7	3.7	3.2	2.6	2.2	2.7	2.6
Spokane, WA	2.1	1.6	1.3	1.0	1.3	1.3	0.5	0.6	0.8	1.3	2.0	2.2
Salt Lake City, UT	1.3	1.4	1.8	2.0	1.7	0.9	0.6	0.9	0.9	1.4	1.4	1.4
Boston, MA	3.6	3.4	3.8	3.6	3.3	3.2	3.2	3.0	3.3	3.2	3.9	3.7

Source: J. A. Ruffner and F. E. Bair, The Weather Almanac, 2nd ed. (New York: Avon Books), 1979, p. 70.

Soil density affects soil thermal conductivity and thus heat flow. Soil density values are used to calculate soil thermal conductivity and transfer function coefficients by the above equations.

Density values for soils are also difficult to estimate and should be measured on-site. Table III shows maximum densities for various soil textures and can be used to estimate soil density for a particular soil based on how it varies from a hard-pack or maximum density.[17]

As discussed in Chapter III, specific heats vary very little as a function of soil type. Soil specific heats do vary with mean soil temperature and moisture content.

Table IV gives the average specific heats of two dry soils at various mean monthly soil temperatures.[18]

TABLE III

MAXIMUM DRY DENSITIES FOR THREE SOIL TEXTURES

SAND	122.5 lbm/ft^3
FINE SAND	116.0
CLAY	108.0

TABLE IV

SPECIFIC HEATS* OF TWO DRY SOILS BASED ON MEAN MONTHLY SOIL TEMPERATURE (MC=0%)

	Mean Monthly Soil Temperature (^oF)						
	80	70	60	50	40	30	20
CLAY	0.181	0.179	0.177	0.175	0.174	0.172	0.169
SAND	0.174	0.172	0.170	0.167	0.165	0.162	0.160

* Specific Heat (Btu/lb-^oF)

Once the specific heat for dry soil is determined, the following equation can be used to estimate the specific heat at various moisture contents:[19]

$$S_{mc} = \frac{(100)(S_s)+(MC)(1.0)}{100 + MC} \qquad (11)$$

where:

S_{mc} = Specific heat at MC moisture content (Btu/lb_{mass}-^{o}F)

S_s = Specific heat of soil (Btu/lb_{mass}-^{o}F)

MC = Moisture content

1.0 = Specific heat of water (Btu/lb-^{o}F)

Calculation of Sol-air Temperatures

The sol-air temperature is a function of solar radiation absorbed by a surface, radiation emitted by the surface and the outdoor temperature. The following equation is used to calculate the hourly sol-air temperatures for a given day per month.[20]

$$t_e = t_o + aI_t/h_o - eI_n/h_o \qquad (12)$$

where:

t_e = Hourly sol-air temperature (^{o}F)

t_o = Hourly outdoor air temperature (^{o}F)

a = Effective absorption coefficient of the surface for solar radiation

h_o = Coefficient of heat transfer by long-wave radiation and convection at the outer surface (Btu/hr-ft^2-^{o}F)

I_t = Hourly solar radiation incident on an unshaded soil surface (Btu/ft^2)

e = Effective hemispherical emittance of surface

I_n = Difference between the long wave radiation incident on the surface from the sky and surroundings, and the radiation emitted by a black-body at outdoor air temperature (Btu/hr-ft^2)

The hourly outdoor air temperature profile for a given day in a month can be calculated by the following equation:

$$t_o = (T_m - DR)DRP_t \qquad (13)$$

where:

T_m = Average daily maximum temperature per month (^oF)

DR = Average daily temperature range per month (^oF)

DRP_t = Percentage of daily range at time t

Values of daily maximum temperature and daily temperature range can be found in Table V for nine selected cities in the United States. Table VI gives the percentage of daily range to be used for each hour of the day.

The parameter I_n is not dependent upon surface conditions; therefore, for horizontal roof surfaces that receive long-wave radiation from the sky only, an appropriate value is about 20 Btu/hr-ft^2.[21]

Estimation of the solar radiation incident on an unshaded soil surface can be made using equation 14.

$$I_t = I_{dn} + I_{ds} \qquad (14)$$

TABLE V

MAXIMUM DAILY TEMPERATURES/MEAN DAILY RANGE
FOR NINE SELECTED U.S. CITIES (°F)

	MONTH											
CITY	J	F	M	A	M	J	J	A	S	O	N	D
Atlanta	51.4	54.5	61.1	71.4	79.0	84.6	86.5	86.4	81.2	72.5	61.9	52.7
GA	18.0	19.0	20.0	21.7	19.8	18.0	17.1	17.8	18.8	20.2	21.1	18.4
Okla. City	47.6	52.6	59.8	71.6	78.7	87.0	92.6	92.5	84.7	74.2	60.9	50.7
OK	21.6	22.6	23.3	22.5	20.8	20.4	22.2	22.9	23.4	23.6	23.5	21.5
San Antonio	61.6	65.6	72.5	80.3	86.2	92.4	95.6	95.9	89.8	81.8	71.1	64.6
TX	21.8	22.2	22.4	21.5	21.5	20.4	22.8	22.5	21.0	22.6	21.9	23.8
Albuquerque	46.9	52.6	59.2	70.1	79.9	89.5	92.2	89.7	83.4	71.7	57.1	47.5
NM	23.4	25.2	26.9	28.7	29.2	29.8	27.0	26.3	26.7	27.6	26.3	22.6
Los Angeles	66.5	67.6	68.6	70.5	73.2	76.5	82.9	83.7	82.5	78.0	73.2	68.0
CA	19.7	19.1	18.8	17.6	17.1	17.0	19.4	19.3	19.7	19.3	21.1	19.9
Columbus	36.4	39.2	49.3	62.8	72.9	81.9	84.8	83.7	77.6	66.4	50.9	38.7
OH	16.0	18.8	20.2	23.9	22.6	23.0	22.4	23.6	24.9	24.4	18.5	16.0
Spokane	31.1	39.0	46.2	57.0	66.5	73.6	84.3	81.9	72.5	58.1	41.8	33.9
WA	21.5	13.7	19.4	21.8	23.7	24.2	29.2	27.9	25.8	20.6	12.6	19.9
Salt Lake	37.4	43.4	50.8	61.8	72.4	81.3	92.8	90.2	80.3	66.4	50.0	39.0
City UT	18.9	21.0	22.5	25.2	28.2	30.2	32.3	31.5	31.0	28.0	21.9	17.5
Boston	35.9	37.5	44.6	56.3	67.1	76.6	81.4	79.3	72.2	63.2	51.7	39.3
MA	13.4	14.2	13.1	15.5	17.0	17.3	16.3	16.0	15.5	13.3	13.0	13.7

Source: J. A. Ruffner and F. E. Bair, The Weather Almanac, 2nd ed. (New York: Avon Books) 1979.

where:

I_{dn} = Direct solar radiation incident on an unshaded soil surface (Btu/ft^2-hr)

I_{ds} = Diffuse solar radiation incident on an unshaded soil surface (Btu/ft^2-hr)

TABLE VI

PERCENTAGE OF DAILY RANGE TO BE USED FOR EACH HOUR

HOUR	%	HOUR	%	HOUR	%	HOUR	%	HOUR	%	HOUR	%
1	87	5	100	9	71	13	11	17	10	21	58
2	92	6	98	10	56	14	3	18	21	22	68
3	96	7	93	11	39	15	0	19	34	23	76
4	99	8	84	12	23	16	3	20	47	24	82

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 25.4

The hourly solar radiation incident on an unshaded surface (I_t) is the sum of the direct solar radiation (I_{dn}) and diffuse solar radiation from the sky (I_{ds}). These hourly values are calculated by "ECROOF". The ASHRAE Fundamentals[22] has an excellent discussion of the procedure used to calculate these values. The basic equations used are briefly mentioned below.

Equation 15 is used to calculate the diffuse radiation component.

$$I_{ds} = CI_{dn}F_{ss} \quad (15)$$

where:

I_{ds} = Hourly diffuse radiation from the sky (Btu/hr-ft^2)

C = Diffuse radiation factor (Table VII)

I_{dn} = Hourly direct normal radiation incident on an unshaded surface (Btu/hr-ft^2)

F_{ss} = Angle factor between surface and sky (F_{ss} = 1.0 for horizontal surfaces)

TABLE VII

SOLAR CONSTANTS

	G	A	B	C
	Solar Declination	Apparent Solar Irradiation	Atmospheric Extinction Coefficient	Diffuse Radiation Factor
January	-20.0	390	.142	.058
February	-10.8	385	.144	.060
March	0.0	376	.156	.071
April	11.6	360	.180	.097
May	20.0	345	.196	.121
June	23.5	344	.205	.134
July	30.6	351	.207	.136
August	12.3	305	.201	.122
September	0.0	378	.177	.092
October	-10.5	387	.160	.073
November	-19.8	391	.149	.063
December	-23.5	--	.142	.057

The direct normal radiation, I_{dn}, can be calculated using Equation 16.

$$I_{dn} = \frac{A}{EXP\ (B/SINb) \times COS\ \theta} \qquad (16)$$

where:

A = Apparent solar irradiation (Table VII)

B = Atmosphere extinction coefficient (Table VII)

b = Solar altitude angle from horizontal

θ = Angle of incidence between incoming radiation and a line normal to the surface

The hourly solar altitude can be found from Equation 17:

$$SinB - CosL\ CosG\ CosH - SinL\ SinG \qquad (17)$$

where:

L = Local latitude

G = Solar declination (Table VII)

H = Hour angle = 0.25 x (number of minutes from local solar noon)

The number of minutes from local solar noon is absed on apparent solar time which must also be known so that comparisions can be made to data calculated and presented by "ECROOF."

The effective absorption coefficient for the roof surface is found by the following Equation 18.

$$a = (SC \times a_c \times CF) + (1\text{-}SC)(a_s) \qquad (18)$$

where:

SC = Percentage of soil surface fully shaded by the soil topping

a_c = Absorption coefficient of the soil cover

CF = Coupling factor

a_s = Absorption coefficient of the soil surface.

The coupling factor characterizes the impact of radiant energy absorbed by the soil cover, on the soil's thermal environment. This impact is a function of the amount of heat transferred to the soil by the cover, by radiation and conduction, and inversely by the amount of heat transferred from the soil cover to the exterior environment by convection, conduction and evaporation. The radiant loss of the soil cover is considered in the effective emittance. The value of the coupling factor is judgemental and can be approximated with reference to the following figure.

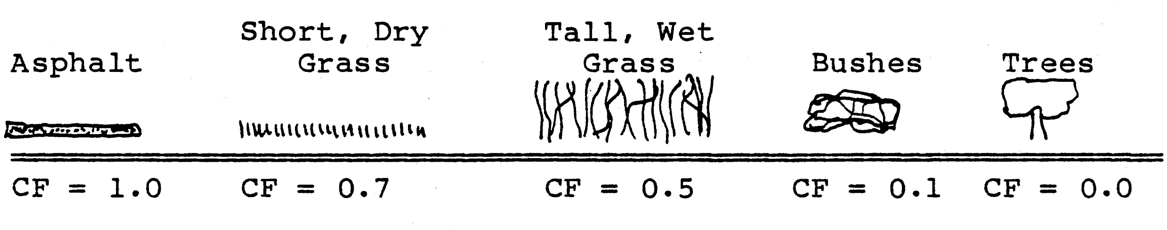


Figure 17. Soil Surface to Soil Topping Coupling Factor

Absorption by any surface is primarily a function of color. Absorption values for typical soils and soil conditions, as well as other natural surfaces, can be found in Table VIII.

TABLE VIII

TYPICAL ABSORPTION COEFFICIENTS OF NATURAL SURFACES

SURFACE	a%	SURFACE	a%
quartz sand	65	sand, wet	91
dark clay, wet	98-92	sand, dry	82
dark clay, dry	84	reflective	20
wet plowed field	95-86	dried grass	84-81
green grass	84-73	yellow leaves	67-64
water, solar altitude 0-30°	2	gray to dark gray	40-50
water, solar altitude 60°	6	green, red and brown	50-70
water, solar altitude 85°	58	dark brown to blue	70-80
white, smooth	25-40	dark blue to black	80-90

Source: M. S. Kersten, "The Thermal Properties of Soils," Bulletin of the University of Minnesota, Eng. Experiment Station Bulletin No. 28, Vol. LII, No. 21, June 1, 1949, Chapter 3, p. 87.

Percent of the soil surface shaded (SC) can only be determined by visual estimation. Consideration must be given to the shading of the soil throughout the day. If the nature of the surface cover is such that at low solar altitudes there is more soil surface exposed than for high solar altitudes , it must be accounted for. Work needs to be done in this area so that given a specific vegetation type and condition, the percentage of shade coverage of the surface for an average day per month can be more accurately estimated. For the purpose of this thesis, it is most important to correctly estimate the relative percentage of shade coverage between various vegetation types or surface conditions.

Hemispherical emissivity is defined as the ratio of the total radiant flux emitted from a surface to the hemisphere surrounding the surface to that emitted by an ideal blackbody at the same temperature.[23] The suffix "ivity" implies properties independent of size, shape and surface conditions. The suffix "ance" implies properties for a particular size, shape and surface condition.[24] The total emittance for a particular surface is a function of the temperature of the emitting surface.[25] There is little data for emittances of soil surfaces. One source by Gubareff, Janssen and Torborg,[26] contains a compilation of radiation properties for many materials. Table IX gives emittances for some natural surfaces. These emittances are described as emissivities, but based on the previous suffix definition, it is assumed there is a terminology inconsistency due to the wide variety of sources used to compile the source previously named.

TABLE IX

EMITTANCES FOR SEVERAL NATURAL SURFACES

Surface	Temp °F	Emittance
Surface Soil	100	.38
Lime Mortar	100	.92
Quartz	100	.89
Gravel	68	.29
Clay	68	.39
Sand	68	.76
Plowed Field	68	.38
Fine Sand	29 - 52	.90

Source: G. G. Gubareff, J. E. Janssen and R. H. Torborg, Thermal Radiation Properties Survey, 2nd ed. (Minneapolis: Honeywell Research Center), 1960, p. 192.

The effective emittance (e) can be calculated from equation 19 below:

$$e = (SC \times e_e) + (1-SC)(e_s) \qquad (19)$$

where:

e_e = Emittance of soil topping

e_s = Emittance of soil

The coefficient of heat transfer by long-wave radiation and convection at the roof surface is difficult to estimate based on existing knowledge. Speltz and Meixel use a series of equations to predict the convection transfer coefficient as a function of surface roughness, wind velocity, and temperature difference between the surface and ambient air.[27] These equations are applicable to surfaces defined by type of earth cover. The model in this thesis defines the surface boundary in terms of the soil surface, regardless of soil cover. In the case of bare soil, the Speltz and Meixel equations are applicable, but lose their validity with soils having a covering. As discussed in Chapter III, the convective film coefficient for some toppings, such as grass surfaces, is a function of depth of still air and the effectiveness of the grass blades in retarding internal convection loops. There has been some study of the variability of the surface convection coefficient as a function of weather/climate conditions for a specific soil surface. Meixel, Shipp and Bligh estimated a range of values for this parameter for several months of the year, each month reflecting differing weather/climate conditions. The values of h_o increased very much in the summer months.[28]

There is not a not a simple method of predicting values for surface convection coefficients that reflect the characteristics of surface toppings that are of benefit in earth covered roofs. Therefore, a method is not presented here.

Actual calculation of the hourly sol-air temperatures is done in the "ECROOF" program. The data required is characteristic to the location and time of concern.

Interactive Computer Design Aid

The methodology previously outlined is modeled in an interactive computer program. This allows a designer to graphically compare effects of several variables on the thermal performance of an earth covered roof. The program has been written for use on a Hewlett-Packard 9845B minicomputer. The program flow chart is shown in Figure 18, and a listing of the program can be found in Appendix A.

This program, called "ECROOF", calculates heat transfer for each hour of the 21st day of each month, for up to twelve months or data sets. The heat transfer is calculated based upon the methodology described in previous sections.

Hourly heat transfer for up to twelve months can be plotted on one graph of Btu/hr-ft^2 vs. hour for direct comparison of monthly changes. Heat transfer can also be plotted for a specific hour or an average of 24 hours on the graph of Btu/hr-ft^2 vs. months.

This program does not calculate transfer function coefficients; they must be input. Transfer function coefficients can be calculated by the computer program "TRANSF". The input format and Job Control Language of this program can be found in Appendix B. Values of transfer function coefficients for various configurations of the earth covered roof system described in Chapter V can be found in Appendix C.

Calculation of heat transfer for a particular time requires information on the sol-air temperatures at that and preceding times, as well as the heat flow at preceding times. Heat flow is assumed to be zero at the start of the calculation. The effect of this assumption becomes negligible as the calculation is repeated for successive 24-hour cycles. The calculations are cycled no less than four times. Cycling terminates when the difference between heat transfer for hour t and hour t+24 is less than 1% of hour t+24. If this does not occur within twenty cycles, cycling stops.

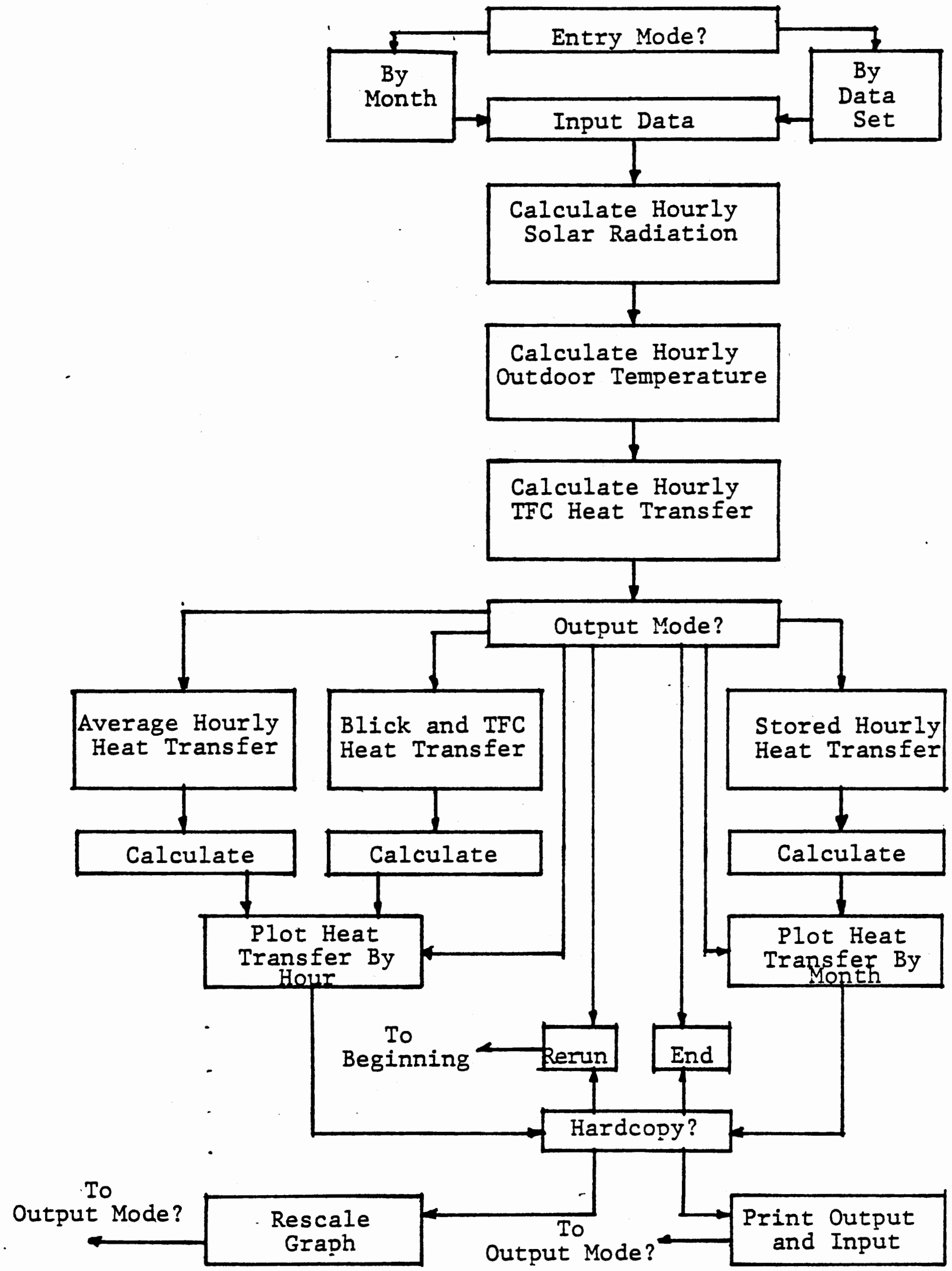


Figure 18. "ECROOF" Program Flowchart

ENDNOTES

[1]E. F. Blick, "A Simple Method for Determining Heat Flow Through Earth Covered Roofs," Proc. Earth Sheltered Building Design Innovations Conf., L. L. Boyer (Ed.) Oklahoma State University, Stillwater, OK 1981, p. III-21.

[2]American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 25.28.

[3]E. F. Blick, "A Simple Method for Determining Heat Flow Through Earth Covered Roofs," Proc. Earth Sheltered Building Design Innovations Conf., L. L. Boyer (ed.) Oklahoma State University, Stillwater, OK (1981), p. III-19.

[4]Ibid., p. III-21.

[5]Ibid.

[6]Ibid.

[7]G. P. Mitalas and P. G. Stephenson, "Room Thermal Response Factor," ASHRAE Transactions, Vol. 73, Pt. 1 (1967), pp. III2.1-2.10.

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[14]American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 25-28.

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[17]American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 4.

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[19]Ibid., p. 72.

[20]American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 25.4

[21]Ibid.

[22]Ibid., pp. 26.2 to 26.9.

[23]Ibid., p. 33.6

[24]G. G. Gubareff, J. E. Janssen and R. H. Torborg, Thermal Radiation Properties Survey, 2nd ed. (Minneapolis: Honeywell Research Center), 1960, p. 4.

[25]Ibid., p. 5.

[26]Ibid., p. 212.

[27]J. J. Speltz and G. D. Meixel, "A Computer Simulation of the Thermal Performance of Earth Covered Roofs." Proc. of the Underground Space Conf. and Expo., Kansas City, MO (June, 1981), p. 97.

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CHAPTER V

MODEL PERFORMANCE

Analysis Background Information

Purpose

The purpose of this chapter is to use the previously formulated performance/design model to quantitatively evaluate the sensitivity of identified parameters on heat transfer through earth covered roofs. It is from this evaluation that an understanding of relative parametric effects is determined and design/performance guidelines formulated.

In order to reliably compare and understand the relative performance of each variable, parameter studies are made relative to a common reference earth covered roof system and a reference radiation condition.

Reference System

The reference earth covered roof system is very basic in design and is not intended to suggest a desirable earth covered roof design. The surface condition is bare soil so that different soil toppings can be better compared and evaluated. Clay soil is common in Oklahoma and is used in the reference roof. The clay soil is very dry with a moisture content of 7% and is well packed. The reference roof is depicted graphically in Figure 19. The supporting roof structure is 6 inches of heavy weight (poured in place) concrete. Bare concrete is the interior surface condition. No additional insulation is included in this reference roof assembly. See Table X for the thermal properties of this roof system.

The reference radiation condition is representative of a bare soil surface condition (no shading or topping), where the absorption and emittance of the clay soil are 0.60 and 0.40 respectively. These values were selected from Tables VIII and IX, Chapter IV.

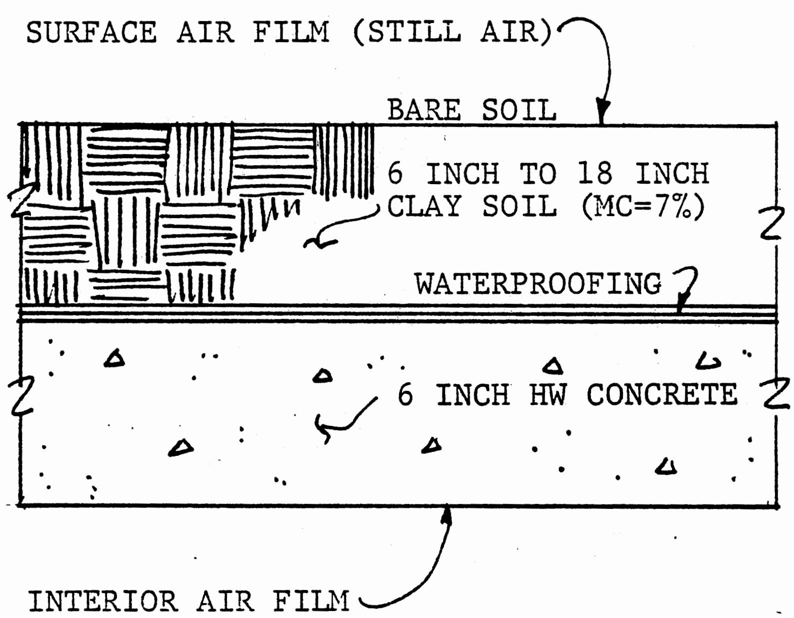


Figure 19. Reference Earth Covered Roof System

TABLE X

THERMAL PROPERTIES OF REFERENCE ROOF SYSTEM

Material Description	Thickness/Thermal Properties				
	d	k	D	S	R
Outside Surface	--	--	--	--	1
Clay Soil, 7% MC	0.5 to 1.5	0.417	95	0.23	--
6" Hw Concrete	0.5	1	140	0.2	--
Inside Surface	--	--	--	--	0.685

d = ft; K = Btu/hr-ft-^{o}F; D = lb/ft^3; S = Btu/lb-^{o}F; R = hr-ft^2-^{o}F/Btu

Overview of Analysis

The following individual sections of analysis include a discussion of parameters involved and determination of their "test" values. A discussion of results is based upon graphical analysis of heat transfer calculated using the model formulated in this thesis. Following the detailed analysis is a discussion of practical applications and relative impacts each parameter has on earth covered roofs.

Overall, the evaluation is divided into four parts, the first being a comparison of Blick's method with the TFC method. The reference earth covered roof, with and without the reference radiation condition, is studied for

12 months for each method. Further explanation of this validation study is made later.

Study of soil and roof characteristics such as soil depth, moisture content and insulation make up the next two parts, while the fourth part deals with the soil surface condition. The surface topping's influence upon heat transfer is primarily in terms of its effect upon incident solar radiation and, in turn, sol-air temperatures.

A secondary study is done so that peak heat transfer can be easily estimated. This study includes factors that can be applied to a steady-state equation to estimate the delayed heat transfer due to mass for various soil and surface conditions.

Parameters held constant for each analysis include structure type and depth, the radiation exchange parameter (I_{dn} included in calculation of sol-air temperature) and the interior film coefficient. The interior film will vary insignificantly in normal conditions and is based upon a non-reflective surface and still air. Variation of structure type and depth could have significant effects, but is beyond the scope of this thesis. The parameter I_{dn} (defined in Chapter IV) is independent of surface conditions and is, therefore, held constant.[1]

Although type of soil topping affects the exterior surface convection coefficient, this coefficient is also held constant. Values of this coefficient are difficult to predict, as explained in Chapter IV; and a value of 1.0

Btu/hr-ft^2-^{o}F is used. This value was selected after a review of references cited in Chapter IV and is representative of nearly still air at the soil surface whether caused by short grass or absence of surface air movement. Tables XI and XII give the actual reference input values used for the heat transfer studies. These values vary only when that particular parameter is being studied.

TABLE XI

CONSTANT INPUT DATA FOR HEAT TRANSFER STUDIES--JANUARY

Parameter	Reference Value	
Latitude =	36	Degrees North
Indoor Design Temperature =	75	^{o}F
Average Maximum Temperature =	47.6	^{o}F
Average Daily Range =	21.6	^{o}F
Surface Cover Absorption =	0	--
Surface Cover Emittance =	0	--
Coupling Factor =	0	--
Shading Coefficient =	0	--
Surface Convection Coefficient =	1	Btu/hr-ft^2-^{o}F
Soil Absorption =	0.6	--
Soil Emittance =	0.4	--
Soil Density =	95	Lb/ft^3
Specific Heat =	0.23	Btu/lb-^{o}F
Soil Depth =	6	Inches
Soil Thermal Conductivity =	0.417	Btu/hr-ft-^{o}F

TABLE XII

CONSTANT INPUT DATA FOR HEAT TRANSFER STUDIES--JULY

Parameter	Reference Value	
Latitude =	36	Degrees North
Indoor Design Temperature =	75	^{o}F
Average Maximum Temperature =	92.6	^{o}F
Average Daily Range =	22.2	^{o}F
Surface Cover Absorption =	0	--
Surface Cover Emittance =	0	--
Coupling Factor =	0	--
Shading Coefficient =	0	--
Surface Convection Coefficient =	1	$Btu/hr\text{-}ft^2\text{-}^oF$
Soil Absorption =	0.6	--
Soil Emittance =	0.4	--
Soil Density =	95	Lb/ft^3
Specific Heat =	0.23	$Btu/lb\text{-}^oF$
Soil Depth =	6	Inches
Soil Thermal Conductivity =	0.417	$Btu/hr\text{-}ft\text{-}^oF$

Analysis and Discussion

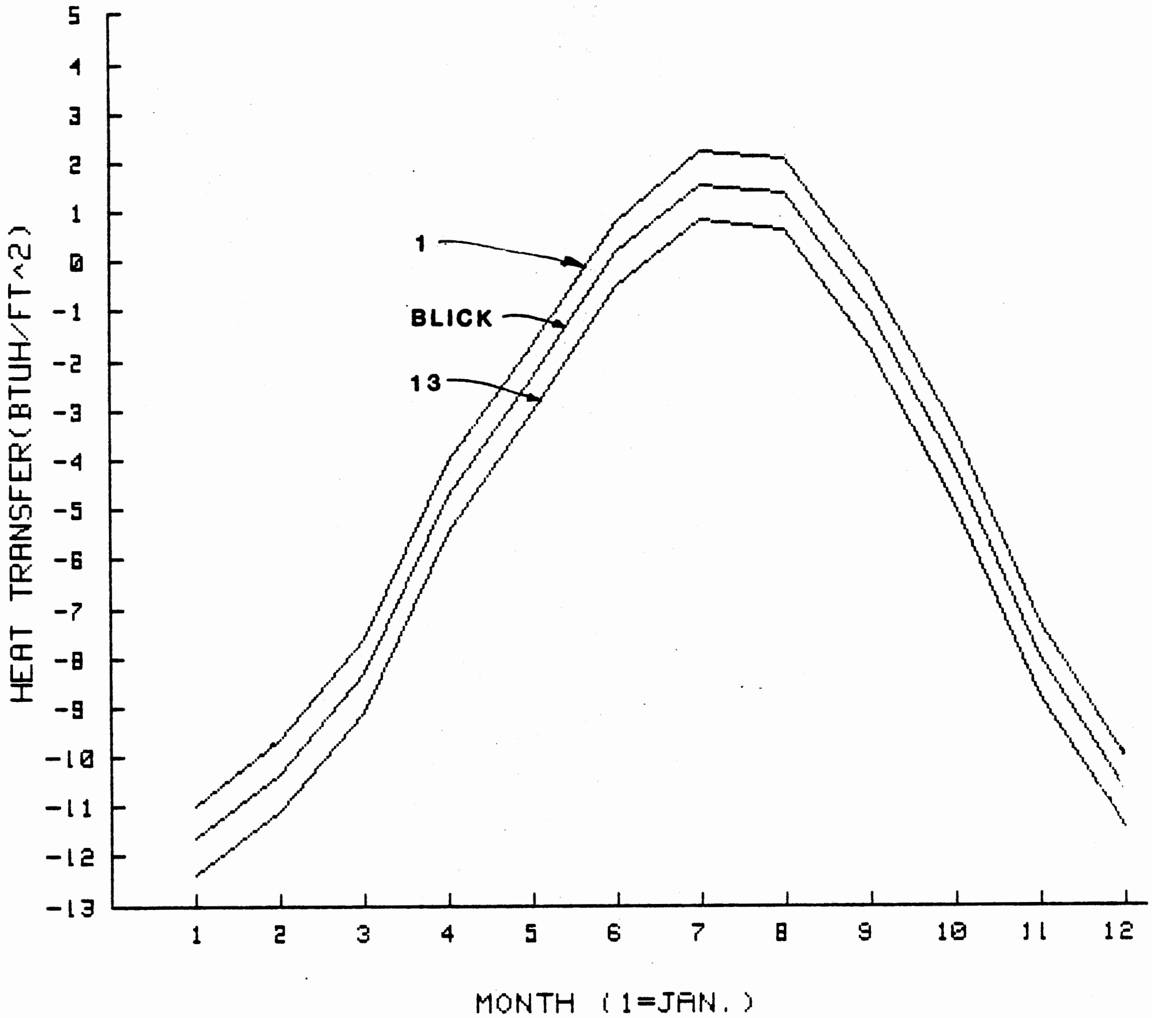
Comparisions With Blick's Method

Blick's methodology is based on the use of an average surface air temperature for each month to calculate heat flow on a monthly basis. Blick's method does not effectively model seasonal time lag nor does it model hourly heat transfer. Its ability to model seasonal time lag is limited by the accuracy of the surface temperature representation of the earth cover and its topping. The TFC methodology is based upon hourly air temperatures for a typical day each month and very effectively models the diurnal variations in heat transfer in shallow soil depths (0 to 18 inches). This method does not model time lag beyond a 24 hour period, although it can potentially be expanded to do so.

Blick compared his simple model to an exact model, as described in Chapter IV, and found a close correlation.[2] Blick's model slightly underestimated January heat loss and slightly overestimated July heat gain for a specific hour.

Similar correlations are evident when Blick's results are compared to results obtained by the TFC methodology formulated in this thesis. Heat transfers obtained from Blick's method and the TFC method are both based on the reference earth covered roof system with 6 inches of soil with and without the reference radiation condition. Heat transfer for the TFC model is calculated for each hour of a typical day for each month of the year, while Blick's model calculated heat transfer based on an average hourly temperature for a typical day for each month.

Figure 20 shows the hourly heat transfer curves that deviate the greatest from Blick's average hourly heat transfer without the reference radiation condition (outdoor air temperature equals sol-air temperature). These extreme hourly heat transfer curves occur in hours 1 and 13. The maximum heat transfers represented by the peaks in heat gain occur in the first hour of a typical day in July. Blick underestimates this peak by 31%. The peak hourly heat loss



1 - Hour 1 - TFC method

Blick - Heat transfer - Blick method

13 - Hour 13 - TFC method

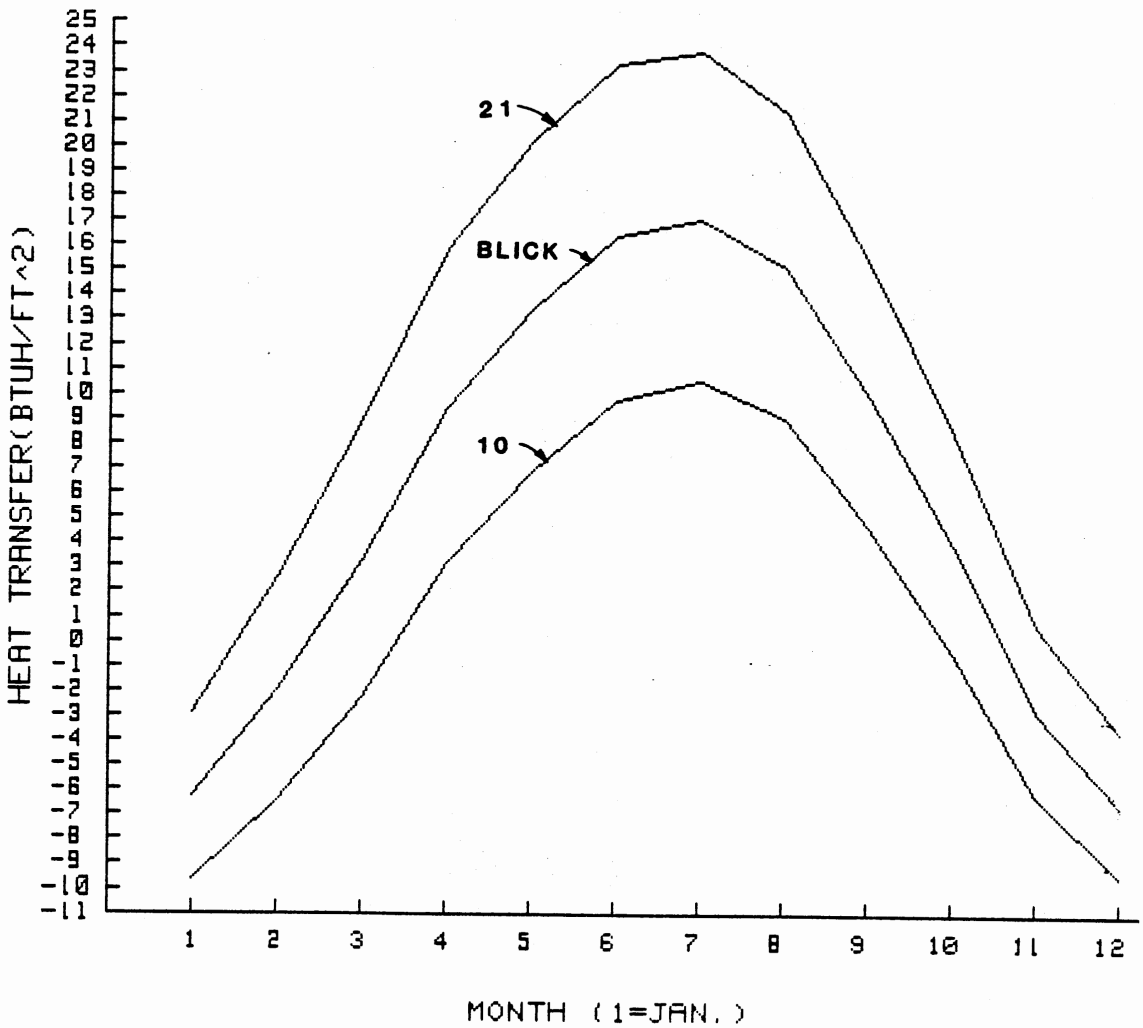
Figure 20. Blick's Method Vs. TFC Method (Without Solar Radiation)

occurs in January in the 13th hour, the early afternoon. Blick overestimates this heat loss by 6%. The actual differences in heat transfer between the Blick curve and each extreme TFC curve are generally equal throughout the year at an average of 0.67 Btu/hr-ft^2 for hour 1 and 0.76 Btu/hr-ft^2 for hour 13.

Figure 21 shows how the introduction of solar radiation (reference radiation condition) shifts the times at which the TFC extreme hourly heat transfer occurs. The magnitude of overall heat transfer increases and the magnitude of Blick's overestimations and underestimations of heat transfer also increases. The times of hourly heat transfer extremes occur in the 10th and 21st hours. Blick underestimates July heat gain by 29% and overestimates January heat loss by 35%. The differences between Blick's curve and the extreme TFC curve are again relatively equal with average differences of 5.10 Btu/hr-ft^2 for the 21st and 10th hours.

Figure 22 and Table XIII show the strong correlation between the heat transfer calculated by Blick and the average TFC hourly heat transfer with the reference radiation condition. Blick's model slightly overestimates January heat loss and underestimates July heat gain, both by less than 1%.

The TFC model correlates well with Blick's model in terms of hourly and average hourly heat transfer for a typical day throughout the year. Again, neither model in

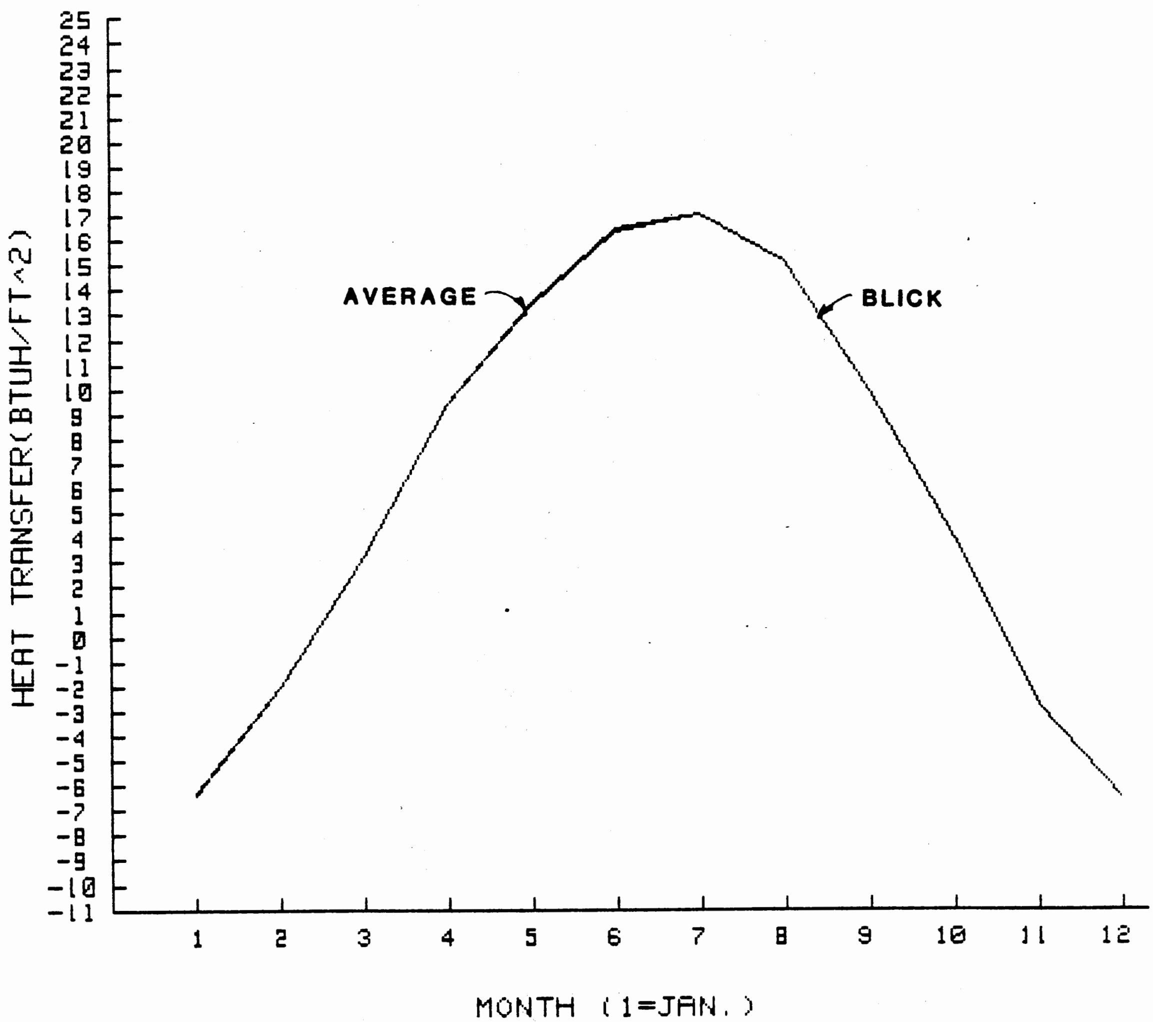


10 - Hour 10 - TFC method

Blick - Heat transfer - Blick method

21 - Hours 21 - TFC method

Figure 21. Blick's Method Vs. TFC Method (With Solar Radiation)



Blick - Heat transfer - Blick method

Average - Average heat transfer - TFC method

Figure 22. Blick's Method Vs. Average TFC

these terms reflect the soil's seasonal mass effect of time lag. The TFC model does, however, model the diurnal mass effects of time lag and diurnal dampening of peak heat transfers.

Blick's model underestimates peak diurnal heat gain and overestimates heat loss throughout the year. Introduction of solar radiation did not greatly affect the correlation of average hourly TFC heat transfer, but it did greatly increase the overestimations and underestimations of peak diurnal heat transfer.

TABLE XIII

HEAT TRANSFER FOR AN AVERAGE HOUR CALCULATED BY THE TRANSFER FUNCTION COEFFICIENT AND BLICK METHODS

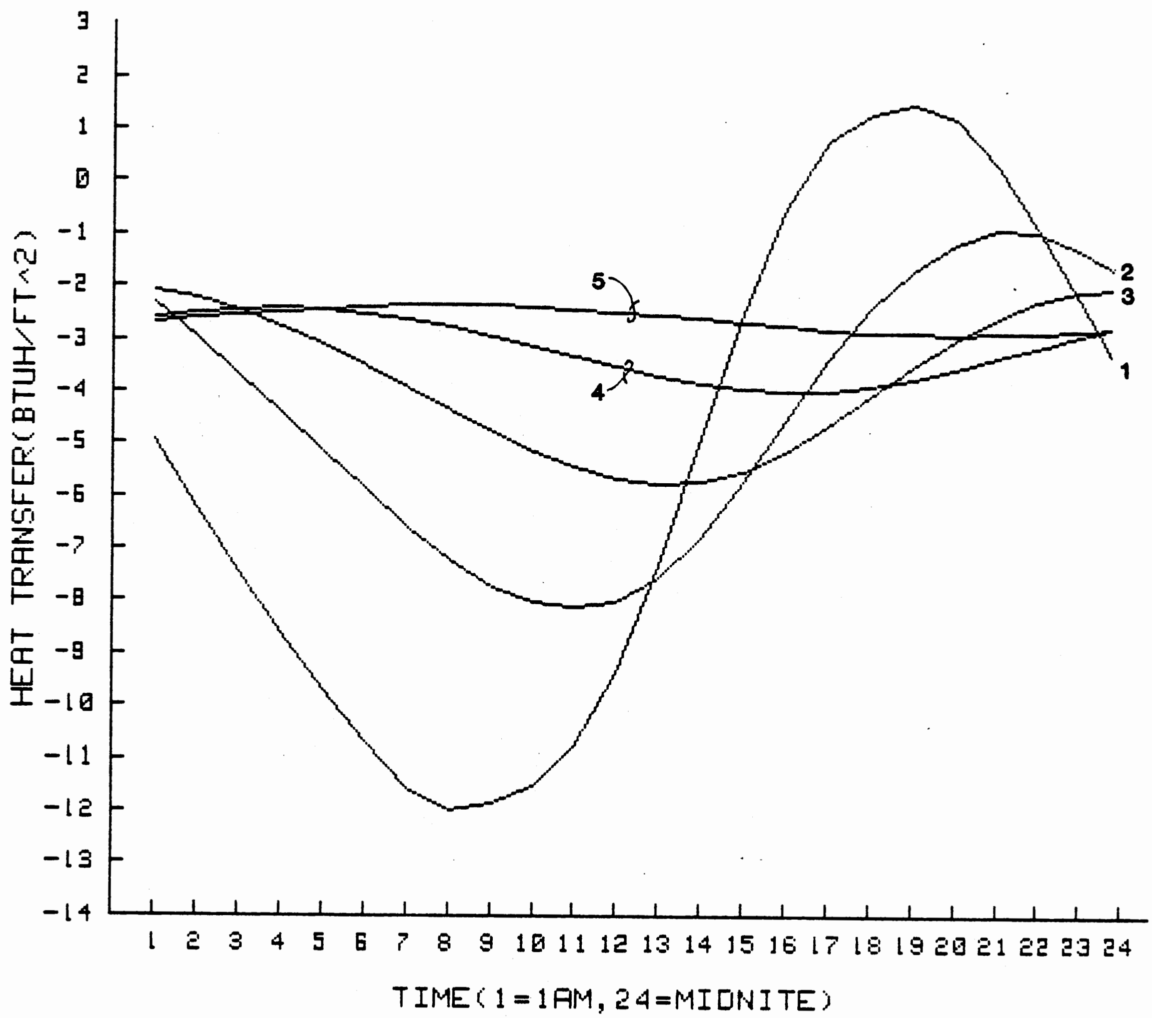
Month	Blick Value ($Btu/hr\text{-}ft^2$)	TFC Average ($Btu/hr\text{-}ft^2$)
January	-6.327	-6.346
February	-2.002	-2.012
March	3.002	3.217
April	9.368	9.383
May	13.379	13.403
June	16.365	16.396
July	17.019	17.052
August	15.082	15.110
September	9.891	9.909
October	3.891	3.909
November	-2.811	-2.822
December	-6.567	-6.586

Soil Parameters

The following two areas of analysis are of major importance because the parameters involved are primarily responsible for the thermal performance desired in earth covered roofs. Both parameters can be manipulated to create the most beneficial performance for a specific case. Soil moisture content can be altered daily and/or seasonally, while a soil depth (although fixed) can be chosen to provide the thermal time lag desired.

Soil Depth. The analysis of the effects of soil depth upon heat transfer with respect to diurnal time frame is based upon the reference roof with varying amounts of clay soil: 3 inches, 6 inches, 9 inches, 13 inches and 18 inches. The 18 inch depth of soil represents the maximum amount of mass that is within the transfer function coefficient program's capability. This study is also based upon the reference radiation condition with a bare soil surface with no surface effects except for surface convection (h_o = 1; or any surface condition where a = 0.6 and e = 0.4). Data in Tables XI and XII provide the input values (held constant) for each analysis.

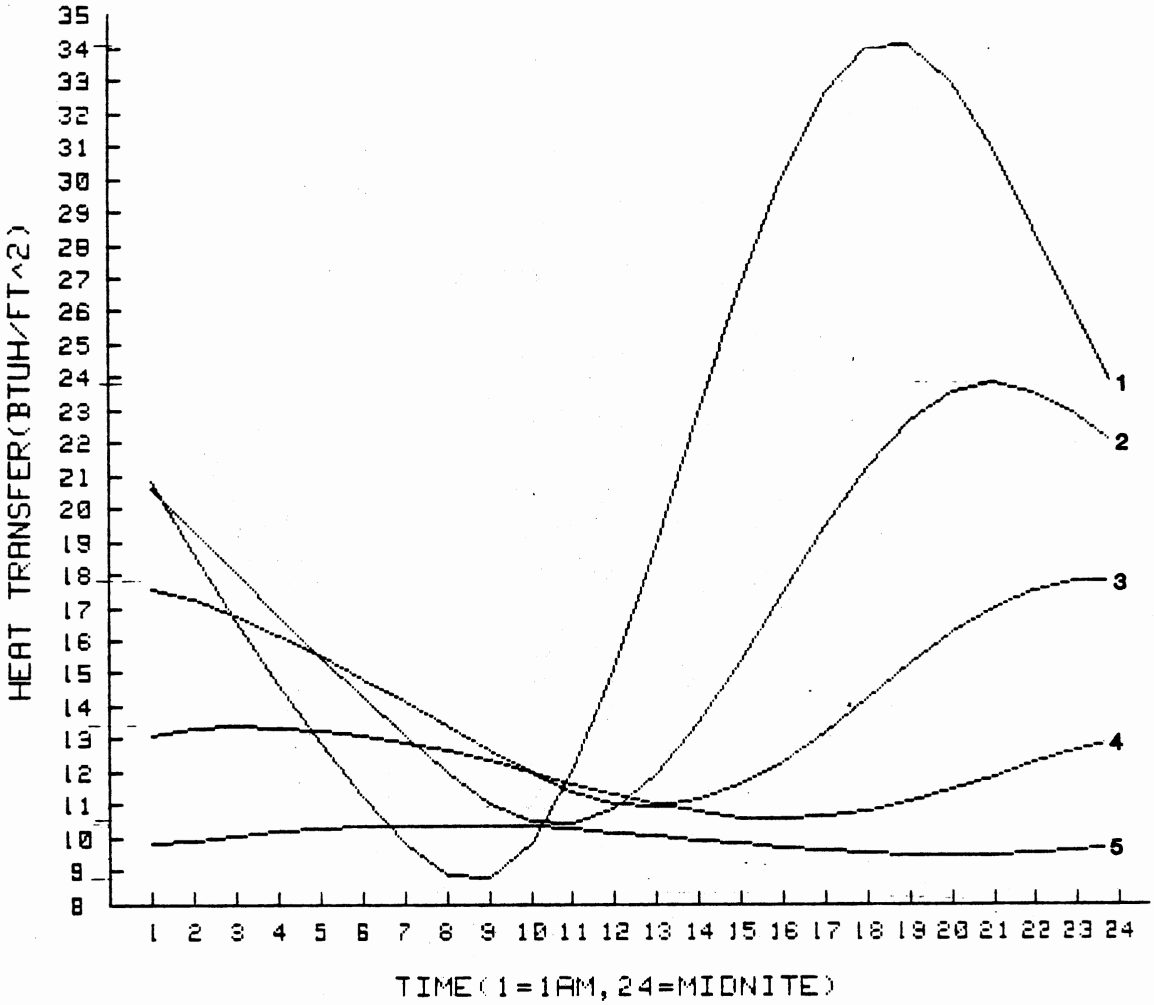
Figures 23 and 24 represent diurnal heat transfer through the reference roof system with various soil depths during the peak load months of July and January. The effects of soil depth and roof mass on heat flow are clearly illustrated by comparison of these curves.



INPUT DATA
VALUES FOR VARIED DATA

1	ROOF R-VALUE	=	2.8	HR-FT^2-F/BTU
2	ROOF R-VALUE	=	3.4	HR-FT^2-F/BTU
3	ROOF R-VALUE	=	3.98	HR-FT^2-F/BTU
4	ROOF R-VALUE	=	4.78	HR-FT^2-F/BTU
5	ROOF R-VALUE	=	5.78	HR-FT^2-F/BTU
1	DEPTH	=	3	INCHES
2	DEPTH	=	6	INCHES
3	DEPTH	=	9	INCHES
4	DEPTH	=	13	INCHES
5	DEPTH	=	18	INCHES

Figure 23. Diurnal Heat Transfer for Various Soil Depths--January



INPUT DATA
VALUES FOR VARIED DATA

1 DEPTH	=	3	INCHES
2 DEPTH	=	6	INCHES
3 DEPTH	=	9	INCHES
4 DEPTH	=	13	INCHES
5 DEPTH	=	18	INCHES
1 ROOF R-VALUE	=	2.8	HR-FT^2-F/BTU
2 ROOF R-VALUE	=	3.4	HR-FT^2-F/BTU
3 ROOF R-VALUE	=	3.98	HR-FT^2-F/BTU
4 ROOF R-VALUE	=	4.78	HR-FT^2-F/BTU
5 ROOF R-VALUE	=	5.78	HR-FT^2-F/BTU

Figure 24. Diurnal Heat Transfer for Various Soil Depths--July

Time lag of heat transfer is indicated by the shift in phase of each curve as the soil mass increases. An example of this is shown in Figure 24; the peak heat gain is shifted almost 10 hours, from hour 18 (late afternoon) for a 3 inch soil depth to hour 8 (early morning) for an 18 inch soil depth. Mass can be a great tool for delaying the peak load to a time when off-peak utility energy or passive energy systems may be taken advantage of.

From this study, it was found that the peak diurnal heat gain in July for this roof system shifts an average of 54 minutes for every added inch of soil. For January, the average shift of maximum diurnal heat loss is 50 minutes per inch of soil. The change in time lag per inch of soil depth increases gradually with depth. For example, it ranges from approximately 44 minutes per inch at shallow depths of 3 to 6 inches to 60 minutes per inch at depths of 12 to 18 inches.

Time of minimum heat gain and heat loss also shift with increased soil depth. The minimum diurnal heat gain in July shifts an average of 44 minutes per inch of soil. The average shift of minimum January heat loss is 52 minutes per inch of soil.

Another indication of change in time lag with soil depth is the stretching of the curves. The time between diurnal peaks increases with depth (time of maximum peak minus time of minimum peak).

For July, the average increase in wavelength with depth is 8 minutes per inch of soil. This relationship is far from linear, with an 85% increase in change of wavelength between depths of 3 to 6 inches and depths of 6 to 9 inches. This percentage increase reduces to 6% between depths of 9 to 13 inches and depths of 13 to 18 inches. For shallow depths (3 to 6 inches), an increase in wavelength of approximately 4 minutes per inch can be expected, and an increase of up to 10 minutes per inch can be expected at depths of 13 to 18 inches.

For January, the pattern is less distinct, with the 3 inch and 18 inch depths falling out of the pattern. Based on the 6 to 13 inch soil depths, an average increase in wavelength of 15 minutes per inch can be expected.

Mass effects are also represented by the reduction in amplitude of the diurnal heat transfer curves with depth. This flattening of the curves toward an average or constant heat flow reduces the necessary capacity of mechanical or passive systems and allows these systems to perform at a higher and more constant efficiency level.

As soil depth increases, overall amplitude (maximum diurnal heat transfer minus minimum diurnal heat transfer) flattens approximately 15% per inch of added soil. This is true for both July and January. Reduction of peak heat transfer for July and January (difference in peak loads for various depths) is approximately 10% per inch of added soil for shallow soils of 3 to 6 inches. For depths of 13 to 18 inches, reduction in peak heat loss in January is 6% per inch. For both months, the average overall reduction from 3 to 18 inches of soil depth is 7% and 8% per inch of soil for July and January, respectively. Discussion of an earth covered roof system's storage and peak reduction capacity relative to soil depth occurs later in this chapter.

Increased soil depth (mass) reduces overall diurnal heat transfer, reduces diurnal heat transfer amplitude, reduces peak heat transfer, increases the period between diurnal peaks, and shifts the times at which peak heat transfer occurs. These mass effects allow improved integration and more efficient use of passive and mechanical space conditioning systems. See Chapter VI for a discussion and correlation of these advantages.

Soil Moisture Content. Soil moisture content is based on the soil's corresponding values of thermal conductivity and specific heat. For a specific soil type, the full range of heat transfer (as influenced by moisture content) can be represented by a maximum and minimum moisture condition. The minimum value of moisture content and its corresponding thermal conductivity and specific heat (at 55^{o}F) is defined by a dry clay soil (7% moisture content) at a density of 95 lb/ft^3. This value of thermal conductivity also represents moisture contents and densities up to 21% at 70 lb/ft^3, as shown in Figure 25. The maximum

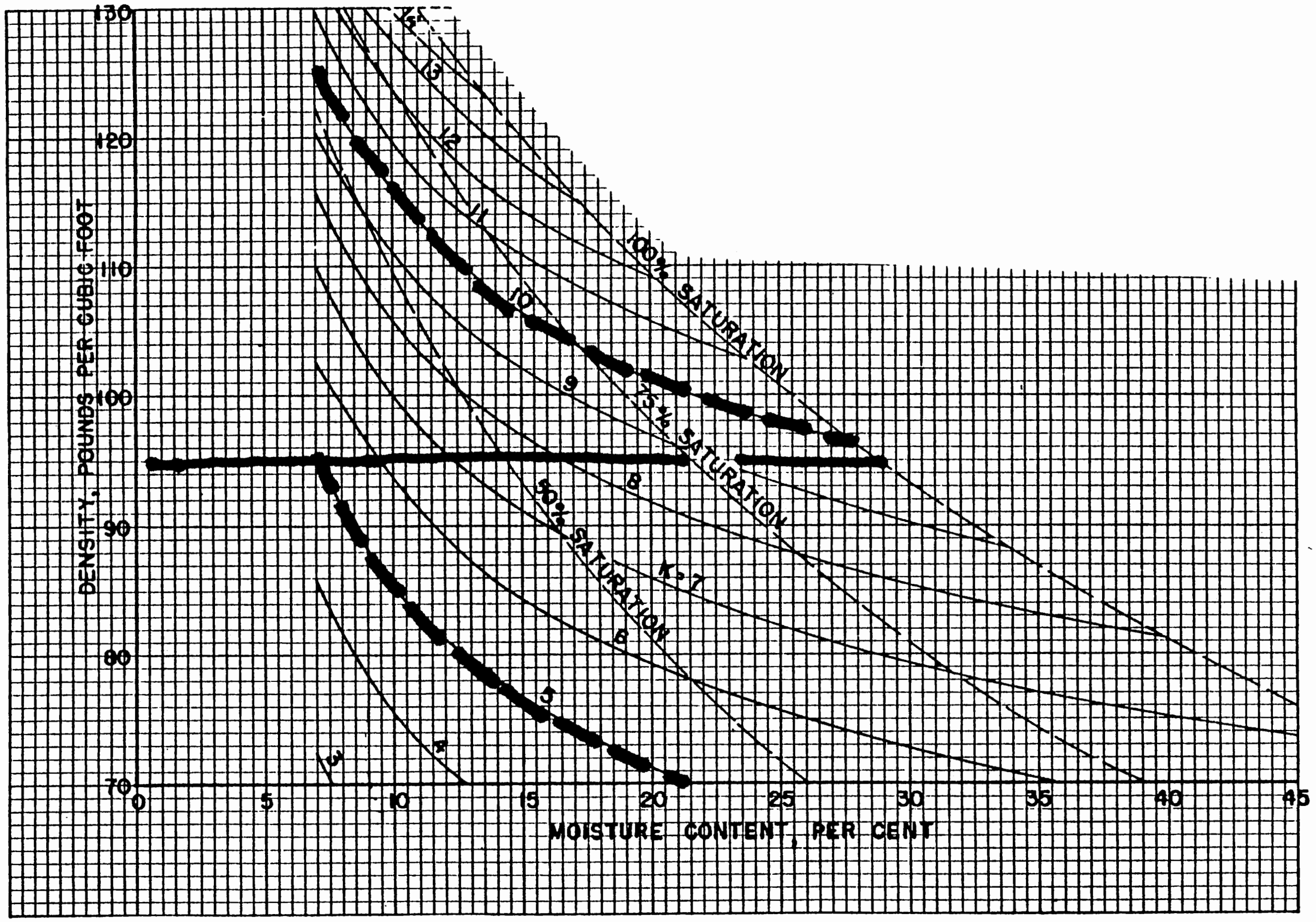
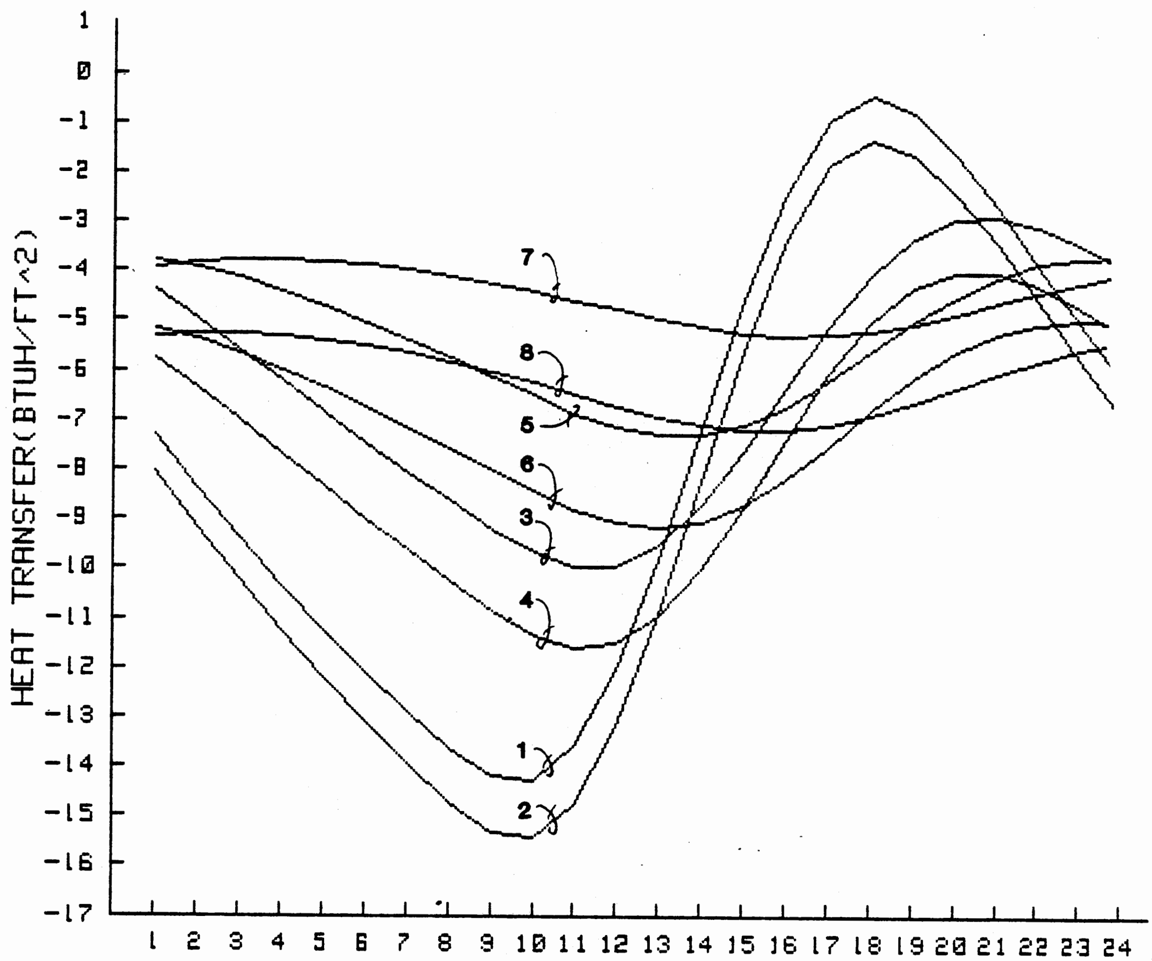


Figure 25. Correlation of Soil Properties Used for Moisture Content Study

values of thermal conductivity are defined at a moisture content of 28% and a density of 95 lb/ft^3 (100% saturation). This value of thermal conductivity also represents a range of moisture contents and densities to 7% at 125 lb/ft^3. Although any given value of thermal conductivity may represent a range of densities and moisture content combinations as shown in Figure 25, moisture contents of 7% (dry) and 28% (saturated), both at 95 lb/ft^3, are analyzed. Only these moisture contents are studied due to the large number of transfer function coefficients that would have to be calculated for each set of data where density, thermal conductivity and/or specific heat were changed.

Figures 26 and 27 indicate heat transfer for depths of 3 inches, 6 inches, 9 inches and 13 inches during the peak load months of January and July with the reference radiation condition. Reference Tables XI and XII for constant parameter values.

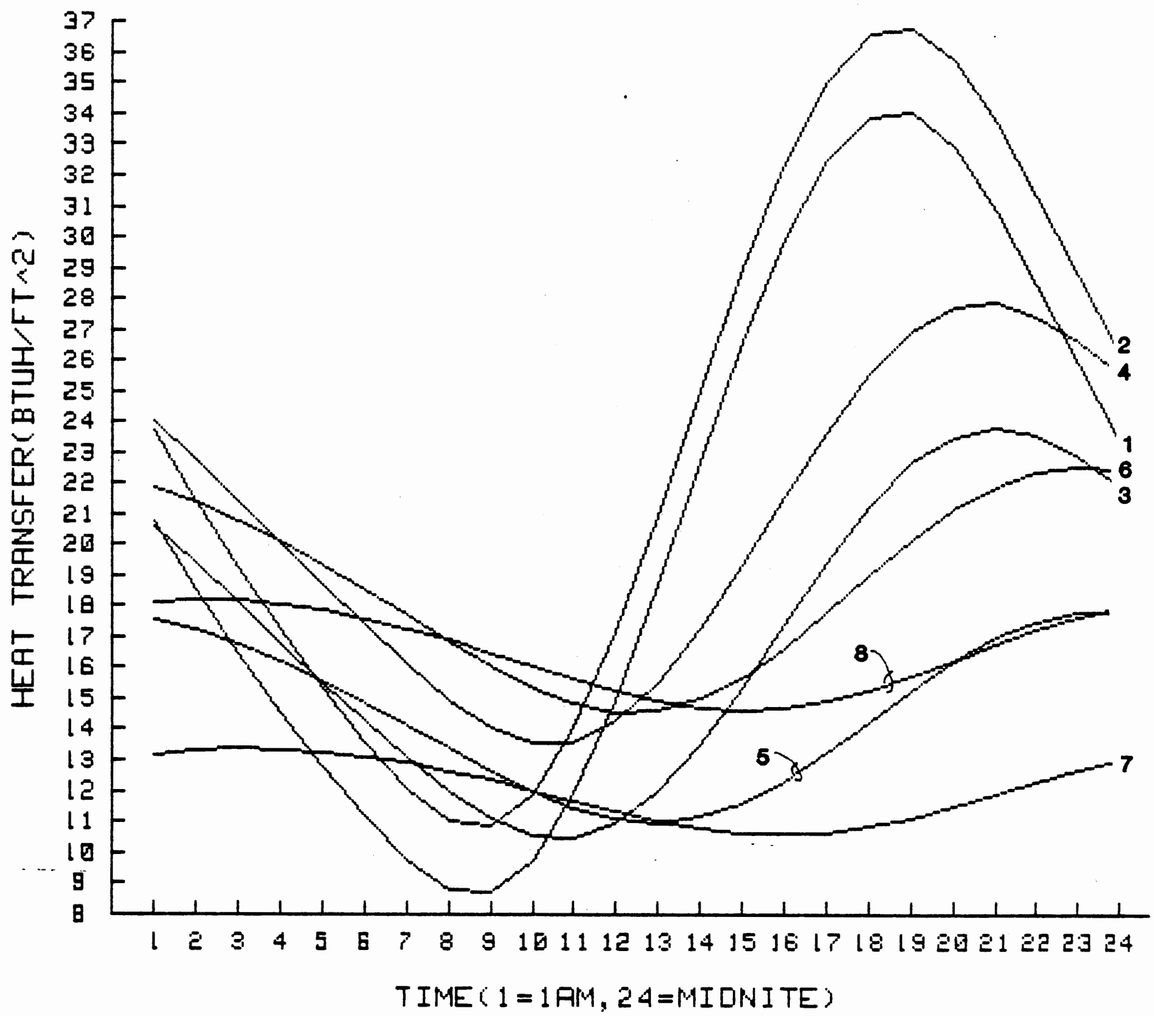
In general, the saturated soil condition for all cases showed a higher rate of heat transfer than for the dry soil condition. This increase in heat transfer is generally equal throughout the day, with the times near the minimum and maximum peak heat transfer showing the largest increases, especially at the shallower depths. These effects of moisture content on heat transfer in the soil are clearly indicated by the shifting of the heat transfer curves up or down. These shifts simply reflect changes in



INPUT DATA
VALUES FOR VARIED DATA

1 ROOF R-VALUE	=	2.8	HR-FT^2-F/BTU
2 ROOF R-VALUE	=	2.5	HR-FT^2-F/BTU
3 ROOF R-VALUE	=	3.4	HR-FT^2-F/BTU
4 ROOF R-VALUE	=	2.8	HR-FT^2-F/BTU
5 ROOF R-VALUE	=	3.98	HR-FT^2-F/BTU
6 ROOF R-VALUE	=	3.08	HR-FT^2-F/BTU
7 ROOF R-VALUE	=	4.78	HR-FT^2-F/BTU
8 ROOF R-VALUE	=	3.48	HR-FT^2-F/BTU
1 DEPTH	=	3	INCHES
2 DEPTH	=	3	INCHES
3 DEPTH	=	6	INCHES
4 DEPTH	=	6	INCHES
5 DEPTH	=	9	INCHES
6 DEPTH	=	9	INCHES
7 DEPTH	=	13	INCHES
8 DEPTH	=	13	INCHES

Figure 26. Diurnal Heat Transfer for Several Depths and Moisture Contents--January



INPUT DATA
VALUES FOR VARIED DATA

1 ROOF R-VALUE	=	2.8	HR-FT^2-F/BTU
2 ROOF R-VALUE	=	2.5	HR-FT^2-F/BTU
3 ROOF R-VALUE	=	3.4	HR-FT^2-F/BTU
4 ROOF R-VALUE	=	2.8	HR-FT^2-F/BTU
5 ROOF R-VALUE	=	3.98	HR-FT^2-F/BTU
6 ROOF R-VALUE	=	3.08	HR-FT^2-F/BTU
7 ROOF R-VALUE	=	4.78	HR-FT^2-F/BTU
8 ROOF R-VALUE	=	3.48	HR-FT^2-F/BTU
1 DEPTH	=	3	INCHES
2 DEPTH	=	3	INCHES
3 DEPTH	=	6	INCHES
4 DEPTH	=	6	INCHES
5 DEPTH	=	9	INCHES
6 DEPTH	=	9	INCHES
7 DEPTH	=	13	INCHES
8 DEPTH	=	13	INCHES

Figure 27. Diurnal Heat Transfer for Several Depths and Moisture Contents--July

the magnitude of rate of heat transfer due to changes in the soil's thermal resistance. Other alterations of the curve's shape that would indicate changes in the soil's diurnal mass effects such as time lag and peak load dampening are not evident or are very small. Reference Figures 26 and 27.

For both months, the actual increase in heat transfer due to increased moisture content at the times of peak load, increases with depth. This increase in heat transfer is most drastic at shallow depths near 3 inches, but begins to stabilize at depths of near 9 inches. For a 3 inch soil depth, the increase in heat transfer from a dry to a saturated soil is only approximately 6 to 7%. This increases to 13 to 15% at 6 inches; 20 to 21% at 9 inches; and 25% at 13 inches.

Increased mass effects would be expected, because of added mass (moisture) to the roof system. There is slight evidence of a fractional increase in time lag, but this change in time lag must be due only to the increase in specific heat and thermal conductivity, because the soil density is equal for both moisture contents.

There are larger reductions in diurnal heat transfer amplitude between soil depths for the dry soil than for the saturated soil. For a dry soil in January, there is a 67% reduction in peak load due to an increase in soil depth from 3 to 13 inches. For the same increase in soil depth with a saturated soil, the reduction in peak load is 57%.

Similar results are evident for July with a difference of 10% between peak load reductions for a dry and saturated soil. The rate of heat transfer increases with moisture content. This increase in rate of transfer reduces the mass effects that would be expected with added mass. Increase in heat transfer due to moisture content increases dramatically with depth and remains relatively constant throughout the day at a given soil depth.

Based upon the analysis of soil moisture content, a recommendation to maintain a dry soil condition year-round to reduce heat loss and gain should be made. Consideration must be given to heat rejection of a wet soil or surface topping due to evaporation. The benefit of this heat rejection at the surface due to evaporation could, particularly in the summer months, be of much greater benefit than a small percentage reduction of heat transfer due to a dry soil. Although evaporation is not rationally analyzed in this thesis, it is intended to be subjectively considered and factored into the coupling coefficient, as defined in Chapter IV.

Roof System Parameters

An analysis of the influence of insulation as part of the earth covered roof system was attempted. This study involved placing a layer of low density R-15 insulation between the soil and structural concrete layer (density =

2.0 lb/ft^3; specific heat = 0.2 Btu/lb-^{o}F; thermal conductivity = 0.25 Btu/hr-ft-^{o}F).

Comparison of diurnal heat transfer through the roof system with and without the insulation layer indicates the insulated roof to have greatly increased mass properties. The expected result is that the insulated roof would have reduced heat transfer with no mass effects. The result, however, does not meet this expectation; and it is concluded that this is an incorrect response. The TFC method equated this low thermal conductivity to mass. A brief investigation failed to discover the specific problem, and it is recommended that this be investigated if this model is to be used or further developed at a later date.

Surface Parameters

Surface conditions are modeled in terms of how several variables that characterize each surface condition affect sol-air temperature. Surface conditions that reduce sol-air temperatures reduce heat gain or increase heat loss and vice-versa. Variables used to directly calculate sol-air temperature are absorption and emittance. Generally, decreasing absorption and/or increasing emittance reduces the sol-air temperature.

Equations 18 and 19 in Chapter IV are used to calculate overall absorption and emittance coefficients. Each equation has two terms: one representing the surface topping and the other representing the soil surface. The shading coefficient, represented in both equations, quantifies the proportion of soil surface shaded and not shaded. The coupling factor represents the influences of heat exchange modes other than radiation and convection; i.e., conduction from topping to soil, transpiration and evaporation. For example, a tree provides a high shading coefficient, but a small coupling factor due to the negligible effects of transpiration or conduction with respect to the soil.

The analysis of surface parameters is in three parts. The first two studies are of bare soil, where the soil shading coefficient, absorption and emittance are varied. The third part contains studies of different soil toppings and how their thermal characteristics modify sol-air temperature at the soil surface.

Shading Coefficient. Bracketed values of shading coefficient are used to represent the range of potential shading of an earth covered roof system--no matter what the source. This study is intended to show the fundamental and extreme effects shading has on heat transfer through an earth covered roof.

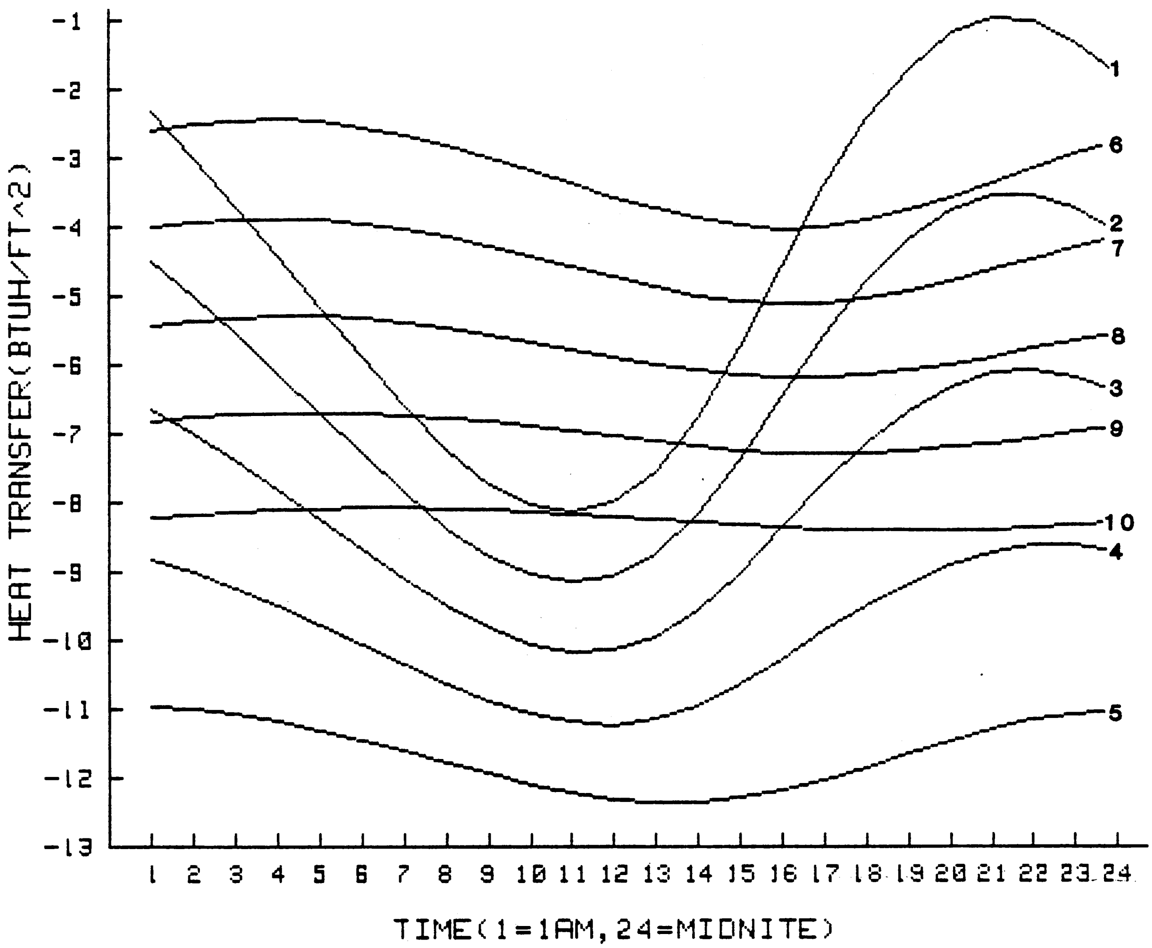
The reference radiation condition is used, and soil depths of 3 inches, 6 inches, 9 inches and 13 inches are studied during the peak load months of July and January.

Reference Tables XI and XII for the constant data for this study. Figures 28 and 29 illustrate the heat transfer for each depth at shading coefficient values of 0, 0.25, 0.50, 0.75 and 1.0.

The difference between soil surface temperature and inside surface temperature is the driving force for heat transfer. Solar radiation has a huge impact on the surface temperature (sol-air temperature). Shading the surface can be the easiest and most versatile way of altering surface temperature and, in turn, heat transfer.

For a given soil depth, the heat transfer curves flatten and shift down in magnitude with increased shading. The amplitude reduction illustrates the change in the temperature difference across the roof system. As the surface shading is increased, the sol-air temperature is reduced and, in turn, the overall heat transfer is reduced.

The peak heat gain in July is reduced by approximately 4.5% for every 5% incremental increase in the shading coefficient. This reduction is the same for all depths studied and equates to an overall reduction in heat gain from 0% shading to 100% shading of 91%. Since the percent reduction is constant for all depths, the shallower the soil depth, the larger the actual reduction. The 3 inch soil depth has a reduction of heat gain of approximately 1.5 Btu/hr-ft^2 for every incremental 5% increase in the shading coefficient. This reduction falls to 0.61 Btu/hr-ft^2 for the 13 inch soil depth. The effect of



INPUT DATA
VALUES FOR VARIED DATA

1 SHADING COEFFICIENT	=	0	
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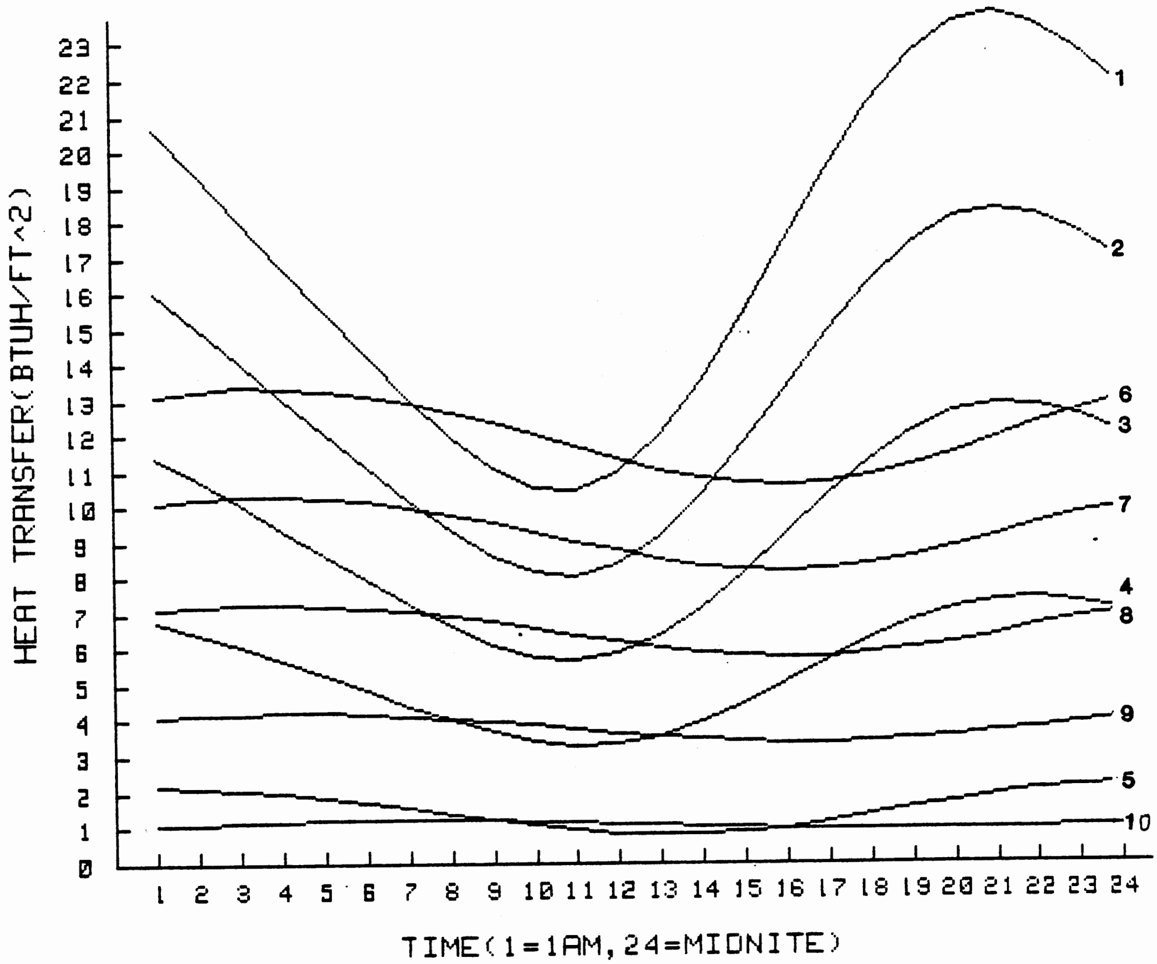
3 SHADING COEFFICIENT	=	.5	
4 SHADING COEFFICIENT	=	.75	
5 SHADING COEFFICIENT	=	1	
6 SHADING COEFFICIENT	=	0	
7 SHADING COEFFICIENT	=	.25	
8 SHADING COEFFICIENT	=	.5	
9 SHADING COEFFICIENT	=	.75	
10 SHADING COEFFICIENT	=	1	
1 DEPTH	=	6	INCHES
2 DEPTH	=	6	INCHES
3 DEPTH	=	6	INCHES
4 DEPTH	=	6	INCHES
5 DEPTH	=	6	INCHES
6 DEPTH	=	13	INCHES
7 DEPTH	=	13	INCHES
8 DEPTH	=	13	INCHES
9 DEPTH	=	13	INCHES
10 DEPTH	=	13	INCHES

Figure 28. Diurnal Heat Transfer for Various Shading Coefficients--January



INPUT DATA

VALUES FOR VARIED DATA

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6 SHADING COEFFICIENT	=	0	
7 SHADING COEFFICIENT	=	.25	
8 SHADING COEFFICIENT	=	.5	
9 SHADING COEFFICIENT	=	.75	
10 SHADING COEFFICIENT	=	1	
1 DEPTH	=	6	INCHES
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3 DEPTH	=	6	INCHES
4 DEPTH	=	6	INCHES
5 DEPTH	=	6	INCHES
6 DEPTH	=	13	INCHES
7 DEPTH	=	13	INCHES
8 DEPTH	=	13	INCHES
9 DEPTH	=	13	INCHES
10 DEPTH	=	13	INCHES

Figure 29. Diurnal Heat Transfer for Various Shading Coefficients--July

shading on heat gain (as defined above) appears to be equal for all depths.

January peak heat loss increases with shading. The increase in heat loss due to shading varies with depth. A soil depth of 3 inches has a 23% increase in heat loss for a change in shading from 0% to 100%, while a 13 inch depth has an overall increase of 52%. Using the 3 inch soil as a reference, there is an approximate 1.4% increase in heat loss for every incremental 5% reduction in shading. This amounts to about 0.85 $Btu/hr/ft^2$ per incremental 5% reduction. The increase in heat loss gets incrementally larger by approximately 0.66% for every added inch of soil. A 9 inch soil, for example, has an increase of 5.4% for every incremental 5% decrease in shading.

For both July and January, there is a consistent shift in phase in the heat transfer curves. This shift is very small at shading coefficients greater than 0.25, although it does increase as the shading coefficients approach 0.0. The largest shifts for a given depth occur in the 0.25 to 0.0 coefficient range. This shift is due to the time difference between when the maximum sol-air temperature occurs and when the maximum outdoor air temperature occurs (no radiation effects at surface or 100% shading). For example, in July the maximum sol-air temperature occurs during hour 12, while the maximum outdoor air temperature occurs three hours later in hour 15. The curves indicate that as shading increases, the significance of the sol-air temperature reduces and the significance of the outdoor air temperature increases; since the times they occur are different, the curves shift toward the time the more dominating temperature occurs. The time shift is approximately 2.5 hours for a change in shading of 0% to 100% for all depths.

It is also interesting to note that, for example, in July the minimum heat gains occur during hour 9; although the actual minimum driving temperature difference occurred earlier--in hour 5. In hour 5, the sol-air temperature should equal the outdoor temperature since there is no solar radiation. If the heat transfer were instantaneous and there were no mass effects, the heat transfer at this minimum load condition would be equal for all shading coefficients. The curves illustrate the storage effect of the soil mass by the increase in minimum heat transfer with decreased shading. This is a carry-over of heat transfer due to heat storage in the soil throughout the day, and is directly represented in Figures 28 and 29 at the time of minimum heat gain. A close comparison of the curves indicates that the increase in minimum heat gain is larger at deeper depths, reflecting the additional mass of a deeper soil cover.

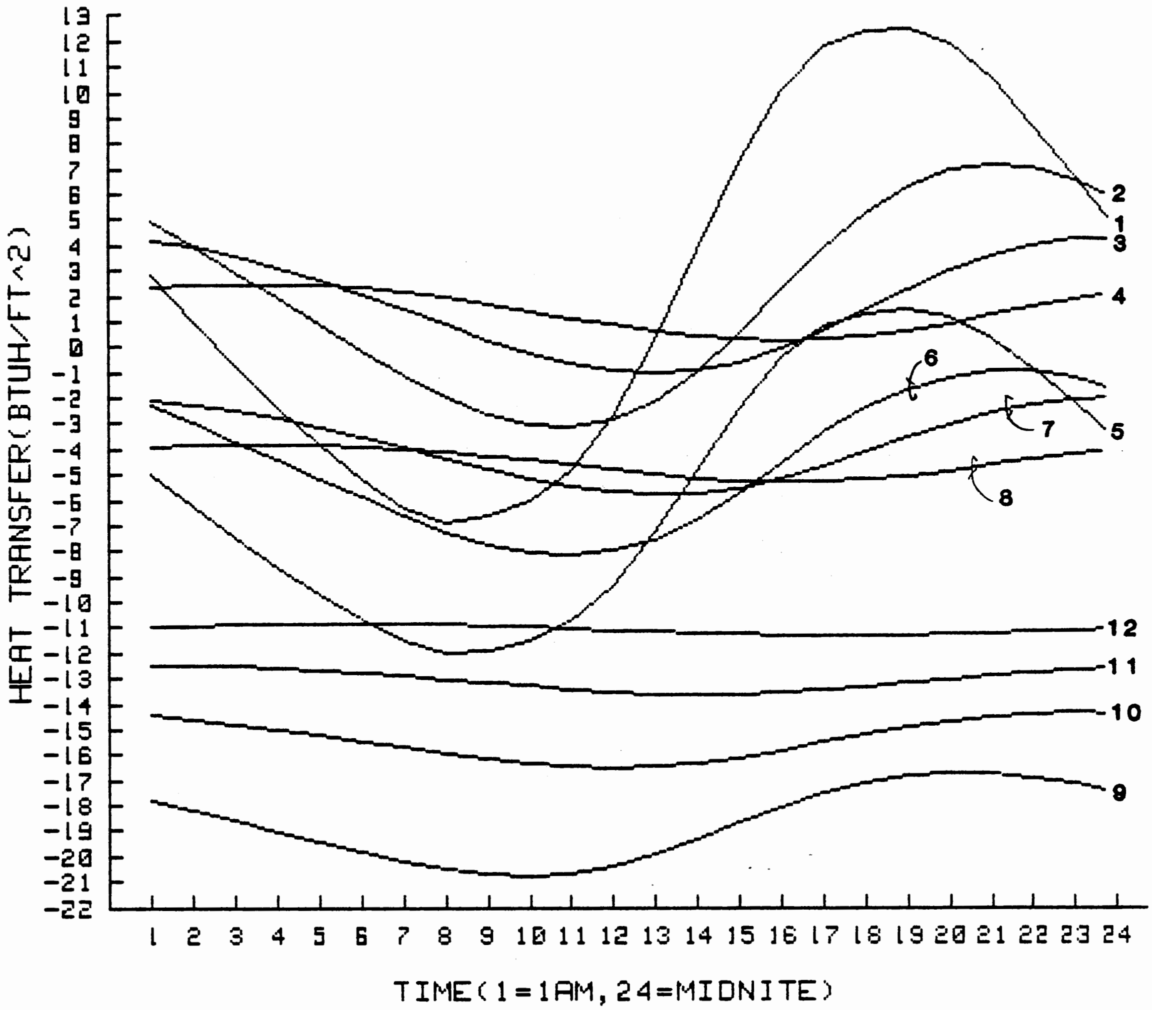
Shading an earth covered roof can greatly affect the peak diurnal heat transfer through that roof. Decreases in peak heat transfer of up to 91% in July and 52% in January are potentially possible. In addition, a small increase in apparent time lag is available for heavily shaded roofs. In July, shading is of vast benefit in reducing overall heat gain and its diurnal variance. In January, a decrease in shading is beneficial in reducing overall heat loss, although the heat loss variance under design radiation conditions throughout the day is much greater.

Absorption and Emittance. Bracketed values of absorption and emittance are used to demonstrate the fundamental effect these two variables have on sol-air temperature and, in turn, heat transfer. The bracketed values represent the limits of these variables' ranges and their corresponding heat transfer.

The practical ability to alter a soil's absorptive and emittive characteristics is questionable, but some degree of control is possible. Data regarding the absorption and emittance values for various soils and toppings are scarce and open to further study and investigation.

Reference Tables XI and XII for the fixed input for this study, and Figures 30 and 31 for the discussion that follows. Again, the study is for the reference roof system described in Figure 19.

From this point on, a change in absorption and emittance (a and e) is defined as a simultaneous incremental increase in e and an equal incremental decrease in a. The range of a and e studied is from a = 0.9 and e = 0.1 to a = 0.1 and e = 0.9 and represents the near extreme limits of these variables.



INPUT DATA
VALUES FOR VARIED DATA

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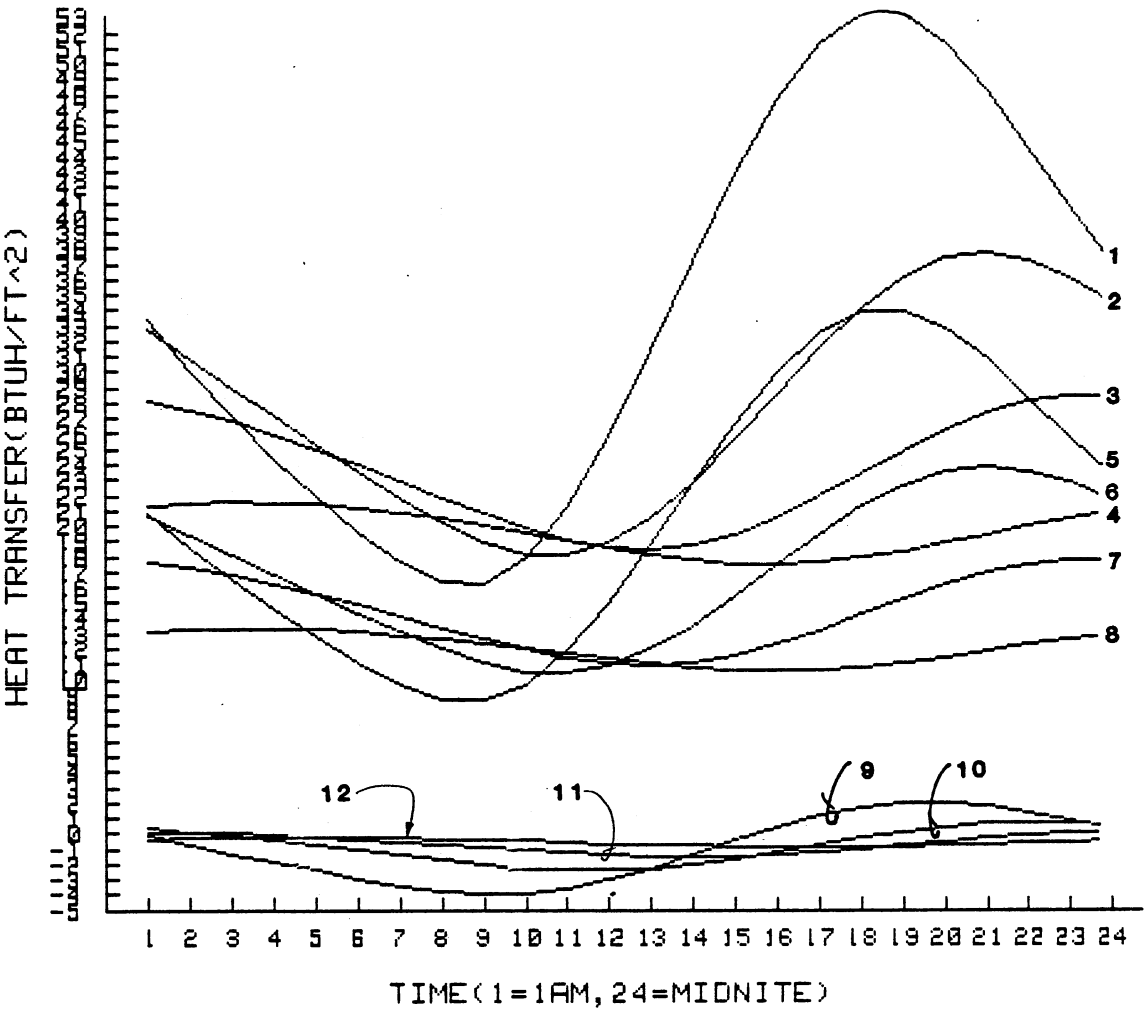
3 SOIL ABSORPTION	=	.1
4 SOIL ABSORPTION	=	.9
5 SOIL ABSORPTION	=	.6
6 SOIL ABSORPTION	=	.1
7 SOIL ABSORPTION	=	.9
8 SOIL ABSORPTION	=	.6
9 SOIL ABSORPTION	=	.1
10 SOIL ABSORPTION	=	.9
11 SOIL ABSORPTION	=	.6
12 SOIL ABSORPTION	=	.1
1 SOIL EMITTANCE	=	.1
2 SOIL EMITTANCE	=	.4
3 SOIL EMITTANCE	=	.9
4 SOIL EMITTANCE	=	.1
5 SOIL EMITTANCE	=	.4
6 SOIL EMITTANCE	=	.9
7 SOIL EMITTANCE	=	.1
8 SOIL EMITTANCE	=	.4
9 SOIL EMITTANCE	=	.9
10 SOIL EMITTANCE	=	.1
11 SOIL EMITTANCE	=	.4
12 SOIL EMITTANCE	=	.9

1 DEPTH	=	3	INCHES
2 DEPTH	=	3	INCHES
3 DEPTH	=	3	INCHES
4 DEPTH	=	6	INCHES
5 DEPTH	=	6	INCHES
6 DEPTH	=	6	INCHES
7 DEPTH	=	9	INCHES
8 DEPTH	=	9	INCHES
9 DEPTH	=	9	INCHES
10 DEPTH	=	13	INCHES
11 DEPTH	=	13	INCHES
12 DEPTH	=	13	INCHES

Figure 30. Diurnal Heat Transfer for Various Absorption and Emittance Coefficients--January



INPUT DATA
VALUES FOR VARIED DATA

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3 SOIL ABSORPTION	=	.1
4 SOIL ABSORPTION	=	.9
5 SOIL ABSORPTION	=	.6
6 SOIL ABSORPTION	=	.1
7 SOIL ABSORPTION	=	.9
8 SOIL ABSORPTION	=	.6
9 SOIL ABSORPTION	=	.1
10 SOIL ABSORPTION	=	.9
11 SOIL ABSORPTION	=	.6
12 SOIL ABSORPTION	=	.1
1 SOIL EMITTANCE	=	.1
2 SOIL EMITTANCE	=	.4
3 SOIL EMITTANCE	=	.9
4 SOIL EMITTANCE	=	.1
5 SOIL EMITTANCE	=	.4
6 SOIL EMITTANCE	=	.9
7 SOIL EMITTANCE	=	.1
8 SOIL EMITTANCE	=	.4
9 SOIL EMITTANCE	=	.9
10 SOIL EMITTANCE	=	.1
11 SOIL EMITTANCE	=	.4
12 SOIL EMITTANCE	=	.9

1 DEPTH	=	3	INCHES
2 DEPTH	=	3	INCHES
3 DEPTH	=	3	INCHES
4 DEPTH	=	6	INCHES
5 DEPTH	=	6	INCHES
6 DEPTH	=	6	INCHES
7 DEPTH	=	9	INCHES
8 DEPTH	=	9	INCHES
9 DEPTH	=	9	INCHES
10 DEPTH	=	13	INCHES
11 DEPTH	=	13	INCHES
12 DEPTH	=	13	INCHES

Figure 31. Diurnal Heat Transfer for Various Absorption and Emittance Coefficients--July

Changes in diurnal heat transfer amplitude due to changes in a and e were relatively equal for the depths of 3 inches, 6 inches, 9 inches and 13 inches. This is true for both January and July. In July, the overall amplitude or range of heat gain throughout the day is reduced approximately 11% for every 10% incremental change in the absorption and emittance. An overall reduction in amplitude of 84% occurred between the extreme values of a and e. January has slightly lower reductions of amplitude, with an overall reduction of 78% between extreme a and e values and approximately 10% for each 10% change in a and e. The amplitude reduces due to the reduced sol-air temperature at the surface and, in turn, the reduced temperature difference across the roof system.

Increases in peak load with changes in a and e seemed to increase with soil depth for January. This increase was consistent throughout soil depths of 3 inches to 13 inches. At 3 inches, the peak load is increased 68% between extreme values of a and e, or about 8% for every incremental change of 10% in a and e. This rises to 100% at 13 inches or 12.5% for every 10% change in the absorption and emittance. During July, the overall reduction of peak heat gain is relatively constant at 96 to 100% or 12% per 10% change in a and e.

At specific values of and e, the change in peak load varies with depth. For January, the peak heat loss is reduced an average of 18 to 24% per inch of soil at a = 0.9 and e = 0.1. This decreased to 5 to 7% at a = 0.1 and e = 0.9.

The wavelength does not change appreciably with changes in absorption and emittance. All values are within 5% of each other, and there does not seem to be a pattern.

There is a phase shift, noticeable at the peak diurnal heat transfer for both January and July. The shift is approximately 1 hour. This is due to the high emittance and low absorption and represents the shift toward the time the design outdoor air temperature occurs. The greatest shift occurs between a = 0.6 and e = 0.4 and a = 0.1 and e = 0.9. A smaller percentage of solar radiation is being absorbed and a larger percentage is being released. This reduces the importance of solar radiation and the time it occurs. Since the time of the sol-air peak in radiation is earlier than the peak outdoor air temperature, the curve shifts toward the time of the peak outdoor air temperature.

The effective absorption and emittance for the roof system has similar effects of heat transfer than does the shading coefficient. This is because they all directly affect sol-air temperature. As the percentage of solar radiation the roof system absorbs is reduced, and the percentage of energy released by the roof system is increased, the peak heat loss in January increases and peak heat gain in July decreases. The diurnal heat transfer also has a reduced range due to the lowered temperature difference across the roof.

<u>Surface Toppings</u>

Six surface toppings (asphalt, dry short grass, wet/tall grass, vines, bushes and trees) are modeled to illustrate their relative effects on heat transfer. The reference earth covered roof system with 6 inches of soil is used. Each topping is modeled in terms of its absorption, emittance, shading coefficient, and coupling factor. The values for these parameters are found in Table XIV.

Soil absorption and emittance are not varied and equal the effective absorption and emittance for the reference radiation condition. In this way, the surface topping will modify the reference radiation condition to characterize the topping's effect on heat transfer. Values for topping absorption and emittance are based upon Tables VIII and IX in Chapter IV, as well as consideration of relative foliage surface area exposed to radiation and foliage densities.

It is assumed that the roof surface has 100% coverage of the topping. Shading coefficients differ due to varying foliage densities. The coupling factor represents the topping's impact on soil surface cooling and/or heating. An example of this is the difference in coupling factors for dry and wet grass. The wet grass contributes less to soil heating due to the cooling effects of transpiration and evaporation; thus, a smaller coupling factor relative to a dry grass. A tree does little more than shade the soil surface and has a minute coupling factor; asphalt has a very high coupling factor.

Table XIV gives the remaining data held constant for this study, and Figures 32 and 33 illustrate the diurnal heat transfer for January and July and each topping.

TABLE XIV

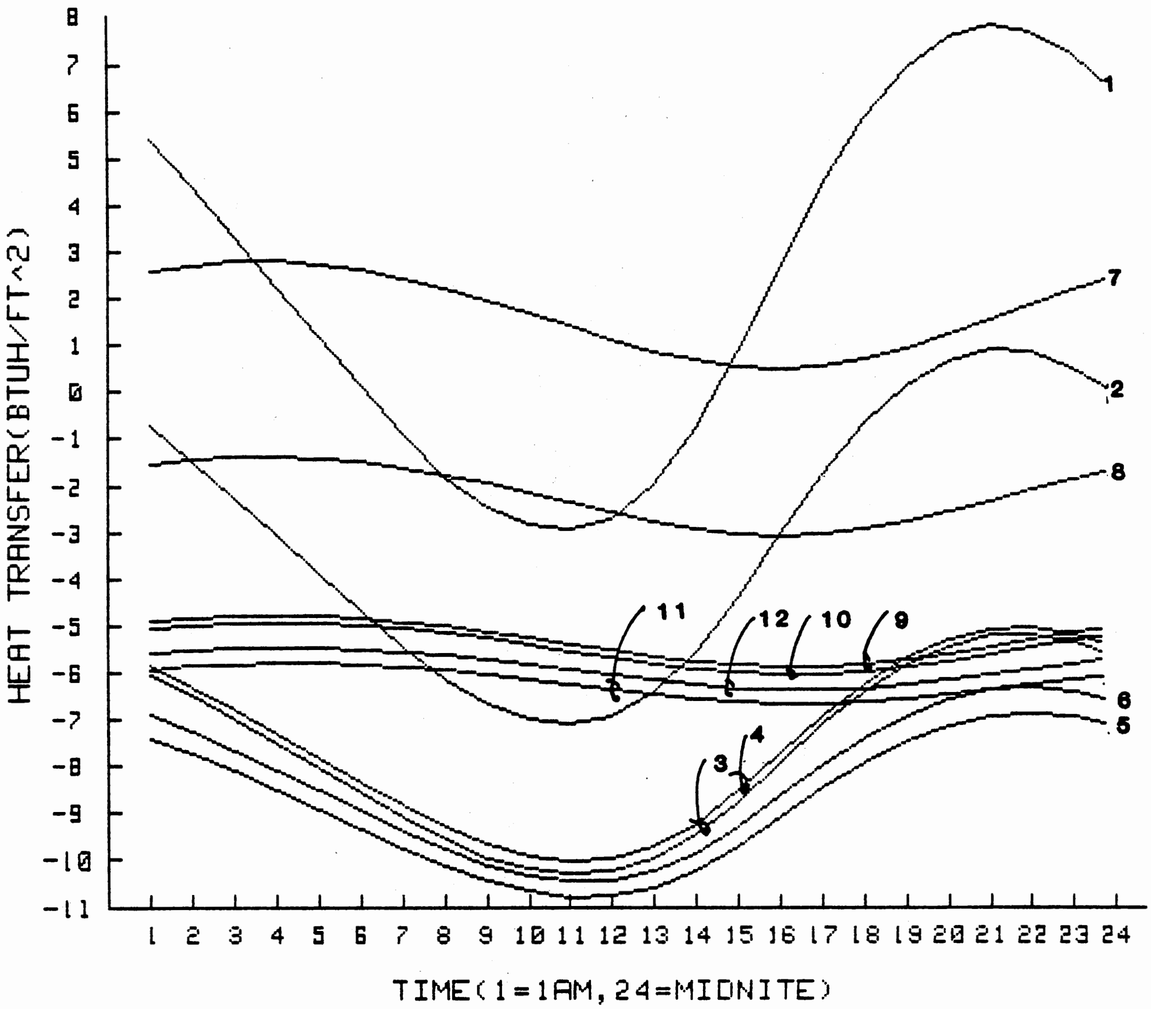
INPUT FOR SURFACE TOPPING STUDY

Surface Topping	a_c	e_c	CF	SC	a_s	e_s
Bare Soil*	0.00	0.00	0.00	0.00	0.6	0.4
Asphalt	0.95	0.15	0.99	1.00	0.6	0.4
Dry Tight Grass	0.85	0.35	0.80	0.90	0.6	0.4
Wet Tall Grass	0.75	0.40	0.50	0.90	0.6	0.4
Vines	0.65	0.30	0.45	0.70	0.6	0.4
Bush	0.55	0.20	0.20	0.65	0.6	0.4
Evergreen Tree	0.45	0.10	0.01	0.50	0.6	0.4

a_c = surface cover absorption; e_c = surface cover emittance; CF = coupling factor, SC = shading coefficient; a_s = soil absorption; e_s = soil emittance

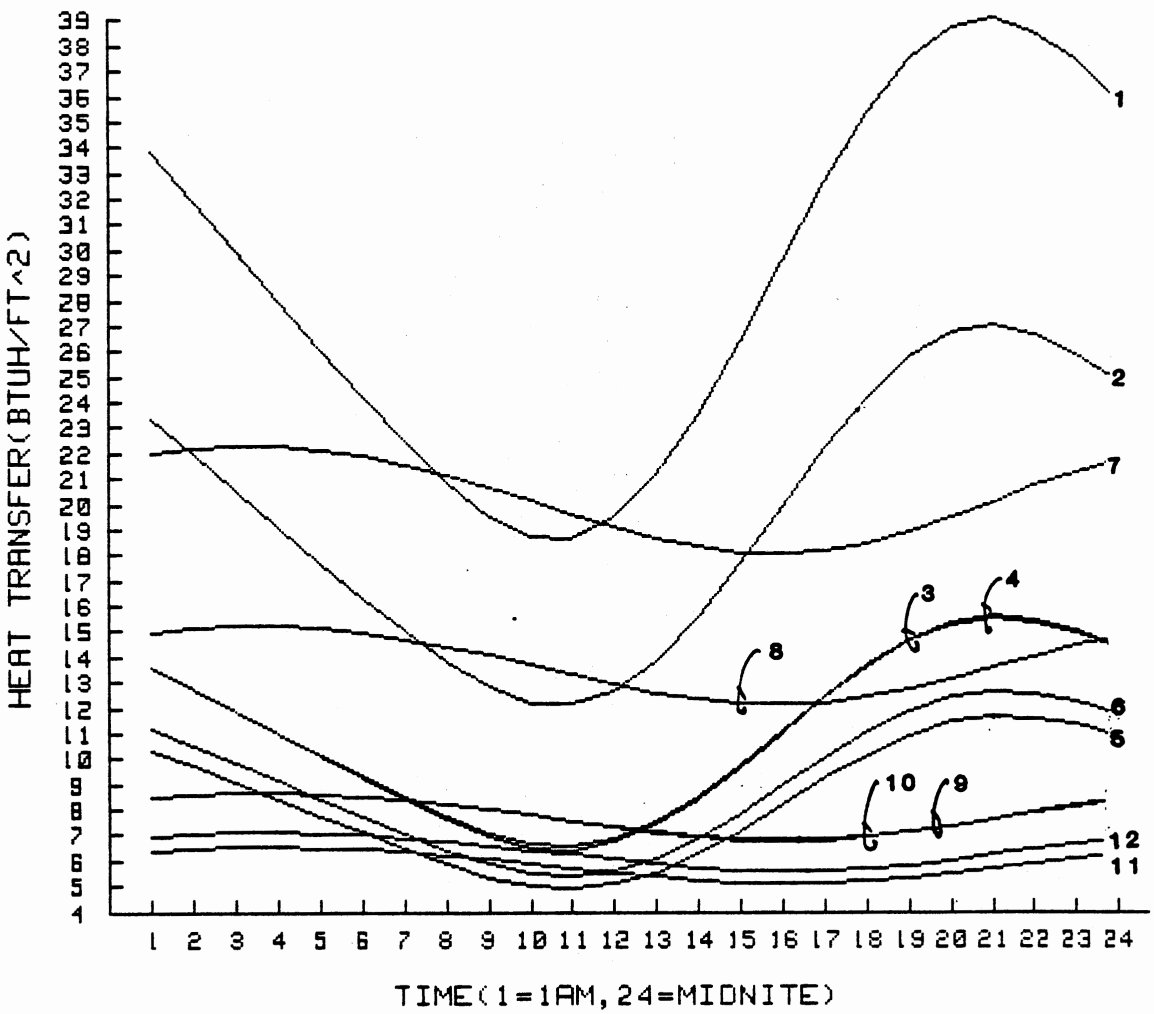
* Bare soil is the reference surface condition

For both January and July, there are three groups of diurnal heat transfer curves. The first group is asphalt and dry short grass. In July, these toppings increase the



1	Asphalt	-	6 inches
2	Dry short grass	-	6 inches
3	Wet tall grass	-	6 inches
4	Vines	-	6 inches
5	Bushes	-	6 inches
6	Evergreen trees	-	6 inches
7	Asphalt	-	13 inches
8	Dry short grass	-	13 inches
9	Wet tall grass	-	13 inches
10	Vines	-	13 inches
11	Bushes	-	13 inches
12	Evergreen trees	-	13 inches

Figure 32. Diurnal Heat Transfer for Various Soil Toppings--January



1	Asphalt	-	6 inches
2	Dry short grass	-	6 inches
3	Wet tall grass	-	6 inches
4	Vines	-	6 inches
5	Bushes	-	6 inches
6	Evergreen trees	-	6 inches
7	Asphalt	-	13 inches
8	Dry short grass	-	13 inches
9	Wet tall grass	-	13 inches
10	Vines	-	13 inches
11	Bushes	-	13 inches
12	Evergreen trees	-	13 inches

Figure 33. Diurnal Heat Transfer for Various Soil Toppings--July

heat gain through the roof system in terms of peak heat gain and diurnal range of heat gain (amplitude). Asphalt increases the amplitude and peak heat gain by approximately 40% over the bare soil condition. Dry grass shows increases of less than 12%, January shows a 33% increase in amplitude and 63% decrease in peak heat loss for asphalt over a bare soil, and approximately a 12% increase in peak heat loss and 12% increase in amplitude for dry grass (both of which improve winter performance). Asphalt and dry grass effectively raise the sol-air temperature at the roof surface primarily due to topping's absorption and lower emittance and high coupling factors.

The second group is for wet, tall grass and vine cover. These toppings show nearly equal thermal performance with a 35% decrease in peak heat gain and 40% decrease in amplitude over a bare soil condition. Peak heat gain for the third group, bushes and trees, is reduced 48% and 50%, respectively, for July relative to a bare surface. Amplitude is reduced 46%. For January, the second and third groups are relatively close together with a bush roof cover showing a 92% increase (the largest) in peak heat loss relative to a bare soil. Trees, wet grass and vine cover show smaller percentage increases in heat loss. Vine cover shows the smallest increase at 20% overall. Amplitude reductions for these toppings range from 40% for vine cover to 44% for bush cover.

The topping that appears to work best for both January and July is grass, due to its seasonal variations. In the summer, the grass could be kept moist and tall to reduce heat gain; while in the winter, it could be kept short and dry to reduce heat loss. Although this study considers evergreen trees, a decidious tree cover would also work well in both seasons. The tree's summer performance would be as shown in Figure 33. In the winter, the shading coefficient would be greatly reduced, thus warming the surface and improving winter performance.

The accuracy of this method of surface topping modeling is limited to the accuracy of the characterizing parameters. Of these parameters, the coupling factor is the most subjective. In order to improve the accuracy of this factor, a more detailed analysis is recommended to study a topping's heat exchange relationship to the soil and air.

Heat Transfer Estimating Guidelines

Based upon the previous studies, several guidelines have been formulated to help in estimating heat transfer through an earth covered roof. These guidelines are accurate only under the conditions of the studies presented in this thesis, and their use under any other conditions should be carefully evaluated.

Generally, the conditions on which the estimation guidelines are based confine their use to the roof construction described in Chapter IV and to locales near 36^{o} north latitude during January and July. In addition, the surface condition must be characterized by an effective absorption of 0.6, an effective emittance of 0.4 and a surface convection coefficient of 1.0 hr-ft^2-^{o}F/Btu. Any surface condition can be used as long as the effective values for absorption and emittance are equal to those just given.

The first step in estimating heat flow through an earth covered roof system similar to the one described in Figure 19, Chapter V, is to calculate the instantaneous heat transfer using equation 20:

$$q = \frac{T_o - T_i}{R} \tag{20}$$

where:

q = Heat flux per unit area (Btu/hr-ft^2)

T_o = Peak sol-air temperature near roof surface (^{o}F)

T_i = Indoor air temperature (^{o}F)

R = Thermal resistance of roof (^{o}F-ft^2-hr/Btu)

The thermal resistance in Equation 20 should represent the overall thermal resistance of the roof system, including any insulation. Equation 20 will give the peak instantaneous heat flux for January or July. This instantaneous heat flux occurs at the same time the sol-air temperature occurs. By applying a storage load factor and storage time factor to this instantaneous load and the hour it occurs, the resulting peak heat transfer and the time it occurs for an earth covered roof can be estimated. The storage load factors and storage time factors are tabulated in Table XVII. The storage load factors were calculated based upon the ratio of heat transfer as calculated by the TFC method for a specific soil depth and moisture content to the heat transfer calculated by Equation 20. The thermal resistance for both the instantaneous and the TFC heat transfer calculations are equal. Equation 21 illustrates this relationship:

$$S_l = q_s/q_i \tag{21}$$

where:

S_l = Storage load factor

q_s = Delayed peak heat flux per unit area (Btu/hr-ft^2)

q_i = Instantaneous peak heat flux per unit area (Btu/hr-ft^2)

The storage load factor represents the peak load reduction due only to the mass of the earth covered roof system. The storage time factors were calculated based upon the ratio of the hour at which the delayed peak heat flux occurs to the time at which the instantaneous peak heat flux occurs. Equation 22 represents this relationship:

$$S_t = t_s/t_i \tag{22}$$

where:

S_t = Storage time factor

t_s = Hour in which q_s occurs (solar time)

t_i = Hour in which q_i occurs (solar time)

The storage time factor represents the time lag due only to the mass of the roof system.

Instantaneous loads were calculated using Equation 20 and were based upon the same thermal resistances used in the TFC methodology to calculate q_s. The time in which q_s occurs was based upon the previous heat transfer studies. Times the peak instantaneous heat flux occur are based upon Table VI in Chapter IV for peak outdoor air temperatures. Peak sol-air temperatures on an unshaded horizontal surface occur in hour 12.

Equation 23 is used to estimate the peak delayed heat transfer due to mass. The appropriate storage load factor is selected from Table XV, based upon the soil depth, soil moisture content and season.

$$q_e = q_i(S_L) \qquad (23)$$

where:

q_e = Estimated delayed heat flux per unit area (Btu/hr-ft^2)

Equation 23 estimates the heat flux through an earth covered roof given the appropriate storage load factor and the instantaneous load for the roof system being investigated. If the roof system being studied has insulation of low mass relative to the entire roof, its effect can be estimated by including the insulation's thermal resistance in the R-value used in Equation 20 to calculate instantaneous heat transfer.

TABLE XV

STORAGE FACTORS[1]

Soil Depth (Inches)		July S_L	July S_t	January S_L	January S_t
3	Dry[2]	0.51	1.57	0.59	3.80
	Wet[3]	0.49	1.57	0.56	3.80
6	Dry	0.43	1.75	0.49	4.24
	Wet	0.42	1.75	0.47	4.24
9	Dry	0.38	1.96	0.40	4.80
	Wet	0.37	1.96	0.39	4.80
13	Dry	0.34	2.25	0.36	5.60
	Wet	0.34	2.25	0.33	5.60
18	Dry	0.32	2.67	0.28	6.40
	Wet	0.32	2.67	0.28	6.40

Factor

[1] at a = 0.6 and e = 0.4
[2] dry soil, MC = 7%
[3] wet soil, saturated at MC = 28%

Equation 24 is used to estimate the time at which the delayed peak load occurs:

$$t_a = t_i(S_t) \tag{24}$$

where:

t_a = Estimated time of delayed peak load (solar time)

Once the peak delayed heat transfer is found, it can be adjusted for increased or decreased shading, absorption, emittance, moisture content, and soil depth. In Table XVI, peak load variance factors are tabulated based upon the analysis and discussion of these parameters in Chapter V. Equation 25 should be used to estimate the new peak load due to changes in these variables:

$$q_n = q_e(1+iV) \tag{25}$$

where:

q_n = New delayed peak load per unit area (Btu/hr-ft^2)

i = Number of incremental unit changes (i.e., 5 added inches of soil depth)

V = Variance factor from Table XVI

Equation 25 estimates the heat transfer for an earth covered roof system after changes in soil depth, shading, absorption or emittance. The variance factors in Table XVI are based upon incremental changes in each variable as defined in the table. For example, if 3 inches of soil were added to a roof with 8 inches of existing soil, what

TABLE XVI

VARIANCE FACTORS

Initial Soil Depth (Inches)	Per Added Inch of Soil			
	Dry[1]		Wet[2]	
	July	January	July	January
3-6	-0.100	-0.108	-0.080	-0.090
7-9	-0.800	-0.087	-0.060	-0.073
10-13	-0.061	-0.065	-0.050	-0.058
14-18	-0.046	-0.051	--	--
Average	-0.068	-0.073	-0.067	-0.078

	Per 5% Shading Increase		Per 10% Change Absorption and Emittance	
	July	January	July	January
3	-0.046	+0.015	-0.120	+0.085
6	-0.046	+0.026	-0.123	+0.102
9	-0.046	+0.040	-0.125	+0.115
13	-0.046	+0.055	-0.126	+0.125
Average	-0.046	+0.034	-0.124	+0.107

1 Dry soil has a moisture content of 7%
2 Wet soil has a moisture content of 28% (saturated)
3 Change is defined as a simultaneous incremental increase in emittance and an equal decrease in absorption

would be the effect on peak heat gain, in July, for a dry soil? From Table XVI, a variance factor of -0.08 per inch of added soil is found. This factor is multiplied by the number of inches added to the soil and then added to 1.0. This number is then multiplied by the heat flux for the initial roof condition to give the heat flux for the roof with the added soil.

By use of these equations, storage factors, and variance factors, the peak heat transfer for January and July can be estimated for a variety of depths, shading coefficients, effective absorptions and emittances, and moisture contents based upon a simple steady state equation.

Systems Integration

The thermal performance of earth covered roofs varies widely based upon variable environmental conditions and roof characteristics. The variables influencing heat transfer can be controlled or modified in order to better integrate the roof's thermal performance with the building's air-conditioning systems--whether passive or mechanical.

It must be noted that the following discussion is based upon the roof's thermal performance independent of any other sources of heat gain or loss, and the actual integration of an air-conditioning system should consider the structure as a whole. Although for structures that are substantially earth sheltered, the roof will be the surface having the greatest unit magnitude of heat transfer.

The most significant variations in diurnal heat transfer are changes in the range of maximum and minimum heat transfer (amplitude), changes in peak load, shifting of the times at which peak loads occur (phase), and changes in the period between maximum and minimum heat transfer (wavelength). Each of these variations is controlled in varying degrees by the parameters studied earlier. By studying the type of air-conditioning system, the type of load variations available and the degree of control of the load variations via the parameters characterizing the roof system components, a successful integration of all can be achieved. An example of this is represented in Table XVII.

Each passive and mechanical system or aspect performs within a time slot and should be matched with the maximum load of the roof. For example, off-peak utility energy is available during non-working hours to reduce utility electric bills by simply designing the roof system to delay the peak loads to night hours. Daylighting and direct solar gain are available during sunlight hours. Daylighting was included because, under the right conditions, solar radiation can supply both solar heating and daylighting. Natural ventilation can be used to offset peak cooling loads during nighttime hours when the air temperature is reduced. The schedules of an unoccupied structure can be

TABLE XVII

ROOF AND CONDITIONING SYSTEM CORRELATION[4]

Strategy	With Shade (100%)					Without Shade				
	Soil Depth (Inches)									
	3	6	9	13	18	3	6	9	13	18
Natural Ventilation	C[1]	C	C	C	--[3]	C	C	C	C	C
Re-Radiation	C	C	C	C	--	C	C	C	C	C
Solar Gain Without Storage	H[2]	H			--		H	H	H	H
Direct Solar Gain	H	H			--	H	H	H	H	H
Daylighting					--	H	H	H	H	
Occupied Unoccupied	H	H			--	H	H	H	H	
Other Heat Source	H	H			--	H	H	H	H	H
Off Peak Utility	C	C	H,C	H,C	--	C	H	C	C	H
Equipment Size Reduction	C	C	C	C	--		H,C	H,C	H,C	H,C
Maximum Operating Efficiency	H,C	C	H,C	H,C	--			H,C	H,C	H,C

1 C = Cooling application
2 H = Heating Application
3 -- = Data not available
4 -- = Based upon diurnal heat transfer

made to coincide with peak heating or cooling loads where a temperature set-back or set-up can be used to reduce energy use. Mechanical equipment can be reduced in size and can operate at greater efficiencies as the diurnal load pattern is flattened.

The full potential of integrating a conditioning system's performance with an erath covered roof's thermal performance is much too vast to fully discuss in this thesis, but it is important to point out the advantages and potentials an earth covered roof system offers on thermal conditioning.

The thermal characteristics of the roof system can be seasonally modified by the type of ground cover and ground cover maintenance habits. A surface cover can provide varying degrees of shade cover, and this can change seasonally. Deciduous trees are a prime example of maximizing shade cover in the summer and minimizing it in the winter. The earth covered roof surface topping should be selected based upon its response to both winter and summer conditions, especially in climates where both seasons can be severe. The surface degree of changeability is also important. Grass can be cut to various heights, doesn't require water in the winter, can be grown in differing densities and colors, and offers wide flexibility. The actual thermal parameters of a surface topping to be considered are the absorption, emittance, shading, insulation value, soil moisture retention, and heat rejection qualities such as evaporation and transpiration.

A word should also be mentioned about sandy soils opposed to the clay soils analyzed. A sandy soil has a typical median density of 115 lb/ft^3 and corresponding thermal conductivities of 9 and 18 Btu/hr-ft-^oF for dry and saturated conditions, respectively. Therefore, the sandier a soil topping becomes, the higher the density and thermal conductivities become. It is expected that, due to this, sandier soils have increased mass effects such as longer diurnal time lags and greater heat storage. Further study is required to analyze the actual differences in the mass effects between clay and sandy soils and to compare the relative benefits of increased mass and increased thermal conductivity.

An earth covered roof system is of little advantage unless it is properly integrated with both the supporting structure and its passive and/or mechanical air-conditioning system. Proper integration of the earth covered roof system with other systems is of prime importance in that improper matching can destroy many of the roof's thermal advantages.

ENDNOTES

[1]E. F. Blick, "A Simple Method for Determining Heat Flow Through Earth Covered Roofs," Proc. Earth Sheltered Building Design Innovations Conf., L. L. Boyer (Ed.), Oklahoma State University, Stillwater, Oklahoma, 1981, p. III-21.

[2]American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Handbook 1981 Fundamentals, p. 25.4.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Review of Goals

The earth covered roof can often be the most critical part of the earth covered envelope. Current literature in the area of earth sheltering does not include an effective method of analyzing or designing an earth covered roof system in terms of the parameters that most affect the roof's thermal performance.

Four major goals are defined in this thesis. The first is to identify parameters that affect heat transfer in earth covered roofs and document empirical data relating to those parameters. The second goal is to formulate a method of estimating heat transfer through an earth covered roof system. The third goal is to model this methodology in an interactive and graphic computer design tool. The fourth goal is to use the methodology to formulate guidelines for designing earth covered roofs in Oklahoma.

Review of Parameters and Methodology

The parameters affecting heat transfer through earth covered roofs fall into four categories. The first includes characteristics of the roof and its construction, such as structure type, ceiling treatment, interior air film and insulation placement, and roof R-value. Soil characteristics such as depth, type, moisture content, density, thermal conductivity, and specific heat make up the second category. The third category of parameters characterizes the roof surface or topping. These variables include surface emittance and absorption, surface convection film coefficient, degree of shading of solar radiation, and evaporation or transpiration of surface moisture. The last category represents environmental variables such as solar radiation intensity, outdoor temperature, indoor temperature, daily range of temperatures, and roof location.

The methodology and computer design tool (Appendix A) allow most of the above-mentioned parameters to be varied so their effects on heat transfer can be studied. Included in the methodology are guidelines for estimating actual values for soil and surface parameters.

The use of transfer function coefficients (TFC's) allows the mass effects of the roof system to be accurately represented. The trasnfer function coefficients must be calculated independent of the computer model. Appendix B includes the job control language for "TRANSF", a program on the Oklahoma State University mainframe computer for calculating these coefficients. Transfer function coefficients are calculated based upon the thickness, thermal conductivity, specific heat, and density of each unique material layer in the roof system.

The transfer function coefficients are input into the computer model along with environmental data and parameters characterizing the roof surface. The surface topping is characterized in terms of shading coefficient, absorption, emittance, and coupling factor. The coupling factor characterizes the topping's impact on heat transfer, and is intended to subjectively consider moisture evaporation, vegetation transpiration, conduction heat transfer from topping to soil and topping to air, and any other aspects of the surface condition that affect heat transfer.

The calculated heat transfer is for a typical day of each month studied and is based on the assumption that the hourly environmental conditions characterizing this typical day remain constant for a series of three to four 24-hour periods. The method accurately calculates diurnal heat transfer and accurately models the roof's "mass effects" within that time frame. For a discussion of scope and limitations, reference Chapter II.

Summary of Analysis and Guidelines

Several variables were held constant throughout the studies and were not independently investigated. The parameters that were investigated were considered unique to earth sheltering or very significant in their effects on heat transfer. Diurnal heat transfer effects were quantified and described in three ways: amplitude (range of peak diurnal heat transfers), phase (time lag), and wavelength (time span between peak diurnal heat transfer occurrences).

Soil depth determines to a large degree the mass in an earth covered roof system; and, in turn, the roof's mass effects. Soil depth significantly affects amplitude, phase and wavelength. For both January and July, the time of peak heat transfer is delayed an average of 50 to 55 minutes for each added inch of soil. The wavelength increases from 6 to 15 minutes for each added inch of soil depending upon season and initial depth. Peak loads for both months are reduced by 10% for each added inch of soil.

The following recommendations are based upon diurnal heat transfer for the reference roof system studied and the conditions and assumptions on which the studies are based. Recommendations regarding soil depth, for example, may be quite different due to the relative diurnal and seasonal benefits of a large soil depth. Where seasonal time lag is a design criterion, soil depths much greater than 12 inches would be desired.

Based upon the reference conditions, a soil depth of 6 to 13 inches is recommended for the area of Oklahoma around Stillwater and Oklahoma City. This range is a function, primarily, of shading and season. For a heavily shaded roof during the winter, 6 inches is best; but as shading is reduced, a deeper soil becomes more attractive. In the summer, the deeper the soil, the better. A compromise would be a depth of 10 to 12 inches.

Soil moisture content has a small effect on heat transfer, relative to the other parameters. Heat transfer increases with moisture content, and this effect increases with depth. Increase in heat transfer, for July and January, from a dry to saturated soil ranges from 6% at a 3 inch soil depth to 25% at 13 inches. It is apparent that a dry soil reduces conduction heat transfer, but this may not always be true. A moist summer soil and surface topping could greatly offset the advantages of a dry soil, due to surface heat rejection caused by evaporation. Realistic variations in soil moisture content, as a method of control of heat transfer, are well within a change from dry to saturated; and expected benefits, therefore, would be small. It is recommended that a summer soil and surface topping be kept as moist as possible, while winter soil should be kept dry.

Although the studies of insulation in this thesis are of little value, the effects of insulation with low relative mass, are very predictable. Insulation reduces the magnitude of heat transfer without significantly affecting the "mass effects" of the roof system. An ideal amount of insulation for an earth covered roof system is primarily a question of "at what insulation R-value does insulation cease to be cost effective." Since the economics of this are beyond the scope of this thesis, it is sufficient to recommend an insulation of sufficient R-value to be cost effective. The method described in Chapter V for estimating heat transfer through earth covered roofs is a very good way to investigate reductions of heat flux due to insulation.

The shading of a roof surface was found to have very significant effects on heat transfer. For every 5% increase in shading coefficient, there is a corresponding 4½% average reduction of peak heat gain for July. For January, there is a 3½% increase in peak heat loss for every 5% increase in shading coefficient. It is recommended, therefore, that shade be maximized during the summer and minimized during the winter. Even though a grass cover provides a good amount of shade, a grass topping is beneficial in January due to its soil retention and insulation characteristics. Therefore, a compromise recommendation for both July and January is a grass cover with deciduous trees. By keeping the grass short and dry during the winter, shading is minimized and insulation due to the grass is maximized. During the summer, the deciduous trees provide additional shade. The grass should be kept longer than in the winter and as moist as possible.

The effective surface absorption and emittance of an earth covered roof system also has significant effects on heat transfer. For every 10% incremental increase in emittance and equal simultaneous decrease in absorption, there is an average 10% increase in peak heat loss for January and 12% decrease in peak heat gain for July.

Because there is little empirical data for absorption and emittance values for soils and natural surfaces, it is difficult to make specific recommendations. Generally for July, the higher the emittance and lower the absorption, the better; for January, the opposite is true.

Based on the individual parameter and surface topping studies, the following roof system is recommended as a compromise between winter and summer for this part of Oklahoma. The earth covered roof system should have 12 inches of soil with a layer of insulation next to the supporting structure. The soil and surface should be kept moist during the summer and dry during the winter. A dry grass kept short is best for the winter while a long, moist grass is best for July. Additional shade provided by deciduous trees is also beneficial. The absorption coefficients of the soil and topping should be as low as possible while their emittances should be as high as possible. Other roof characteristics are those defined for the reference roof. This recommendation is based entirely on the findings in this thesis and the assumptions on which they are based. This recommendation should not be applied without careful evaluation of roof system and environmental parameters.

Future Work

There are three main areas of potential future work and development regarding thermal performance of earth covered roofs and the methodology formulated in this thesis.

The first area of future work is to research and study parameters such as absorption, emittance, thermal conductivity, moisture content, surface convection coefficient, etc. so that more accurate values characterizing soils, grasses and other earth cover materials can be estimated. It is also important to understand within what range each parameter can be realistically expected to vary and the degree of control a person can be expected to have on that parameter. For example, could the surface absorption be seasonally varied from 0.1 to 0.9 in order to minimize heat loss in the winter and minimize heat gain in the summer?

The coupling factor is included in the methodology so that parameters such as evaporation can be subjectively considered. The concept of the coupling factor could be developed so that the impact a surface topping has on a roof system's thermal performance is analytically based.

The second area of future study regards the computer model. The model currently calculates heat transfer on a diurnal basis assuming continuous 24-hour periods of equal weather conditions. The model could be expanded to model a change in the weather pattern. In order to study the mass effects of an earth covered roof beyond a diurnal timeframe, the weather conditions between the conditions represented by a typical day in each month could be interpolated and heat transfer for several days or months could be calculated. By modeling the weather for extended periods, the monthly, seasonal or yearly mass effects could be estimated and studied.

The third category of future work regards applying the methodology and computer model to walls, whole building envelopes and passive storage systems. The model would have to be expanded to include vertical surfaces and to calculate the heat transfer for many surfaces or constructions. The model in this form could predict the mass effects of a rammed earth wall or entire envelope. It could be applied to any structure.

A further expansion would be to include, in the model, the algorithm for calculating transfer function coefficients. Other areas of investigation include studying the apparent anomalies of the transfer function algorithm. As previously discussed, the inclusion of an insulation layer in the earth covered roof system resulted in illogical results. In addition to this, the results for a 12 inch soil depth also made no sense; although the data for 11 inches and 13 inches did represent what would be expected. Further study to correct these anomalies is important to the future use of the method.

Conclusions

The parameters affecting heat transfer through an earth covered roof system are well defined, and their thermal performance and actual values are empirically, but not necessarily analytically, predictable. Parametric performance is even less predictable between climatic regions and for surface toppings. The methodology in this thesis attempts to analytically predict parameter effects on heat transfer and to predict actual values for these parameters. Whether the TFC model formulated is any better than other models is questionable, but it is important to say that three features of it are important.

First, the capability of the user to interact with the model in a design-oriented way is critical to its practical use. It must be easy for the user to quickly judge the relative impact that parameters have on thermal performance so that the designer can reach his design goals.

The method should also be simple enough to be sensitive to variations in the parameters of concern. Many existing large, complex models hold much of the input data constant, or values are assumed, so that study of these variables is difficult. For this reason, many models make it difficult to study relative effects of surface toppings, for example.

The third important aspect of the overall methodology is the inclusion of available data and analytical methods to estimate parameter values. Often, in other models, parameters are assumed to have a value or the value is poorly researched so it is held constant. This is not to say that variables were not held constant for those very reasons in the parameter analysis in this thesis. Use of the model to analyze earth covered roof thermal performance has resulted in design guidelines and a quick estimation procedure.

Of the identified variables affecting heat transfer, several parameters that are considered unique or important to earth covered roofs were studied. Soil depth is an important aspect of earth covered roofs, as it determines to a great extent the "mass effects" of the roof system. Since the soil depth is fixed, it is important to study the overall roof system and its desired performance before a depth is selected.

Soil moisture content and characteristics of the surface topping should be considered features of the roof system that can be, to varying degrees, seasonally controlled. The relative impact of moisture content is small. The characteristics of the surface cover, such as the shading coefficient and the coupling factor, have very significant effects on heat transfer and should be carefully considered.

The concept of earth sheltering has provided a viable means of reducing energy use. There are many factors to consider in the design of earth sheltered buildings, and the roof system could be an important part of that design. This thesis has researched, analyzed and formulated a method to aid in the understanding, design and prediction of heat transfer through earth covered roofs.

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APPENDICES

APPENDIX A

"ECROOF" LISTING

When the "ECROOF" program is loaded, press the "Run" key. After each question is answered, press the "Cont." key for the next question. Each question is self-explanatory. Be prepared to run either several data sets for a particular month or one month for several data sets.

Reference the thesis body for estimation of parameter values. The user may input new TFC sets and store them under a user-defined label or call up a previously stored TFC set which can be reviewed, modified, relabeled and/or restored. Once values for all parameters for a month or data set are input, the user has the opportunity to review all the values and change them.

Once all values have been reviewed, the calculations begin. The calculation status is presented on the CRT.

The first menu appears when calculations are complete. This menu has seven options that are self-explanatory and regard the graphic format and type of data to be displayed.

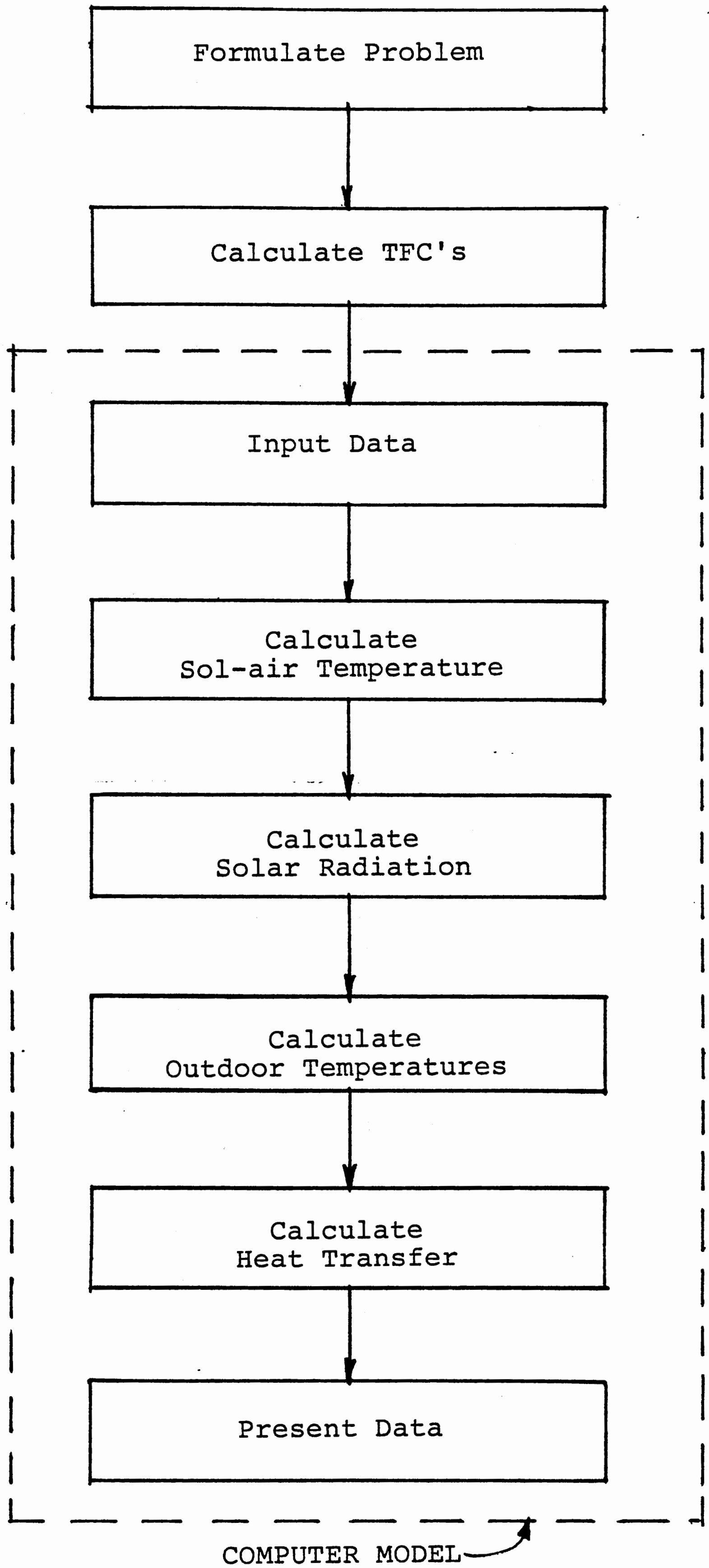
The second menu appears when the item selected from menu one is completed. These menu items identify hardcopy formats and route the user to other parts of the program. A feature included in this menu is the ability to redefine the scales of each graph so that the graphic output may be fine tuned.

Any time during the program, the process can be stopped and restarted from the beginning with all the input data intact by pressing the "Stop" key and then the "Cont." key. This allows the user to quickly re-enter data and make any changes he desires by pressing "Cont." for each unchanged question and entering the new value for each changed variable. All default values are zero.

This model calculates diurnal heat transfer for solar radiation conditions typical of the 21st day of each month and weather conditions for a typical day each month. See thesis body for further discussion. The diurnal heat transfer is calculated for the same weather and radiation conditions for several consecutive 24-hour periods until the heat transfer becomes uniform between 24-hour periods.

Heat transfer can also be calculated by Blick's method and by the instantaneous equation, found in the thesis body, for comparison purposes. These options are identified in Menu 1.

The process for the entire methodology and a listing of "ECROOF" follow.


Formulate Problem
Calculate TFC's
Input Data
Calculate
Sol-air Temperature
Calculate
Solar Radiation
Calculate
Outdoor Temperatures
Calculate
Heat Transfer
Present Data
COMPUTER MODEL

```
10 !     RE-STORE "ESROOF:T15"
20    OPTION BASE 1
30    PRINTER IS 16
40    PRINT PAGE
50    PRINT "               ****************************************************
"
60    PRINT "               *                                                  *
"
70    PRINT "               *                                                  *
"
80    PRINT "               *          THIS PROGRAM WAS RESEARCHED             *
"
90    PRINT "               *            DESIGNED AND TESTED BY                *
"
100   PRINT "               *                                                  *
"
110   PRINT "               *                  CHARLES D JONES                 *
"
120   PRINT "               *                    1/81 TO 5/83                  *
"
130   PRINT "               *                                                  *
"
140   PRINT "               *                                                  *
"
150   PRINT "               ****************************************************
"
160   PRINT LIN(6)
170   PRINT "PRESS CONT TO GO ON"
180   PAUSE
190   PRINT PAGE
200   DEG
210   DIM Month$(20)[12],Data$(1)[20],Answer$(3)[1]
220   REAL Solair(49,12),Tout(24,12),Tmax(12),Dr(12),Srise(12),Sset(12)
230   REAL Pdr(24),H(24),Sng(24,12),Dec(12),Idn(24,12),Ids(24,12),Itot(24,12)
240   REAL Bst(12),Aat(12),Cst(12),Heat(12),Id(24,12),F(13)
250   REAL B(18,13),D(18,13),Ht(48,12),Tsum(12),Htt(48,12),Aver(12)
260   REAL Lat(12),Tin(12),Abss(12),Absc(12)
270   REAL Tfa(13),Hta(13)
280   REAL Emis(12),Emic(12),Cf(12),Sc(12),Ho(12),Rroof(12),Sum(12)
290   REAL Abs(12),Emi(12),Den(13),Sh(13),Depth(13),I(13),Cond(13)
300   REAL Savb(18),Savd(18),Cns(12),C(12),Hb(48,12),Hs(48,12),Hba(13),Hst(13)
310   DATA .142,.144,.156,.180,.196,.205,.207,.201,.177,.160,.149,.142
320   MAT READ Bst
330   DATA .058,.060,.071,.097,.121,.134,.136,.122,.092,.073,.063,.057
340   MAT READ Cst
350   DATA 390,385,376,360,350,345,344,351,365,378,387,391
360   MAT READ Aat
370   DATA -20,-10.8,0,11.6,20.0,23.45,20.6,12.3,0,-10.5,-19.8,-23.45
380   MAT READ Dec
390   DATA .87,.92,.96,.99,1.0,.98,.93,.84,.71,.56,.39,.23,.11,.03,0,.03,.1,.21,
.34,.47,.58,.68,.76,.82
400   MAT READ Pdr
410   EXIT GRAPHICS
420   INPUT "ENTER JOB TITLE OR DESCRIPTION OR FIGURE TITLE(18CHAR.)",Data$
430   K=0
440   INPUT "ENTER ANY OTHER EXPLANATION YOU WISH(18CHAR)",Data1$
450   PRINT "YOU MAY RUN SEVERAL `DATA SETS´ FOR ONE MONTH OR SEVERAL"
460   PRINT "`MONTHS´ FOR ONE DATA SET"
470   INPUT "DATA SETS OR MONTHS",Z$
480   IF Z$[1,1]="D" THEN S=1
490   IF Z$[1,1]="D" THEN GOTO Data
500   DISP "HOW MANY MONTHS DO YOU WISH TO INVESTIGATE-";M;
510   INPUT M
520   DISP "WHICH MONTH TO START BY NUMBER -";Month;
530   INPUT Month
540   PRINT PAGE
550   PRINT "DO YOU WANT(1)CONSECUATIVE MONTHS(EX:1,2,3,...)"
560   PRINT "             (2)EVERY OTHER MONTH(EX:1,3,5,...)"
570   PRINT "             (3)EVERY OTHER 2 MONTHS(EX:1,4,7,...)"
580   PRINT "             (4)EVERY OTHER 3 MONTHS(EX:1,5,9,...)"
590   DISP "SELECT (1)(2)(3)OR(4)"
600   INPUT S
610   N=Month+S*M-S
620   GOTO 670
```

```
630 Data:  !
640   INPUT "WHICH MONTH DO YOU WISH TO RUN DATA SETS FOR",Dmonth
650   INPUT "HOW MANY DATA SETS DO YOU WISH TO INVESTIGATE",N
660   Month=1
670   FOR J=Month TO N STEP S
680   DISP "MONTH NAME OR DATA SET NAME FOR";J;
690   INPUT Month$(J)
700   GOTO Enviorn
710 Change:  !
720   PRINTER IS 16
730   PRINT PAGE
740   PRINT "YOU MAY CHANGE THE FOLLOWING PARAMETERS BY GROUP"
750   PRINT "***ENVIORNMENT***"
760   PRINT "LATITUDE"
770   PRINT "INDOOR DESIGN TEMP"
780   PRINT "AVERAGE MAX TEMP FOR MONTH"
790   PRINT "AVERAGE DAILY RANGE FOR MONTH"
800   PRINT LIN(1)
810   PRINT "***SURFACE***"
820   PRINT "SURFACE COVER ABSORPTION"
830   PRINT "SURFACE COVER EMITTANCE"
840   PRINT "SURFACE SHADING COEFFICIENT"
850   PRINT "COUPLING FACTOR"
860   PRINT "SURFACE CONVECTION COEFFICIENR"
870   PRINT LIN(1)
880   PRINT "***SOIL***"
890   PRINT "ROOF R-VALUE"
900   PRINT "SOIL ABSORPTION"
910   PRINT "SOIL EMITTANCE"
920   DISP "CHANGE (1)ENVIORNMENT,(2)SOIL,(3)SURFACE,(4)GO ON";
930   INPUT A
940   IF A=1 THEN Enviorn
950   IF A=2 THEN Soil
960   IF A=3 THEN Surface
970   IF A=4 THEN GOTO 1740
980 Enviorn:  !
990   DISP "ROOF LATITUDE FOR   ";Month$(J);"-";Lat(J);
1000  INPUT Lat(J)
1010  DISP "INDOOR DESIGN TEMPERATURE FOR   ";Month$(J);"-";Tin(J);
1020  INPUT Tin(J)
1030  DISP "AVERAGE MAXIMUM TEMP. FOR    ";Month$(J);"-";Tmax(J);
1040  INPUT Tmax(J)
1050  DISP "AVERAGE DAILY RANGE FOR   ";Month$(J);"-";Dr(J);
1060  INPUT Dr(J)
1070  IF A=1 THEN GOTO Change
1080 Surface: !
1090  DISP "SURFACE COVER ABSORPTION FOR   ";Month$(J);"-";Absc(J);
1100  INPUT Absc(J)
1110  DISP "SURFACE COVER EMITTANCE FOR   ";Month$(J);"-",Emic(J);
1120  INPUT Emic(J)
1130  DISP "SURFACE COVER TO SOIL COUPLING FACTOR FOR   ";Month$(J);"-",Cf(J);
1140  INPUT Cf(J)
1150  DISP "PERCENTAGE OF SOIL SHADED BY SURFACE COVER FOR   ";Month$(J);"-",Sc(
J);
1160  INPUT Sc(J)
1170  IF (Sc>1) OR (Cf>1) OR (Emic>1) OR (Emis>1) OR (Abss>1) OR (Absc>1) THEN 1
090
1180  DISP "SURFACE CONVECTION COEFFICIENT FOR   ";Month$(J);"-",Ho(J);
1190  INPUT Ho(J)
1200  IF A=3 THEN GOTO Change
1210 Soil: !
1220  K=50
1230  DISP "SOIL ABSORPTION FOR   ";Month$(J);"-",Abss(J);
1240  INPUT Abss(J)
1250  DISP "SOIL EMITTANCE FOR   ";Month$(J);"-",Emis(J);
1260  INPUT Emis(J)
1270  IF A=2 THEN GOTO Change
1280  INPUT "(1)DO YOU WISH NEW TFC SET OR(2)USE LAST ONE?",L
1290  IF L=2 THEN GOTO 1730
1300  INPUT "OLD(PREVIOUSLY STORED) OR NEW TFC DATA SET",No$
1310  IF No$[1,1]="N" THEN Xdum=1
1320  INPUT "FILE NAME",File$[1,6]
1330  IF POS(File$," ")<>0 THEN GOTO 1320
1340  ASSIGN File$&":T15" TO #1,Xdum
```

```
1350  IF (Xdum=0) AND (No$[1,1]="N") THEN GOTO 1300
1360  IF (Xdum=1) AND (No$[1,1]="O") THEN GOTO 1300
1370  IF Xdum=1 THEN CREATE File$&":T15",8,256
1380  IF Xdum=1 THEN ASSIGN File$&":T15" TO #1
1390  IF Xdum=0 THEN READ #1;Savb(*),Savd(*),Savf,Savden,Savsh,Savdep,Savi,Savco
n
1400  PRINTER IS 0
1410  IF No$[1,1]="O" THEN GOTO Decode
1420  DISP "ROOF R-VALUE FOR TFC TO BE INPUT  ";Month$(J);"-",I(J);
1430  INPUT I(J)
1440  DISP "SOIL DENSITY FOR THIS TFC SET?";Den(J);
1450  INPUT Den(J)
1460  DISP "SOIL SPECIFIC HEAT FOR THIS TFC SET?-";Sh(J);
1470  INPUT Sh(J)
1480  DISP "SOIL DEPTH IN INCHES FOR THIS TFC SET?";Depth(J);
1490  INPUT Depth(J)
1500  DISP "SOIL THERMAL CONDUCTIVITY";Cond(J);
1510  INPUT Cond(J)
1520  DISP "HOW MANY B AND D TFC'S?";F(J);
1530  INPUT F(J)
1540  FOR T=1 TO F(J)
1550  DISP "VALUE OF B";T,"(";B(T,J),")";
1560  INPUT B(T,J)
1570  DISP "VALUE OF D";T,"(";D(T,J),")";
1580  INPUT D(T,J)
1590  NEXT T
1600  INPUT "WOULD YOU LIKE TO REVIEW OR CHANGE TFC DATA",Aaaa$
1610  IF Aaaa$[1,1]="Y" THEN GOTO 1420
1620  IF No$[1,1]="O" THEN GOTO 1650
1630  INPUT "DO YOU WISH TO SAVE THIS DATA SET(UNDER FILE NAME JUST CHOSEN)",Aa$
1640  IF Aa$[1,1]="Y" THEN GOTO End
1650  INPUT "DO YOU WISH TO RE-SAVE CHANGED DATA UNDER SAME NAME OR NEW NAME",C$
1660  IF C$[1,1]="N" THEN GOTO 1730
1670  PURGE File$&":T15"
1680  INPUT "REPEAT FILE NAME OR GIVE NEW FILE NAME",File$
1690  Xdum=1
1700  CREATE File$&":T15",8,256
1710  ASSIGN File$&":T15" TO #1
1720  GOTO End
1730  GOTO Change
1740  IF (J=N) AND (L=2) THEN GOTO Equal
1750  NEXT J
1760  GOTO Solar
1770 Decode:!
1780  FOR T=1 TO Savf
1790  LET B(T,J)=Savb(T)
1800  LET D(T,J)=Savd(T)
1810  NEXT T
1820  LET Den(J)=Savden
1830  LET Sh(J)=Savsh
1840  LET Depth(J)=Savdep
1850  LET I(J)=Savi
1860  LET F(J)=Savf
1870  LET Cond(J)=Savcon
1880  GOTO 1600
1890 Equal:!
1900  FOR J=Month TO N STEP S
1910  FOR T=1 TO F(Month)
1920  LET B(T,J)=B(T,Month)
1930  LET D(T,J)=D(T,Month)
1940  NEXT T
1950  LET Den(J)=Den(Month)
1960  LET Sh(J)=Sh(Month)
1970  LET Depth(J)=Depth(Month)
1980  LET I(J)=I(Month)
1990  LET F(J)=F(Month)
2000  NEXT J
2010  GOTO Solar
2020 Solar:!
2030  IF Z$[1,1]="D" THEN Month=1
2040  PRINT PAGE
2050  PRINT "CALCULATING SOLAR FOR MONTH OR DATA SET:"
2060  FOR J=Month TO N STEP S
2070  PRINT "     ";J;
```

```
2080  IF Z$[1,1]="D" THEN Dec(J)=Dec(Dmonth)
2090  IF Z$[1,1]="D" THEN Aat(J)=Aat(Dmonth)
2100  IF Z$[1,1]="D" THEN Bst(J)=Bst(Dmonth)
2110  IF Z$[1,1]="D" THEN Cst(J)=Cst(Dmonth)
2120  Srise(J)=(ACS(-(SIN(Lat(J))*SIN(Dec(J)))/(COS(Lat(J))*COS(Dec(J))))-180)/-
15
2130  Sset(J)=(ACS(-(SIN(Lat(J))*SIN(Dec(J)))/(COS(Lat(J))*COS(Dec(J))))+180)/15
2140  FOR I=1 TO 24
2150  IF I>12 THEN GOTO 2190
2160  IF I<Srise(J) THEN GOTO 2270
2170  H(I)=15*(12-I)
2180  GOTO 2210
2190  IF I>Sset(J) THEN GOTO 2270
2200  H(I)=15*(I-12)
2210  Sng(I,J)=COS(Lat(J))*COS(Dec(J))*COS(H(I))+SIN(Lat(J))*SIN(Dec(J))
2220  IF Sng(I,J)=0 THEN Sng(I,J)=.01
2230  Id(I,J)=Aat(J)/EXP(Bst(J)/Sng(I,J))
2240  Idn(I,J)=Id(I,J)*Sng(I,J)
2250  Ids(I,J)=Cst(J)*Idn(I,J)
2260  Itot(I,J)=Idn(I,J)+Ids(I,J)
2270  NEXT I
2280  NEXT J
2290  GOTO Tout
2300 Tout:!
2310  IF Z$[1,1]="D" THEN Month=1
2320  PRINT PAGE
2330  PRINT "CALCULATING OUTDOOR TEMPERATURES FOR MONTH OR DATA SET:"
2340  FOR J=Month TO N
2350  PRINT "    ";J;
2360  FOR I=1 TO 24
2370  Tout(I,J)=Tmax(J)-Pdr(I)*Dr(J)
2380  NEXT I
2390  NEXT J
2400  GOTO Solair
2410 Solair:!
2420  PRINT PAGE
2430  PRINT "CALCULATING SOLAIR TEMPERATURES FOR MONTH OR DATA SET:"
2440  IF Z$[1,1]="D" THEN Month=1
2450  FOR J=Month TO N STEP S
2460  PRINT "   ";J;
2470  Abs(J)=Sc(J)*Absc(J)*Cf(J)+(1-Sc(J))*Abss(J)
2480  Emi(J)=Sc(J)*Emic(J)+(1-Sc(J))*Emis(J)
2490  FOR I=1 TO 24
2500  Solair(I,J)=Tout(I,J)+Abs(J)*Itot(I,J)/Ho(J)-Emi(J)*20/Ho(J)
2510  NEXT I
2520  NEXT J
2530 Heat:!
2540  PRINT PAGE
2550  PRINT "CALCULATING HEAT TRANSFER FOR DATA SET OR MONTH:"
2560  Error=.01
2570  IF Z$[1,1]="D" THEN Month=1
2580  FOR J=Month TO N STEP S
2590  PRINT "    ";J;
2600  Ht(I,J)=0
2610  Ncount=0
2620  Cns(J)=0
2630  C(J)=0
2640  FOR T=1 TO F(J)
2650  Cns(J)=Cns(J)+B(T,J)
2660  NEXT T
2670  C(J)=Cns(J)*Tin(J)
2680  FOR I=1 TO 24
2690  Ht(I,J)=0
2700  Ip24=I+24
2710  Ht(Ip24,J)=0
2720  Solair(Ip24,J)=Solair(I,J)
2730  NEXT I
2740  FOR K=24 TO 48
2750  FOR T=1 TO F(J)
2760  Pp=K+1-T
2770  Ht(K,J)=Ht(K,J)+B(T,J)*Solair(Pp,J)-D(T,J)*Ht(Pp,J)
2780  NEXT T
2790  Ht(K,J)=Ht(K,J)-C(J)
2800  NEXT K
```

```
2810  Ncount=Ncount+1
2820  FOR I=1 TO 24
2830  Dum=Ht(I+24,J)
2840  IF ABS(Dum)<1.0E-4 THEN 2870
2850  Err=ABS((Ht(I,J)-Dum)/Dum)
2860  IF Err>Error THEN 2900
2870  NEXT I
2880  IF Ncount<4 THEN 2900
2890  GOTO 2940
2900  FOR I=1 TO 24
2910  Ht(I,J)=Ht(I+24,J)
2920  NEXT I
2930  IF Ncount<30 THEN 2740
2940  NEXT J
2950  GOTO Choice
2960 Blick:!
2970  IF Z$[1,1]="D" THEN Month=1
2980  FOR J=Month TO N STEP S
2990  Tsum(J)=0
3000  FOR I=1 TO 24
3010  Tsum(J)=Tsum(J)+Solair(I,J)
3020  NEXT I
3030  NEXT J
3040  IF Z$[1,1]="D" THEN Month=1
3050  FOR J=Month TO N STEP S
3060  Hba(J)=0
3070  Hba(J)=(Tsum(J)/24-Tin(J))/I(J)
3080  NEXT J
3090  K=5
3100  GOTO Blickprint_1
3110 Choice:!
3120  PRINTER IS 16
3130  IF P=20 THEN GOTO 3170
3140  PRINT PAGE
3150  Tmax=20
3160  Tmin=-20
3170  IF K=15 THEN GOTO Ghour
3180  PRINT PAGE
3190  PRINT "YOU MAY :"
3200  PRINT "(1)PLOT AVERAGE HOURLY LOAD FOR EACH MONTH BEING INVESTIGATED"
3210  PRINT "(2)PLOT LOAD FOR ONE OR MORE SPECIFIED HOURS FOR EACH"
3220  PRINT "   MONTH BEING INVESTIGATED"
3230  PRINT "(3)PLOT LOAD FOR A 24 HOUR PERIOD FOR ONE OR MORE SPECIFIED MONTHS"
3240  PRINT "(4)END PROGRAM"
3250  PRINT "(5)RERUN WITH NEW DATA"
3260  PRINT "(6)PLOT HEAT TRANSFER BY TFC MRTHOD AND BY BLICK METHOD"
3270  PRINT "   ON SAME GRAPH FOR EACH MONTH BEING INVESTIGATED"
3280  PRINT "   (TFC LOAD FOR SPECIFED OR AVERAGE HOUR FOR EACH MONTH STUDIED"
3290  PRINT "   AND LOAD CALCULATED BY BLICK METHOD ON SAME GRAPH)"
3300  PRINT "(7)PLOT STORED ENERGY IN EARTH MASS BASED ON INPUT ROOF SYSTEM"
3310  PRINT "   (INSTANTANEOUS LOAD MINUS LOAD JUST CALCULATED)"
3320  DISP "SELECT (1),(2),(3),(4),(5),(6),OR (7)";
3330  INPUT An
3340  P=0
3350  IF An=1 THEN Averg
3360  IF An=2 THEN Which
3370  IF An=3 THEN Ghour
3380  IF An=4 THEN End_1
3390  IF An=5 THEN 500
3400  IF An=6 THEN K=5
3410  IF An=6 THEN Which_1
3420  IF An=7 THEN K=15
3430  IF An=7 THEN Store
3440  GOTO 3320
3450 Which_1: !
3460  PRINT "YOU MAY DISPLAY ANY SPECIFIC HOURS(TFC METHOD)HOUR OR AVERAGE"
3470  PRINT "HOURLY LOAD(TFC METHOD).  SELECT WHICH."
3480  INPUT "(1)SPECIFIC HOURS OR (2)AVERAGE HOUR",W
3490  IF W=1 THEN GOTO Which
3500  IF W=2 THEN K=6
3510  IF W=2 THEN GOTO Averg
3520 Which:!
3530  INPUT "WHICH HOUR IS TO BE THE LAST DISPLAYED",A
3540  INPUT "WHICH HOUR IS TO START THE DISPLAY",B
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3550  C=B+A-1
3560  INPUT "DO YOU WANT TO DISPLAY CONSECUATIVE HOURS OR JUST(N) THE START & EN
D",W$
3570  IF W$[1,1]="Y" THEN Ss=1
3580  IF W$[1,1]="N" THEN Ss=A-B
3590  GOTO Gmonth
3600 Ghour:!
3610  PLOTTER IS "GRAPHICS"
3620  GRAPHICS
3630  IF Z$[1,1]="M" THEN GOTO 3670
3640  Y=1
3650  LET X=N
3660  GOTO 3710
3670  DISP "HOW MANY MONTHS DO YOU WISH HOURLY DATA PLOTTED ON ONE GRAPH?";
3680  INPUT X
3690  DISP "WHICH MONTH TO START, BY NUMBER?";
3700  INPUT Y
3710  LOCATE 23,115,10,90
3720  SCALE 0,24.7,Tmin,Tmax
3730  AXES 1,1,0,Tmin
3740  Z=Y+S*X-S
3750  FOR J=Y TO Z STEP S
3760  IF K=15 THEN Ht(1,J)=Hs(1,J)
3770  MOVE 1,Ht(1,J)
3780  FOR I=2 TO 24
3790  IF K=15 THEN Ht(I,J)=Hs(I,J)
3800  DRAW I,Ht(I,J)
3810  NEXT I
3820  LORG 5
3830  LABEL J
3840  NEXT J
3850  LOCATE 23,115,0,10
3860  SCALE 0,24.7,0,4
3870  FOR I=1 TO 24
3880  MOVE I,3
3890  LORG 5
3900  CSIZE 2.5,.6
3910  LABEL I
3920  NEXT I
3930  MOVE 12,1
3940  CSIZE 3,.6
3950  LORG 5
3960  LABEL "TIME(1=1AM,24=MIDNITE)"
3970  LOCATE 0,10,10,90
3980  SCALE 0,8,Tmin,Tmax
3990  FOR I=Tmin TO Tmax
4000  CSIZE 2.5,.6
4010  MOVE 16,I
4020  LABEL I
4030  NEXT I
4040  T=Tmax+Tmin
4050  IF T=0 THEN T=1
4060  MOVE 12,T/2
4070  DEG
4080  LDIR 90
4090  CSIZE 3,.6
4100  LABEL "HEAT TRANSFER(BTUH/FT^2)"
4110  PRINTER IS 16
4120  IF K=5 THEN GOTO Store
4130  IF K=15 THEN GOTO Question
4140  GOTO Question
4150  FOR J=Month TO N STEP S
4160  PRINT ,J;SPA(5);Hst(J)
4170  NEXT J
4180  IF K=15 THEN K=0
4190  GOTO 7200
4200 Gmonth:!
4210  PLOTTER IS "GRAPHICS"
4220  GRAPHICS
4230  LOCATE 23,115,10,90
4240  SCALE 0,12.3,Tmin,Tmax
4250  AXES 1,1,0,Tmin
4260  FOR I=B TO C STEP Ss
4270  MOVE 1,Ht(I,1)
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4280  FOR J=2 TO 12
4290  DRAW J,Ht(I,J)
4300  NEXT J
4310  LORG 5
4320  LABEL I
4330  NEXT I
4340  IF K=5 THEN GOTO Blick
4350  LOCATE 23,115,0,10
4360  SCALE 0,12.4,0,8
4370  FOR J=1 TO 12
4380  MOVE J,6
4390  LORG 5
4400  CSIZE 2.5,.6
4410  LABEL J
4420  NEXT J
4430  MOVE 6,1
4440  CSIZE 3,.6
4450  LORG 5
4460  LABEL "MONTH (1=JAN.)"
4470  LOCATE 0,10,10,90
4480  SCALE 0,8,Tmin,Tmax
4490  FOR I=Tmin TO Tmax
4500  CSIZE 2.5,.6
4510  MOVE 16,I
4520  LABEL I
4530  NEXT I
4540  T=Tmax+Tmin
4550  IF T=0 THEN T=1
4560  MOVE 12,T/2
4570  DEG
4580  LDIR 90
4590  CSIZE 3,.6
4600  LABEL "HEAT TRANSFER(BTUH/FT^2)"
4610  PRINTER IS 16
4620  IF K=5 THEN GOTO 2660
4630  IF K=10 THEN GOTO 2660
4640  GOTO Question
4650 Gmonth_1:!
4660  PLOTTER IS "GRAPHICS"
4670  GRAPHICS
4680  LOCATE 23,115,10,90
4690  SCALE 0,12.3,Tmin,Tmax
4700  AXES 1,1,0,Tmin
4710  MOVE 1,Aver(Month)
4720  FOR J=Month TO N STEP S
4730  DRAW J,Aver(J)
4740  NEXT J
4750  LABEL "TFC AV"
4760  IF K=6 THEN GOTO Blick
4770  LOCATE 23,115,0,10
4780  SCALE 0,12.4,0,8
4790  FOR J=1 TO 12
4800  MOVE J,6
4810  LORG 5
4820  CSIZE 2.5,.6
4830  LABEL J
4840  NEXT J
4850  MOVE 6,1
4860  CSIZE 3,.6
4870  LORG 5
4880  LABEL "MONTH (1=JAN.)"
4890  LOCATE 0,10,10,90
4900  SCALE 0,8,Tmin,Tmax
4910  FOR I=Tmin TO Tmax
4920  CSIZE 2.5,.6
4930  MOVE 16,I
4940  LABEL I
4950  NEXT I
4960  T=Tmax+Tmin
4970  IF T=0 THEN T=1
4980  MOVE 12,T/2
4990  DEG
5000  LDIR 90
5010  CSIZE 3,.6
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```
5020  LABEL "HEAT TRANSFER(BTUH/FT^2)"
5030  PRINTER IS 16
5040  GOTO Question
5050 Averg:!
5060  FOR J=Month TO N STEP S
5070  Sum(J)=0
5080  FOR I=1 TO 24
5090  Sum(J)=Ht(I,J)+Sum(J)
5100  NEXT I
5110  Aver(J)=Sum(J)/24
5120  NEXT J
5130  GOTO Gmonth_1
5140 End:!
5150  FOR T=1 TO F(J)
5160  LET Savb(T)=B(T,J)
5170  LET Savd(T)=D(T,J)
5180  NEXT T
5190  LET Savden=Den(J)
5200  LET Savsh=Sh(J)
5210  LET Savdep=Depth(J)
5220  LET Savi=I(J)
5230  LET Savf=F(J)
5240  LET Savcon=Cond(J)
5250  ASSIGN File$&":T15" TO #1
5260  PRINT #1;Savb(*),Savd(*),Savf,Savden,Savsh,Savdep,Savi,Savcon
5270  GOTO 1730
5280 Print:!
5290  DUMP GRAPHICS
5300  PRINTER IS 16
5310  PRINT PAGE
5320  PRINT "****ENVIORNMENTAL DATA****"
5330  PRINT "2=LATITUDE(DEGREES),Lat"
5340  PRINT "3=INDOOR DESIGN TEMP.(DEG.F.),Tin"
5350  PRINT "4=AVERG. MAX. TEMP.(DEG.F.),Tmax"
5360  PRINT "5=AVERG. DAILY RANGE(DEG.F.),Dr"
5370  PRINT ""
5380  PRINT "****SURFACE DATA****"
5390  PRINT "6=SURFACE COVER ABSORPTION(%),Absc"
5400  PRINT "7=SURFACE COVER EMITTANCE(%),Emic"
5410  PRINT "8=COUPLING FACTOR(%),Cf"
5420  PRINT "9=SHADE COVER(%),Sc"
5430  PRINT "10=CONVECTION COEFFICIENT(BTU/Hr-Ft^2-F),Ho"
5440  PRINT ""
5450  PRINT "****SOIL DATA****"
5460  PRINT "11=ROOF R-VALUE(Hr-FT^2-F/BTU),I"
5470  PRINT "12=SOIL ABSORPTION(%),Abss"
5480  PRINT "13=SOIL EMITTANCE(%),Emis"
5490  PRINT "14=SOIL DENSITY(Lb/Ft^3),Den"
5500  PRINT "15=SOIL SPECIFIC HEAT(BTU/Lb-F),Sh"
5510  PRINT "16=SOIL DEPTH(FT),Depth"
5520  PRINT "18=SOIL THERMAL CONDUCTIVITY(BTU/Hr-Ft-F),Cond"
5530  PRINTER IS 0,WIDTH(80)
5540  PRINT SPA(30),Data$
5550  PRINT SPA(30),Data1$
5560  PRINT SPA(35),"INPUT DATA"
5570  PRINT SPA(29),"VALUES FOR VARIED DATA"
5580  PRINT LIN(1)
5590  P1=0
5600  P2=0
5610  P3=0
5620  P4=0
5630  P5=0
5640  P6=0
5650  P7=0
5660  P8=0
5670  P9=0
5680  P10=0
5690  P11=0
5700  P12=0
5710  P13=0
5720  P14=0
5730  P15=0
5740  P16=0
5750  P17=0
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5760  P18=0
5770  INPUT "HOW MANY PARAMETERS DID YOU VARY",V
5780  FOR L=1 TO V
5790  DISP "VARIED PARAMETER",L,"= (REFERENCE ABOVE)";
5800  INPUT Cv
5810  IF Z$[1,1]="D" THEN Month=1
5820  FOR J=Month TO N STEP S
5830  IF P2=1 THEN GOTO 5890
5840  IF Cv=2 THEN GOTO 5870
5850  P2=0
5860  GOTO 5890
5870  IF J=N THEN P2=1
5880  PRINT TAB(10);J;"LATITUDE FOR ";Month$(J);TAB(55);" = ";Lat(J);TAB(65);" D
EG.N"
5890  IF P3=1 THEN GOTO 5950
5900  IF Cv=3 THEN GOTO 5930
5910  P3=0
5920  GOTO 5950
5930  IF J=N THEN P3=1
5940  PRINT TAB(10);J;"INDOOR DESIGN TEMP. FOR ";Month$(J);TAB(55);" = ";Tin(J);
TAB(66);"DEG F"
5950  IF P4=1 THEN GOTO 6010
5960  IF Cv=4 THEN GOTO 5990
5970  P4=0
5980  GOTO 6010
5990  IF J=N THEN P4=1
6000  PRINT TAB(10);J;"AVERG. MAX. TEMP. FOR ";Month$(J);TAB(55);" = ";Tmax(J);T
AB(65);" DEG.F."
6010  IF P5=1 THEN GOTO 6070
6020  IF Cv=5 THEN GOTO 6050
6030  P5=0
6040  GOTO 6070
6050  IF J=N THEN P5=1
6060  PRINT TAB(10);J;"AVERAGE DAILY RANGE FOR ";Month$(J);TAB(55);" = ";Dr(J);T
AB(65);" DEG.F."
6070  IF P6=1 THEN GOTO 6130
6080  IF Cv=6 THEN GOTO 6110
6090  P6=0
6100  GOTO 6130
6110  IF J=N THEN P6=1
6120  PRINT TAB(10);J;"TOPPING ABSORPTION FOR ";Month$(J);TAB(55);" = ";Absc(J);
TAB(65);" %"
6130  IF P7=1 THEN GOTO 6190
6140  IF Cv=7 THEN GOTO 6170
6150  P7=0
6160  GOTO 6190
6170  IF J=N THEN P7=1
6180  PRINT TAB(10);J;"SURFACE COVER EMITTANCE FOR ";Month$(J);TAB(55);" = ";Emi
c(J);TAB(65);" %"
6190  IF P8=1 THEN GOTO 6250
6200  IF Cv=8 THEN GOTO 6230
6210  P8=0
6220  GOTO 6250
6230  IF J=N THEN P8=1
6240  PRINT TAB(10);J;"COUPLING FACTOR FOR ";Month$(J);TAB(55);" = ";Cf(J);TAB(6
5);" %"
6250  IF P9=1 THEN GOTO 6310
6260  IF Cv=9 THEN GOTO 6290
6270  P9=0
6280  GOTO 6310
6290  IF J=N THEN P9=1
6300  PRINT TAB(10);J;"SHADING COEFFICIENT FOR ";Month$(J);TAB(55);" = ";Sc(J);T
AB(65);" %"
6310  IF P10=1 THEN GOTO 6370
6320  IF Cv=10 THEN GOTO 6350
6330  P10=0
6340  GOTO 6370
6350  IF J=N THEN P10=1
6360  PRINT TAB(10);J;"SURFACE CONVECTION COEFFICIENT FOR ";Month$(J);TAB(55);"
= ";Ho(J);TAB(65);"BTUH/BTU-Ft^2-F"
6370  IF P11=1 THEN GOTO 6430
6380  IF Cv=11 THEN GOTO 6410
6390  P11=0
6400  GOTO 6430
```

```
6410  IF J=N THEN P11=1
6420  PRINT TAB(10);J;"ROOF R-VALUE FOR ";Month$(J);TAB(55);" = ";I(J);TAB(65);"
HR-FT^2-F/BTU"
6430  IF P12=1 THEN GOTO 6490
6440  IF Cv=12 THEN GOTO 6470
6450  P12=0
6460  GOTO 6490
6470  IF J=N THEN P12=1
6480  PRINT TAB(10);J;"SOIL ABSORPTION FOR ";Month$(J);TAB(55);" = ";Abss(J);TAB
(65);" %"
6490  IF P13=1 THEN GOTO 6550
6500  IF Cv=13 THEN GOTO 6530
6510  P13=0
6520  GOTO 6550
6530  IF J=N THEN P13=1
6540  PRINT TAB(10);J;"SOIL EMITTANCE FOR ";Month$(J);TAB(55);" = ";Emis(J);TAB(
65);" %"
6550  IF P14=1 THEN GOTO 6610
6560  IF Cv=14 THEN GOTO 6590
6570  P14=0
6580  GOTO 6610
6590  IF J=N THEN P14=1
6600  PRINT TAB(10);J;"SOIL DENSITY FOR ";Month$(J);TAB(55);" = ";Den(J);TAB(65)
;"LB/FT^3"
6610  IF P15=1 THEN GOTO 6670
6620  IF Cv=15 THEN GOTO 6650
6630  P15=0
6640  GOTO 6670
6650  IF J=N THEN P15=1
6660  PRINT TAB(10);J;"SOIL SPECIFIC HEAT FOR ";Month$(J);TAB(55);" = ";Sh(J);TA
B(65);"BTU/LB-F"
6670  IF P16=1 THEN GOTO 6730
6680  IF Cv=16 THEN GOTO 6710
6690  P16=0
6700  GOTO 6730
6710  IF J=N THEN P16=1
6720  PRINT TAB(10);J;"DEPTH FOR ";Month$(J);TAB(55);" = ";Depth(J);TAB(65);"INC
HES"
6730  IF P18=1 THEN GOTO 6790
6740  IF Cv=18 THEN GOTO 6770
6750  P18=0
6760  GOTO 6790
6770  IF J=N THEN P18=1
6780  PRINT TAB(10);J;"SOIL THERMAL CONDUCTIVITY FOR ";Month$(J);TAB(55);" = ";C
ond(J);TAB(65);"BTU/Hr-Ft-F"
6790  NEXT J
6800  NEXT L
6810  INPUT "DO YOU WANT A RECORD OF CONSTANT INPUT DATA",Bq$
6820  IF Bq$[1,1]="N" THEN GOTO Choice
6830  PRINT LIN(5)
6840  PRINT SPA(30);Data$
6850  PRINT SPA(30);Data1$
6860  PRINT SPA(20),"REFERENCE SYSTEM INPUT DATA - JANUARY"
6870  PRINT LIN(1)
6880  IF P2=0 THEN PRINT TAB(10);"LATITUDE = ";TAB(53);Lat(Month);TAB(60);" DEG
N"
6890  IF P3=0 THEN PRINT TAB(10);"INDOOR DESIGN TEMP = ";TAB(53);Tin(Month);TAB(
60);" F"
6900  IF P4=0 THEN PRINT TAB(10);"AVERG. MAX. TEMP. = ";TAB(53);Tmax(Month);TAB(
60);
6910  IF P5=0 THEN PRINT TAB(10);"AVERG. DAILY RANGE = ";TAB(53);Dr(Month);TAB(6
0);" F"
6920  IF P6=0 THEN PRINT TAB(10);"SURFACE COVER ABSORPTION =";TAB(53);Absc(Month
)
6930  IF P7=0 THEN PRINT TAB(10);"SURFACE COVER EMITTANCE =";TAB(53);Emic(Month)
;TAB(60);" %"
6940  IF P8=0 THEN PRINT TAB(10);"COUPLING FACTOR =";TAB(53);Cf(Month);TAB(60);"
 %"
6950  IF P9=0 THEN PRINT TAB(10);"SHADING COEFFICIENT =";TAB(53);Sc(Month);TAB(6
0);" %"
6960  IF P10=0 THEN PRINT TAB(10);"SURFACE CONVECTION COEFFICIENT =";TAB(53);Ho(
Month);TAB(61);"BTU/Hr-Ft^2-F"
6970  IF P11=0 THEN PRINT TAB(10);"OVERALL ROOF R-VALUE =";TAB(53);I(Month);TAB(
60);" HR-FT^2-F/BTU"
```

```
6980  IF P12=0 THEN PRINT TAB(10);"SOIL ABSORPTION =";TAB(53);Abss(Month);TAB(60
);" %"
6990  IF P13=0 THEN PRINT TAB(10);"SOIL EMITTANCE =";TAB(53);Emis(Month);TAB(60)
;" %"
7000  IF P14=0 THEN PRINT TAB(10);"SOIL DENSITY =";TAB(53);Den(Month);TAB(60);"
LB/FT^3"
7010  IF P15=0 THEN PRINT TAB(10);"SPECIFIC HEAT =";TAB(53);Sh(Month);TAB(60);"
BTU/LB-F"
7020  IF P16=0 THEN PRINT TAB(10);"SOIL DEPTH =";TAB(53);Depth(Month);TAB(60);"
FT"
7030  IF P18=0 THEN PRINT TAB(10);"SOIL THERMAL CONDUCTIVITY =";TAB(53);Cond(Mon
th);TAB(60);" BTU/Hr-Ft-F"
7040  PRINTER IS 16
7050  GOTO Choice
7060 Question:!
7070  PRINTER IS 16
7080  PRINT PAGE
7090  PRINT "YOU MAY:"
7100  PRINT "(1)PRINT COPY OF GRAPH ONLY"
7110  PRINT "(2)PRINT COPY OF GRAPH WITH INPUT DATA"
7120  PRINT "(3)OUT PUT A NEW GRAPH FORM "
7130  PRINT "(4)RERUN PROGRAM WITH NEW DATA"
7140  PRINT "(5)END PROGRAM"
7150  PRINT "(6)RE-SCALE GRAPH AND REDRAW GRAPH"
7160  PRINT "(7)PRINT OUT VALUES FOR BLICK AND TFC AVERAGE HEAT TRANSFER"
7170  INPUT "DO YOU WANT (1)(2)(3)(4)(5)(6)OR(7)",E
7180  IF E=1 THEN DUMP GRAPHICS
7190  IF (E=1) AND (K=15) THEN GOTO 4150
7200  IF (E=2) AND (K<>15) THEN GOTO Print
7210  EXIT GRAPHICS
7220  IF E=3 THEN GOTO Choice
7230  IF E=4 THEN GOTO 420
7240  IF E=5 THEN GOTO End_1
7250  IF E=6 THEN GOTO Re_scale
7260  IF E=7 THEN Print_2
7270  GOTO 7170
7280 End_1:!
7290  STOP
7300  END
7310 Store:!
7320  IF Z$[1,1]="D" THEN Month=1
7330  FOR J=Month TO N STEP S
7340  Hst(J)=0
7350  FOR I=1 TO 24
7360  Hb(I,J)=(Solair(I,J)-Tin(J))/I(J)
7370  Hs(I,J)=Hb(I,J)-Ht(I,J)
7380  PRINTER IS 0
7390  Hst(J)=Hst(J)+Hs(I,J)
7400  NEXT I
7410  PRINT Hst(J)
7420  NEXT J
7430  PRINTER IS 16
7440  IF K=5 THEN GOTO Which
7450  IF K=15 THEN GOTO 3140
7460  GOTO 3170
7470 Blickprint:!
7480  FOR J=Y TO Z STEP S
7490  MOVE 1,Hb(1,J)
7500  FOR I=2 TO 24
7510  DRAW I,Hb(I,J)
7520  NEXT I
7530  LORG 5
7540  LABEL "A";J
7550  NEXT J
7560  K=0
7570  GOTO 3850
7580 Blickprint_1:!
7590  MOVE 1,Hba(1)
7600  FOR J=Month TO N
7610  DRAW J,Hba(J)
7620  NEXT J
7630  LABEL "BLICK"
7640  K=0
7650  IF W=2 THEN GOTO 4770
```

```
7660  IF W=1 THEN GOTO 4350
7670 Re_scale:!
7680  INPUT "MAXIMUM VALUE FOR HEAT TRANSFER",Tmax
7690  INPUT "MINIMUM VALUE FOR HEAT TRANSFER",Tmin
7700  P=20
7710  GOTO Choice
7720 Print_2:!
7730  INPUT "(1)SCREEN OR(2)PRINTER",Z
7740  IF Z=1 THEN PRINTER IS 16
7750  IF Z=2 THEN PRINTER IS 0
7760  PRINT ,Data$
7770  PRINT ,Data1$
7780  PRINT SPA(24);"BLICK";SPA(25);"TFC AVERAGE"
7790  PRINT SPA(24);"_______________";SPA(16);"_______________"
7800  FOR J=Month TO N STEP S
7810  PRINT " ";J;TAB(9);Month$(J);TAB(24);Hba(J);TAB(43);Aver(J)
7820  NEXT J
7830  PRINTER IS 16
7840  GOTO Question
```

APPENDIX B

JOB CONTROL LANGUAGE FOR CALCULATION OF ASHRAE TRANSFER FUNCTION COEFFICIENTS

The name of the program is TRANSF. The program computes the transfer function coefficients (B and D) required for the cooling/heat load and energy simulation programs which use the transfer function method for transient response of building components.

The input cards are:

(Card 1): DT, LU2, N2 (F10.3, I2, 1X, I2)

DT = Sampling time interval (Eg. 1.0) = 1.0

0.6 = LU2 = Logical unit 2 on which the output BT, DT, UWRT is given in name list form to suit CHLOAD, CHLSYM (Eg: 7 will give punch output)

01 = N2 = Number of copies of the list on LU2 (Eg: 4 will give 4 copies)

(Card 2): Description (80A1) (Eg: South wall coefficients)

(Card 3): Description (80A1) (Eg: Slab components) If the wall is made up of M layers

(Card 3+1): (Inside)

. : XL, XK, D, SH, RES, TEXT (5F10.4,30A1)

(Card 3+M): (Outside)

XL = Thickness of the layer (ft)

XK = Thermal conductivity (Btu/hr-ft^2-^{o}F)

D = Density (lbm/ft^3)

SH = Specific resistance of the layer when there is negligible heat storage (hr-ft^2-^{o}F/Btu)

TEXT = Description of the layer (Eg: Outside air surface resistance)

(Card 4+M): Blank card to stop above input

(Card 5+M): ICASE (I1) ICASE = 1 for ramp input of temperatures

10 = Repeat cards 1 through (5+M) for additional wall or roof sections

APPENDIX C

TRANSFER FUNCTION COEFFICIENTS

3 INCH CLAY SOIL - 7%MC -R = 2.8

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.25	0.417	95.0	0.23	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.00	Outside Film

N	b_n	d_n
0	0.4594096394D-04	0.1000000000D+01
1	0.3367990565D-02	-0.1482450249D+01
2	0.9605474532D-02	0.5828538139D+00
3	0.3502470576D-02	-0.5430929883D-01
4	0.1601547977D-03	0.3588547939D-03
5	0.5555418029D-06	-0.1167780025D-12
6	0.6787443399D-10	0.3336082127D-12
7	0.2192957562D-15	-0.3401790561D-20

3 INCH CLAY SOIL - SATURATED - R = 2.5

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.25	0.833	95.0	0.36	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.6755554265D-04	0.1000000000D+01
1	0.3924640842D-02	-0.1483863737D+01
2	0.9719931434D-02	0.5680298489D+00
3	0.3002437407D-02	-0.4259911453D-01
4	0.1066849958D-03	0.2364496779D-03
5	0.2380726826D-06	-0.2962444490D-07
6	0.1286839000D-10	-.2715789334D-13
7	-0.3991461919D-15	

6 INCH CLAY SOIL - 7%MC - R = 3.4

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.50	0.417	95.0	0.23	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.1279627038D-06	0.1000000000D+01
1	0.1290609364D-03	-0.2000188284D+01
2	0.1454094553D-02	0.1295677480D+01
3	0.2155736570D-02	-0.3019119602D+00
4	0.6198264878D-03	0.2154770987D-01
5	0.3409210762D-04	-0.2585106293D-03
6	0.2848167717D-06	0.4134052748D-06
7	0.2485273736D-09	-0.3718862517D-10
8	0.1131566412D-13	0.1240939949D-15

6 INCH CLAY SOIL - SATURATED - R - 2.8

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.6850	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.50	0.833	95.0	0.36	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.4547670001D-06	0.1000000000D+01
1	0.2427517169D-03	-0.1935509944D+01
2	0.2059671260D-02	0.1180724060D+01
3	0.2350910601D-02	-0.2434582798D+00
4	0.4948776000D-03	0.1273220018D-01
5	0.1772409470D-04	-0.9823987105D-04
6	0.7851983404D-07	0.5922040092D-07
7	0.2666181593D-10	-0.1538211111D-11
8	-0.7332409031D-15	0.9410626860D-18

6 INCH CLAY SOIL - 7%MC - R = 18.5

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.500	1.000	140.0	0.20	0.0	HW Concrete
3	0.378	0.025	2.0	0.20	0.0	R 15 Insulation
4	0.500	0.417	95.0	0.23	0.0	Clay Soil
5	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.3080224964D-10	0.1000000000D+01
1	0.4798266492D-06	-0.2505701404D+01
2	0.1664538766D-04	0.2186590962D+01
3	0.6342077450D-04	-0.7833246439D+00
4	0.5075581924D-04	0.1096592507D+00
5	0.1000415867D-04	-0.4655713052D-02
6	0.4742339980D-06	0.5529866557D-04
7	0.4763906828D-08	-0.1549418066D-06
8	0.8192296385D-11	0.9928809431D-10
9	0.7245122548D-14	-0.7593854745D-15

6 INCH CLAY SOIL - SATURATED - R = 17.9

LAYER	d.	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.0	0.0	0.0	0.0	15.000	R 15 Insulation
4	0.50	0.833	95.0	0.36	0.0	Clay Soil
5	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.3160983697D-08	0.1000000000D+01
1	0.2974022230D-05	-0.2422816145D+01
2	0.3711711185D-04	0.1989239785D+01
3	0.6352742769D-04	-0.6342954604D+00
4	0.2187571822D-04	0.7143973133D-01
5	0.1493721618D-05	-0.1312421366D-02
6	0.1584843436D-07	0.3361831772D-05
7	0.1738293235D-10	-0.4954203018D-09
8	0.8612043712D-15	0.1298693108D-14

9 INCH CLAY SOIL - 7%MC - R = 4.0

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.75	0.417	95.0	0.23	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.8372547100D-10	0.1000000000D+01
1	0.2399005658D-05	-0.2510685736D+01
2	0.1044045172D-03	0.2266390357D+01
3	0.4746905319D-03	-0.8915272547D+00
4	0.1121069772D-03	0.1494854613D+00
5	0.1121069772D-03	-0.9198827677D-02
6	0.6943999789D-05	0.1483442221D-03
7	0.9584736466D-07	-0.4907697602D-06
8	0.2404522430D-09	0.2688925469D-09
9	0.8541765875D-13	-0.1253775076D-13

9 INCH CLAY SOIL -SATURATED - R = 3.1

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	0.75	0.833	95.0	0.36	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	0.9985416938D-09	0.1000000000D+01
1	0.8476510502D-05	-0.2387392312D+01
2	0.2344148902D-03	0.1997693958D+01
3	0.7521789868D-03	-0.6955357856D+00
4	0.5070591952D-03	0.9403265902D-01
5	0.8167520133D-04	-0.3939008794D-02
6	0.2947565173D-05	0.3630583666D-04
7	0.1968500754D-07	-0.4979370695D-07
8	0.1840306445D-10	0.6966755886D-11
9	0.5522294373D-14	-0.6897429129D-16

13 INCH CLAY SOIL - 7%MC - R = 4.8

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	1.08	0.417	95.0	0.23	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	-0.2353672812D-13	0.1000000000D+01
1	0.4125957700D-08	-0.3184541118D+01
2	0.1312150247D-05	0.3947026042D+01
3	0.2291588406D-04	-0.2410763418D+01
4	0.7725764365D-04	0.7614330431D+00
5	0.7315666436D-04	-0.1207219873D+00
6	0.2219077163D-04	0.8762350544D-02
7	0.2201671527D-05	-0.2463884233D-03
8	0.6814839761D-07	0.2206593940D-05
9	0.5983002661D-09	-0.5595471136D-08
10	0.1301946791D-11	0.3379701502D-11
11	0.7078810200D-14	-0.3439959150D-15

13 INCH CLAY SOIL - SATURATED - R = 3.5

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	1.08	0.833	95.0	0.36	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	-0.1310063169D-13	0.1000000000D+01
1	0.4294722379d-07	-0.2983877358D+01
2	0.6330892756D-05	0.3388745700D+01
3	0.6822403684D-04	-0.1832736836D+01
4	0.1501323111D-03	0.4850958670D+00
5	0.9149714737D-04	-0.5887116487D-01
6	0.1686274304D-04	0.2851785069D-02
7	0.9209602941D-06	-0.4526627856D-04
8	0.1359215407D-07	0.1869271724D-06
9	0.4691922536D-10	-0.1584411854D-09
10	0.2986348146D-13	0.2196556621D-13

18 INCH CLAY SOIL - 7%MC - R = 5.8

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.50	1.000	140.0	0.20	0.0	HW Concrete
3	1.50	0.417	95.0	0.23	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	-0.1132427485D-13	0.1000000000D+01
1	0.2485014277D-12	-0.4042175239D+01
2	0.1349575477D-08	0.6742745859D+01
3	0.1353667806D-06	-0.6011562847D+01
4	0.1843089484D-05	0.3107392406D+01
5	0.6594425833D-05	-0.9486602825D+00
6	0.8062349203D-05	0.1680455194D+00
7	0.3783350643D-05	-0.1646958203D+00
8	0.7117621537D-06	0.8255107063D-03
9	0.5363017501D-07	-0.1901834059D-04
10	0.1567026973D-08	0.1802603180D-06
11	0.1679276537D-10	-0.6451082547D-09
12	0.7168036109D-13	0.7978622030D-12

18 INCH CLAY SOIL - SATURATED - R = 4.0

LAYER	d	k	D	S	R	Description
1	0.0	0.0	0.0	0.0	0.685	Inside Film
2	0.5	1.000	140.0	0.20	0.0	HW Concrete
3	1.5	0.833	95.0	0.36	0.0	Clay Soil
4	0.0	0.0	0.0	0.0	1.000	Outside Film

N	b_n	d_n
0	-0.7638334409D-13	0.1000000000D+01
1	0.1240576659D-10	-0.3743040144D+01
2	0.2224190074D-07	0.5673753838D+01
3	0.1084763922D-05	-0.4479565683D+01
4	0.8551779274D-05	0.1977468085D+01
5	0.1855527834D-04	-0.4894727384D+00
6	0.1366155910D-04	0.6525374621D-01
7	0.3705324739D-05	-0.4341925540D-02
8	0.3754414877D-06	0.1295639540D-03
9	0.1378114386D-07	-0.1522788010D-05
10	0.1719401656D-09	0.6116404266D-08
11	0.6591700251D-12	-0.7268340012D-11
12	0.5946617364D-14	0.2220874297D-14

VITA

Charles David Jones

Candidate for the Degree of

Master of Architectural Engineering

Thesis: ANALYSIS OF THE THERMAL PERFORMANCE OF EARTH COVERED ROOFS BASED UPON A FORMULATED INTERACTIVE COMPUTER DESIGN AID

Major Field: Architectural Engineering

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