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Regional Analysis of Ground and Above-Ground Climate

Kenneth Labs
Undercurrent Design Research
New Haven, Connecticut

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Part of the National Program for
Building Thermal Envelope Systems
and Insulating Materials

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Prepared by

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New Haven, Connecticut

Part of
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Building Thermal Envelope Systems and Insulating Materials

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Insulating Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

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Undercurrent

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for the US Department of Energy
Innovative Structures Program
Oak Ridge National Laboratory

REGIONAL ANALYSIS OF GROUND AND ABOVE-GROUND CLIMATE

FOR EVALUATING THE SUITABILITY OF EARTH TEMPERING PRACTICES FOR ENERGY CONSERVATION IN ARCITECTURAL DESIGN

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Abstract

The regional suitability of underground construction as a climate control technique is discussed with reference to 1) a bioclimatic analysis of long-term weather data for 29 locations in the United States to determine appropriate above ground climate control techniques, 2) a data base of synthesized ground temperatures for the coterminous United States, and 3) monthly dew point ground temperature comparisons for identifying the relative likelihood of condensation from one region to another. It is concluded that the suitability of earth tempering as a practice and of specific earth sheltered design stereotypes varies geographically; while the subsurface almost always provides a thermal advantage on its own terms when compared to above ground climatic data, it can, nonetheless, compromise the effectiveness of other, regionally more important climate control techniques.

Also contained in the report are reviews of above and below ground climate mapping schemes related to human comfort and architectural design, and detailed description of a theoretical model of ground temperature, heat flow, and heat storage in the ground. Strategies of passive climate control are presented in a discussion of the building bioclimatic analysis procedure which has been applied in a computer analysis of 30 years of weather data for each of 29 locations in the United States. The report contains 237 pages, 61 illustrations, and 26 tables, in addition to two sets of bioclimatic data and ground temperature tables comprising over 190 pages.

Acknowledgment

This work brings together and applies several methods of ground and above ground climate analysis for the purpose of identifying issues in determining the suitability of earth tempering practices within the broader context of climate control. While the authors of the analysis methods used in this paper are identified in the technical discussions, a special acknowledgment is felt to be appropriate here, since this work borrows so heavily upon the contributions of other individuals.

The theoretical model of ground temperature variation used in this report was developed in the nineteenth century. Although numerous experimentors in various fields of the sciences have sought to test the validity of the model, the first effort to analyze a large body of data statistically—and with reference to building engineering—was made by Kusuda and Achenbach at the National Bureau of Standards in the 1960s. Their compilation and least squares analysis of recorded data has greatly aided in understanding the limitations of the theoretical model, and has prepared the way for making theoretical estimates of ground temperatures when only air temperature data is available as a means for approximating input for the model. Examination of average temperature of a specified soil profile was also introduced by Kusuda and Achenbach.

Bioclimatic analysis of weather data for identifying climate control needs was introduced in the 1960s by the Olgyay brothers. This report utilizes a well-known extension of that concept devised by Baruch Givoni. The application of Givoni's "Building Bioclimatic Chart" to a large number of stations in th U.S. was initiated by Donald Watson, FAIA, in work performed for the Department of Housing

and Urban Development with cooperation of the National Association of Home Builders Research Foundation. That work has been extended in scope and refined in detail for this report in order to make specific comparisons between ground and above ground climate.

This report was prepared for the U.S. Department of Energy, under sponsorship of the Oak Ridge National Laboratory, Innovative Structures Program. Their support is greatly appreciated. A special thanks is due to Robert Frew, Keith Harrington, and Carleton Williams, of Arga Associates of New Haven, who have provided computational services for both the ground climate synthesis and the bioclimatic analysis of weather data.

Nomenclature

A_a A_s A_x	temperature amplitudes at depths a, s, and x; (F)
a	an arbitrary depth; (ft)
Btu	British Thermal Unit, a unit of heat energy
b	an arbitrary depth; (ft)
C	Centigrade temperature
Cal	one "large" (or dietary) calorie, a unit of heat energy equal to 1000 "small" calories (1 Cal = 1 kcal)
cal	one "small" calorie, a unit of heat energy
c	specific heat; (Btu/(F)lb)
clo	a unit of clothing insulation
cm	centimeter
D	damping depth, defined by the relation $D = \sqrt{365\alpha/\pi}$; (ft)
DBT	dry bulb temperature, read from a dry bulb thermometer; (F)
DPT	dew point temperature; the saturated water vapor pressure at DPT is the ambient vapor pressure; (F)
d	symbol for differential
ET	effective temperature (old ASHRAE scale), an empirically-derived moisture-temperature index describing conditions of equal comfort sensation; (F)
ET*	the new ASHRAE effective temperature scale, a more recent index which supercedes the old ET scale; (F)
e	Euler's number, defined by the relation $e = \ln^{-1}(1)$; dimensionless, approximately 2.718282
F	Fahrenheit temperature
f	surface film conductance coeeficient
ft	feet
GT	globe temperature, read directly from a (black) globe thermometer; an index of the combined effect of DBT, air movement, and MRT; (F)
hr	hour
I	Thornthwaite's Moisture Index, defined by the relation (1955 version), I = 100 [(P/PE)-1], dimensionless

in	inches
K	Kelvin temperature
k	Thermal conductivity; (Btu/ft(day)F or Btu/ft(hr)F); also a symbol designating 1000
L	lag time term; (days/ft)
ln	natural logrithm, defined by the relationship $\ln x = \int_1^x dt/t$
ly	Langley, a unit of energy density equivalent to 1 cal/cm^2
MRT	mean radiant temperature; (F)
m	meter
met	a unit of metabolic heat produced through a unit area of skin, 1 met corresponds to sitting quietly; ($Btu/(ft^2)hr$)
P	cyclical time period (usually one year expressed as 365 days, sometimes one day expressed as 24 hours); also precipitation (inches or mm)
PE	potential evapotranspiration, the amount of water that is expected to be lost from the soil by evaporation and evapotranspiration from plants when the soil is supplied with a surplus of water (inches or mm)
Q_x Q_s	energy flow through horizontal depth x or through the surface s
q	thermal transmission, power, heat flow rate; (Btu/hr)
R	thermal resistance; ($ft^2(hr)F/Btu$)
r	logrithmic decrement, defined by the relation $r = \sqrt{\pi/365\,\alpha}$; (1/ft)
s	designates the ground surface, depth x=0
sec	seconds
T	temperature; (F)
T_m	mean annual ground temperature; (F)
T_a	mean annual air temperature; (F)
t	time; (days)
t_o	phase time constant; (days)
V	apparent velocity of temperature wave (ft/day)
W	Watts, a unit of energy flow rate
WBT	wet bulb temperature, read from a wet bulb thermometer

WBGT	wet bulb globe temperature index, a weighted average of the dry bulb, naturally-convected wet bulb, and globe temperature, according to the relation WBGT = 0.7 WBT + 0.2 GT + 0.1 DBT; (F)
x	an arbitrary depth; (ft)
α	thermal diffusivity ($k/\rho c$); (ft^2/day)
Δ	incremental difference or change
θ	a constant
π	pi, ratio of circumference of a circle to its diameter; dimensionless, approximately 3.14159
ρ	density; (pounds/ft^3)
ϕ	decrement factor, defined by the relation $\phi = e^{-xr}$; dimensionless
ω	radial or angular frequency; (radians/day)

Conversion factors

Temperature (T)	ΔF (F - 32)	x 5/9 x 5/9	= ΔC = C
Heat energy (Q)	Btu	x 1055 x 0.2929 x 252 x 0.252	= joules = Whr = cal = Cal or kcal
Thermal transmission (q) (heat flow rate; power)	Btu/hr	x 0.2929 x 0.07	= W = cal/sec
Energy density	Btu/ft^2	x 0.2717 x 0.2717	= cal/cm^2 = ly
Heat flux (energy density flow rate)	$Btu/ft^2(hr)$	x 3.152	= W/m^2
Thermal conductance	$Btu/ft^2(hr)F$	x 5.674	= W/m^2K
Coef of heat transfer (U)	$Btu/ft^2(hr)F$	x 5.674 x 0.4882	= W/m^2K = $cal/cm^2(hr)C$
Thermal conductivity (k)	Btu/ft(hr)F Btu/ft(hr)F $Btu/ft^2(hr)F/in$	x 0.01729 x 0.004134 x 0.1441	= W/cmK = cal/cm(sec)C = W/mK
Thermal resistance (R)	$ft^2(hr)F/Btu$	x 0.1761	= m^2K/W
Thermal diffusivity (α)	ft^2/hr ft^2/day	x 0.2581 x 6.194	= cm^2/sec = cm^2/sec
Metabolic heat production	met	x 18.4 x 58.2 x 50	= $Btu/ft^2(hr)$ = W/m^2 = $kcal/m^2(hr)$

Preface

While the ostensible purpose of this report is to provide consumers and designers with suggestions as to the suitablity of earth tempering practices in various parts of the United States, the background data that is contained herein should be of much broader interest to other audiences as well. In anticipation of the interest of different readers, the report is presented in four major parts which are written independently of one another.

The Technical Document, Part II, explains in detail the theory of the ground temperature model used in synthesizing the data presented in Part IV. It also discusses the basis for the bioclimatic analysis procedure, and the role of earth tempering as a climate control technique. The Technical Document also contains a review of climatic mapping schemes related to comfort analysis and architectural design.

Ground temperatures synthesized by the theoretical model are presented in an extensive series of tables in Part IV. It contains keys to the selection of the appropriate tables for any given generalized area in the United States. The tables should be of immediate use to engineers considering, for example, the value of earth pipes and the implications of different depths of placement of them.

Bioclimatic data has been analyzed for this report for 29 different regions in the United States. Data sheets for each, and a brief explanation of the procedure, are presented in Part III. These tables should be of interest to architects, and in particular, to those dealing with problems of cooling in the early design stages.

The conclusions to the report are presented in a separate discussion as Part I. All data contained in this section are excerpted from

Parts III and IV (the methodology having been explained in Part II, Technical Document), so no effort is made in the conclusions to describe or defend the methods of inquiry and analysis.

The virtue of examining climatic factors lies in their broad applicability and independence of individual building designs. As a shortcoming, climatic analysis in itself is meaningful only in the context of useful generalizations about building performance within specified sets of climatic conditions. At present, we know very little about the performance of underground structures in different climates, and much of what we are learning at present is based upon simulation, rather than experience. The conclusions made here, then, should be read more as suggestions than conclusions, and they must be evaluated in the light of this scanty knowledge. Future work may prove, disprove, or refine the conclusions. The data base prepared for and contained in this report is not, on the other hand, subject to change; its meaning and value can only be enhanced by the work of other present and future workers.

REGIONAL SUITABILITY

INTRODUCTION

Increasing energy costs have caused residents of nearly all regions in the United States to consider new or previously unfamiliar design alternatives for reducing heating and cooling loads. Popular among these are earth tempering practices, including subgrade or embanked walls, sod roofs, and earth-air heat exchangers. It is clear from much of the popular literature that the characteristics of ground climate are not well understood. Moreover, the supposed thermal benefits are often misrepresented to the public by poorly informed builders and designers. "Earth heating" and "earth cooling" are bandied about recklessly as the solution to building both in polar zones and the Southeast Sunbelt--seemingly, wherever climate control is necessary. Such claims are rarely substantiated by performance documentation, and make little or no reference to the technical literature.

The little existing literature that does discuss earth tempering practices is obscure and does not consider compatibility between these and other proven climate control techniques. In order to arrive at an impartial assessment of the thermal advantages and disadvantages of earth tempering, it must be evaluated within the broader context of all passive design alternatives. Some earth tempering devices may enhance the performance of traditional design responses to climate, while others may compromise what are regionally-preferred approaches to climate control.

The discussions which follow are intended to provide arguments in favor of and counter to earth tempering in various parts of the country, and to identify specific design issues of concern for each. Building climatology as a whole is not a well developed science, and the study of earth tempering is only just beginning. As a result-

although this report is based on state of the art procedures and the best available data—none of the analyses contained herein should be considered truly conclusive. It should also be noted here that "suitability" of earth tempering is assessed in this report only on the basis of its appropriateness as a passive climate control device—and in the context of competing strategies of climate control. There are many reasons for building underground which are unrelated to energy conservation, and many of these may also be viewed in terms of regional suitability (areas of high incidence of tornadoes, huricanes, grass fires, etc.). Since the present interest in underground construction is largely a response to increasing energy costs, however, it is felt that a comparison of ground and above ground climate and the implications of such a comparison merit special attention.

It should not be inferred from the conclusions of this report that earth tempering is anywhere unsuitable, per se, only that other climate control alternatives may be preferable or more effective from the sole standpoint of passive techniques of climate control. Moreover, earth tempering under most all conditions is likely to reduce the cost of mechanical methods of climate control, all other things being equal. Trade-offs between maximizing passive control techniques and maximizing efficiency of mechanical systems can offset one another, so the conclusions of this report are not absolute. In either case, the data presented here should lead to a better understanding of the value and limitations of earth tempered design.

EARTH TEMPERING AS A WINTER CLIMATE CONTROL STRATEGY

The strategies of climate control are limited in winter to heat conservation—through restriction of conduction and infiltration heat losses from the interior—and to heat supply, the only passive source of which is the sun (see Figure A). The heat conservation value of underground construction may be attributed to three factors: 1) infiltration rates are normally substantially reduced as a result of removing the structure from exposure to winds; 2) the ground offers a relatively warmer thermal environment than the above ground during winter; 3) the earth has an insulating effect and heat storage capacity that retards the rate of heat loss from underground walls to the surface.

The initial relative reduction in temperature differential between air and ground (see Table A) is mostly only of academic interest, since the building itself alters the natural ground temperature once it begins losing heat to the soil. Accordingly, it is preferred here to emphasize earth sheltering as a practice which reduces conductive losses to the air, by forcing heat escaping from the wall to follow a long path to the surface (see Figure B). It is the length of this path and not a high thermal resistance of soil which contributes to the insulating effect (or, more properly, the shape factor) of recessed placement. Overall resistance appreciates rapidly with depth through the first 4 feet or so of soil, after which the rate of heat loss reduction flattens out. This steady state concept of heat loss allows a soil of average thermal conductivity (k = 0.8 Btu/hr(ft)F) outside a wall extending from a depth of 2 feet to 12 feet below horizontal grade to be thought of as having an inherent resistance of about R17.5. This is a simplistic analysis, but one which readily

lends some meaning to the insulative value of recessed construction. Snow cover can add significantly to the earth's insulative effect by reducing heat exchange at the surface. Since the building is ultimately—although indirectly—coupled predominantly to the air, the value of earth sheltering as a heat conservation strategy may be inferred from conventional indeces of seasonal heating demand.

Heat conservation vs. solar supply

The magnitude of the heating season is usually characterized by its number of heating degree days, computed to base 65F. These can be used to compare the overall significance of heat conservation measures and, therefore, the regional importance of earth sheltering, super-insulation, and related practices. Base 65F heating degree days are given in Table B for each of the 29 study areas examined here.

A better index of the relative need for extreme heat conservation measures are heating degree days computed to a lower base than 65F. Degree days computed to base 50F, for example, indicate more directly the severity of the heating season. These are given in Table C, as are the percentage of annual hours falling below 50F (1% annual hours = 87 2/3 hours). The cities are listed in descending order of Base 50F heating degree days.

The need for heat conservation measures can be somewhat offset by the availability of solar heat energy. An index of solar heating demand versus solar availability is the ratio of January monthly insolation received on a vertical south-facing surface to January heating degree days. Ratios have been computed using base 65F heating degree days for over 200 stations; Figure C portrays the general distribution of these over most of the contiguous United States. Ratios for the 29 study areas are presented in ascending order (decreasing conservation need) in Table D.

The rank order of importance of earth sheltering as a winter climate control strategy may be inferred directly from Table C for "non-solar" designs, and from Table D for "solar" designs for the 29 study areas. Not surprisingly, Minneapolis tops both lists, while Miami and Los Angeles fall at the bottoms. The internal order of cities varies mostly as a result of cloudiness: Seattle, for instance, has neither a particularly severe nor mild winter by the 50F heating degree day index, but since very little winter sunshine is available as a heating resource, it is superceded only by Minneapolis on the solar:HDD ratio list.

It is not possible to define a single cut-off point above or below which earth sheltering is appropriate, although the obvious trend is clear that its value diminishes rapidly southward of the 30 to 40 solar:HDD range. In regions of high solar:HDD ratios, earth sheltering may be viewed as either less necessary, or a useful complement to passive solar design. Additional local criteria can be important in clarifying the value of earth sheltering and its most appropriate manifestation; among these are the strength and persistence of winter winds, the frequency and magnitude of "cold snaps" and other departures from winter average conditions, and the day to day dependability of the solar resource. Winter design temperatures published for sizing mechanical equipment provide clues to extreme conditions which are not represented in monthly averages. These are included in Table C. Ultimately, the decision to build underground must consider summer conditions as well as those of winter; summer considerations will be more important in determining the most suitable form.

	CONDUCTION	CONVECTION	RADIATION	EVAPORATION
PROMOTE GAIN			promote solar gain	
RESIST LOSS	minimize conduction	minimize infiltration		
RESIST GAIN	minimize conduction	minimize infiltration	minimize solar gain	
PROMOTE LOSS	earth cooling	promote ventilation	radiation to sky	evaporative cooling

Figure A. Strategies of climate control.

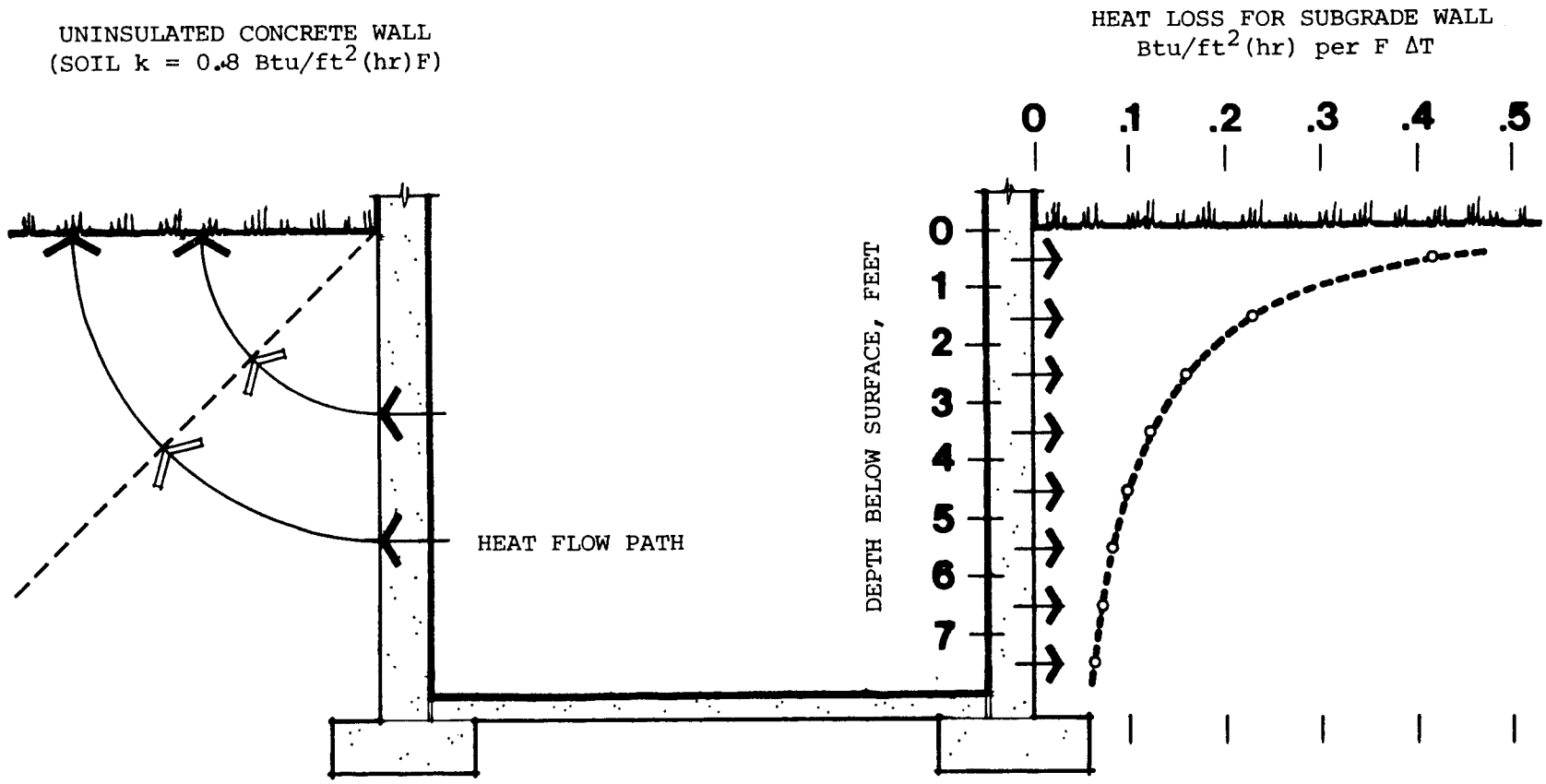

Figure B. Steady state theory of heat loss for winter predicts a circular path of heat flow from wall to surface, which may be graphed as a function of depth.

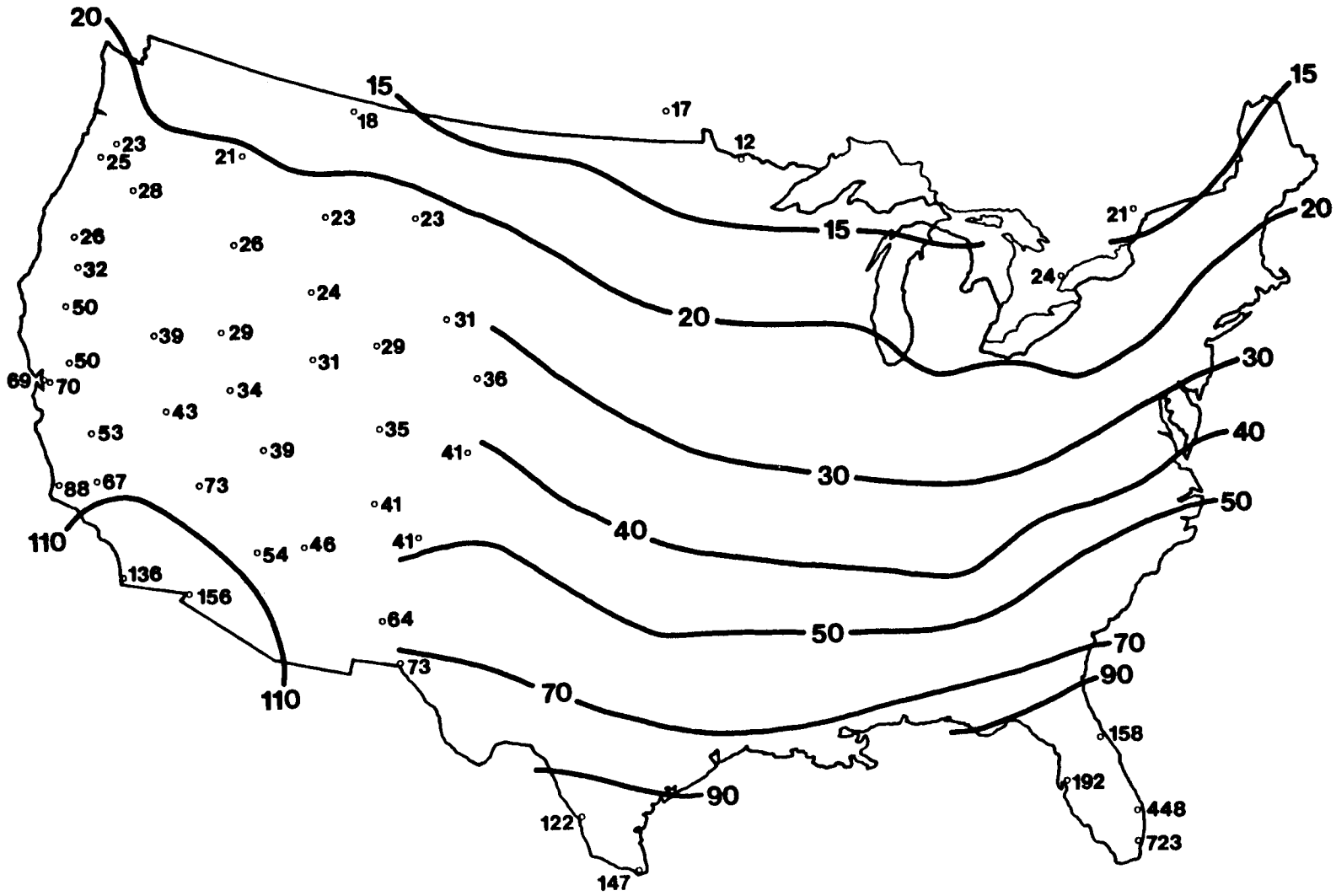

Figure C. Ratio of January monthly insolation on south vertial surfaces to January monthly heating degree days, base 65F.

EARTH TEMPERING AS A SUMMER CLIMATE CONTROL STRATEGY

Evaluation of the summer performance of earth tempering must consider not only its anticipated benefits, but its negative consequences as well. On the positive side, the ground normally offers a milder climate than the above ground during the peak of the overheated season, and in some areas, the temperature of the earth surrounding an underground building is low enough to serve as a cooling source. On the negative side, ground cooling is often accompanied by condensation, and the nature of most earth sheltering schemes interferes with the building's ability to exploit ventilating breezes.

While it is important that the advantages of ground climate be considered on its own terms, it is also necessary that earth sheltered construction be considered within the broader context of other regionally-appropriate summer climate control strategies. These have been identified in Figure A as mechanisms of restricting heat gain from entering the interior, and of promoting heat loss from the interior. Givoni's Building Bioclimatic Chart (Figure D) provides a method whereby long term weather records can be analyzed to identify the significance of each of these strategies. The relative importance of thermal mass versus ventilation, for instance, provides valuable insights into whether earth covered construction compromises or enhances exploitation of other passive design alternatives. Both positive and negative attributes of earth tempering are discussed in the following sections.

Earth cooling and coolth conservation

An at-least initial or potential reduction in seasonal cooling demand seems to be apparent from a comparison of cooling degree days (CDD) computed for different soil profiles and the air to bases 78F and 78ET*, respectively; these are presented in Table E1. As discussed in the following paragraphs, the temperature of the soil surrounding an earth sheltered structure is likely to be elevated several degrees above the predicted undisturbed temperature, as a result of carryover of winter heat losses from the building being stored in the soil. For this reason, CDD computed to a lower temperature, such as 65F, for both soil and air may provide a better basis for comparison of soil versus air cooling demand. These are given in Table E2. If not a better guide to overheatedness, this lower base better distinguishes most of the cities from one another.*

Direct comparison of simultaneous normal air and ground temperatures provides a less abstract measure of the value of ground climate. Table F lists daily average air temperatures for each of the 29 study areas for the 21st day of July, as well as the predicted normal average temperatures of the 0-6 and 2-12 foot soil profiles for the same date; these are given in order of diminishing temperature difference between air and the 2-12 foot profile temperature. The ranking offers an indication of the relative favorability of ground versus above ground climate on a regional basis. It must be noted, however, that 1) actual temperatures of ground surrounding an earth sheltered

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Although 65F is not itself an index of overheatedness, and its relationship to air conditioning energy consumption is largely unsubstantiated, it may be noted that CDD to base 65F are routinely computed and published by the National Climatic Center. Base 65F CDD are readily available for cities other than those published in this report, whereas CDD to base 78ET are not. Both 65F and 78F CDD are computed in the ground temperature tables contained in this report.

building are likely to be significantly higher than the undisturbed ground temperature predictions given here, and 2) ground profile temperatures continue to rise throughout the summer, reaching a peak in August for the 0-6 foot profile, and in September for the 2-12 foot profile.

No rules can be given for "correcting" the predictions of natural summer ground temperatures to account for the building's disturbance, as very few measurements have actually been made. One experiment found the temperature of the soil-wall interface of an insulated masonry basement wall in Columbus, Ohio to remain a fairly constant 76F (averaged over the 0-6 foot depth of the wall) throughout the months of July and August. This averages about 10F in excess of the predicted undisturbed temperature for the region. Even in Columbus, where undisturbed ground temperatures appear favorable for cooling (roughly comparable to Indianapolis or New York), the estimated heat flux outward through the wall during August and September barely exceeded 1.5 $Btu/ft^2(hr)$. Considerable caution must be exercised in interpreting the tables; if this 10F elevation in ground temperature could be extrapolated to other parts of the country, for example, then it would be expected that heat would flow into earth sheltered buildings from the surrounding walls during the summer months throughout the "Sunbelt" south of Atlanta and Jackson, Mississippi.

It is not clear that significant elevation of temperature is inevitable in southern zones: increases in temperatures observed in northern areas are due to warming of the soil by heat escaping from the building itself. As natural winter soil temperatures approach indoor comfort limits, the heat lost to and stored in the soil presumably decreases; the degree of soil temperature increase in excess of undisturbed conditions presumably also decreases. More field data is necessary in order to ascertain how much of a summer temperature elevation can be expected in southern regions (this will also be related to the amount of insulation—if any—used). There is no reason to

suspect that summer ground temperatures will ever be lower than undisturbed ground temperatures, unless deliberate attempts are made to do so through any of a number of ground temperature modification techniques—although long term mechanical cooling could depress surrounding soil temperatures in poorly insulated buildings.

The earth does isolate subgrade walls from outside air, and accordingly has an insulating effect from exterior sources of heat gain. Earth sheltering can be viewed as a coolth conservation device which is of value in extremely overheated areas where air conditioning is necessary for much of the cooling season. From a conservation standpoint alone, insulation fulfills the same function. If surrounding ground temperatures are below comfort zone limits, the ground can serve as a sink for internal heat gain, a function not served by insulation. Under many circumstances, however, ventilation can flush out internally generated heat, so earth coupling is not the only potential passive means of dissipating internal heat gains.

Condensation

Condensation occurs when the temperature of a surface falls below the dew point temperature of the air to which it is exposed. In temperate zones, dew point temperature peaks twice daily in a camelback fashion. The first peak (the daily maximum) is reached usually 3 to 4 hours after sunrise, and the second follows about 3 or 4 hours after sunset. These are nearly equal, and since they occur during daylight hours when windows are most likely to be open, the daily maximum dew point temperature is felt to be the best indicator of potential condensation conditions. These have been computed for the 21st day of July, and appear in Table G.

The possibility of condensation occurring on subgrade walls can be surmised by comparing the undisturbed temperature of the soil to the

daily maximum dew point temperature. Soil temperatures for the 2-12 foot profile are given in Table G along with the difference between them and the dew points given for each location. For general reference, soil temperature for the 6 foot depth in July is in most cases within 1F of the 2-12 foot profile average.

No actual predictions of condensation can be made because the temperature of the inside wall surface itself depends on if and how well the wall is insulated, and upon how much the surrounding ground temperature has been elevated above the predicted undisturbed value. On the other hand, indoor humidity levels are normally significantly higher than out-of-doors, since cooking, bathing, and the inhabitants themselves add moisture to the air. To some degree, the higher indoor dew point temperature offsets the higher-than-undisturbed soil temperature of the wall. Although high negative temperature differences between the soil and dew point temperatures suggest a significant likelihood of condensation, and high positive values suggest little likelihood, the zero point does not necessarily represent a crossover between where there should be concern and where not.

Ventilation and Dehumidification

Ventilation is the single most important climate control strategy for most of the continental United States; it is, for example, theoretically capable of maintaining indoor comfort for over two-thirds of the overheated period in 20 of the 29 study regions (see Table H). Ventilation is the only above ground climate control strategy of major significance in southern coastal regions, where it satisfies the cooling requirement for virtually all overheated hours when relative humidity is less than 80 percent. With passive dehumidification systems still in their infancy, ventilation remains the only nonmechanical design approach that helps to aid distress—if not provide comfort—when relative humidity exceeds 80 percent. As a result, the "ventilation

effectiveness" column of Table H understates the total number of hours in which ventilation is applicable in the absence of mechanical dehumidification or air conditioning. For this reason, Table I presents the percentage of annual hours during which dehumidification is necessary, both with and without a sensible cooling requirement. Ventilation hours are also summed with these to provide an alternative expression for the total value of air movement when mechanical controls are not utilized.

One way of interpreting these data is to argue that earth tempering techniques are superfluous in regions where the total cooling requirement is substantially met by ventilation. In such regions (falling at the bottom of Table H), earth sheltering may be viewed as an effective alternative to ventilation only if earth temperatures are low enough to provide significant cooling. This view follows from the assertion that earth sheltering, as a general rule, impedes natural ventilation. This admittedly arguable position is elaborated upon in subsequent sections.

It may also be noted that in some areas, the dust or chemical pollutant content of the air can be so high as to make ventilation unpracticable at times when it is thermally desirable or theoretically capable of providing comfort. Such conditions necessitate a closer scrutinizing of all alternative strategies.

Thermal Mass

High thermal mass construction executes the strategy of radiative cooling. Thermal mass construction is most effective in regions where there is little moisture in the air to block the transmission of outgoing radiation; consequently, high mass construction is common to almost all arid zones of the world as a traditional climate control device. Earth cover has been a means of incorporating thermal mass

into design in many of these areas.

Since the sink for radiative cooling is the sky, the roof is the single most important radiative cooling surface. Accordingly, although Givoni's Building Bioclimatic Chart (Figure D) assumes an entirely massive construction, his analysis technique is here considered to provide a useful measure of when and where earth covered roofs along provide significant benefit, without regard for wall construction. The results of the computer analysis of weather data for the 29 study areas is given in Table J. These are presented in rank order, with those regions in which earth covering provides the greatest benefit topping the list. It should be noted here that the analysis procedure only considers conditions in which massive construction would be effective in establishing comfort conditions inside; it does not consider when such construction might actually be counterproductive. For instance, in humid regions, high mass construction offers little daytime benefit (when ventilation is more important, and ventilation defeats the single-sided cycling that makes mass valuable), and compromises the effectiveness of what little nighttime cooling that may be available through ventilation and thermal radiation to the sky.

Evaporative Cooling

Evaporative cooling refers to the lowering of dry bulb air temperature by misting or passing air through wetted porous mats ("swamp" or "desert" coolers). The change of phase from liquid to water vapor absorbs heat from the air, thereby depressing its temperature. This is essentially a passive "air conditioning" technique, rather than one of architectural climate control. Because of this, there is no necessary relationship—neither supportive nor adversative—between evaporative cooling and earth tempering. Certain design approaches to underground construction can, however, enhance the effectiveness of evaporative cooling. These are discussed in the design implications

section, later in this paper. The results of the evaporative cooling analysis are presented in Table K.

Minimize Solar Gain

Rooftop vegetation can be a useful means of minimizing solar heat gain through the roof. A leafy ground cover reflects about 20 percent of incident solar radiation and shades the surface from much of the remainder. Solar heat that is intercepted at leaf level is either convected away by air as sensible heat, or converted into latent heat without rise in dry bulb temperature by evapotranspiration from leaf surfaces.

Research has shown that a well irrigated turf can dissipate 70-90 percent of the solar load by evaporation, and in the presence of hot, dry winds, the rate of heat loss can actually exceed the rate of solar receipt. The magnitude of heat dissipation by evapotranspiration can be surmised by converting the potential evapotranspiration rate for any given area into the heat of vaporization. July values range from 1340 $Btu/ft^2(day)$ for Phoenix to 502 $Btu/ft^2(day)$ for San Francisco.

The argument can be made that a simple roof spray system utilizing perorated pipe or spray heads is a much less costly alternative to vegetation in dissipating solar heat—especially since rooftop planting requires irrigation, anyway, in most climates. Roof spray systems can be operated intermittently as needed, and add no design weight to walls, columns, and footings. Lightweight roof-mounted shading panels and well-ventilated or well-insulated attics also reduce heat gain. As a result, it is here recommended that the climatic value of an earth covered roof be judged primarily on its usefulness as thermal mass for cooling.

Cooling Degree Day Reduction

An index of the ability of earth sheltering to reduce cooling demand may be obtained by expressing the number of annual degree days for a specified soil profile and annual air cooling degree days as a simple ratio. These have been computed arbitrarily to bases 65F and 78ET* for both the 0-6 foot and 2-12 foot soil profiles. They are presented in Tables E1 and E2 in rank order, with the greatest reductions (i.e., the smallest ratios) heading the list.

As might be expected, earth sheltering is most able to reduce or eliminate cooling requirements in northern zones, where mean annual ground temperatures are low. Most noteworthy here are those cities at the bottom of the list, where the ground actually represents a greater cooling load than the air with reference to base 65F cooling degree days. Also noteworthy is the fact that cooling degree day reductions are nearly always substantially lower for the deeper 2-12 foot profile than for the 0-6 foot profile. Another advantage of the deeper profile is the fact that its maximum temperature lags behind that of the surface by approximately six weeks in a soil of average thermal diffusivity, and behind that of the 0-6 foot profile by about one month.

Compatability Ratio

It was noted in a foregoing section that earth sheltering can be regarded as an impediment to maximum ventilation effectiveness, whereas earth covered roofs are fully compatible with the thermal mass strategy. One index of the overall compatibility of earth covered construction with these other passive design alternatives is obtained by dividing the percentage annual hours of mass effectiveness by those of ventilation effectiveness. Hours in excess of 80 percent relative humidity have been added to the ventilation hours, while hours below

the 5 mm Mercury vapor pressure line (refer to Figure D) have been added to mass effectiveness hours. With reference to the Building Bioclimatic Chart presented earlier, the index is formulated,

$$\text{Compatibility Ratio} = \frac{\text{zones (10-14)}}{\text{zones (9-11, 15)}}$$

When the ratio is greater than one (mass favored), it is assigned a positive value; when it is less than one (ventilation favored), the reciprocal of the ratio is used, and given a negative sign. These ratios are listed in rank order, with those cities favoring earth covering listed at the top, and those in which earth sheltering may compromise the most appropriate strategy at the bottom, in Table L.

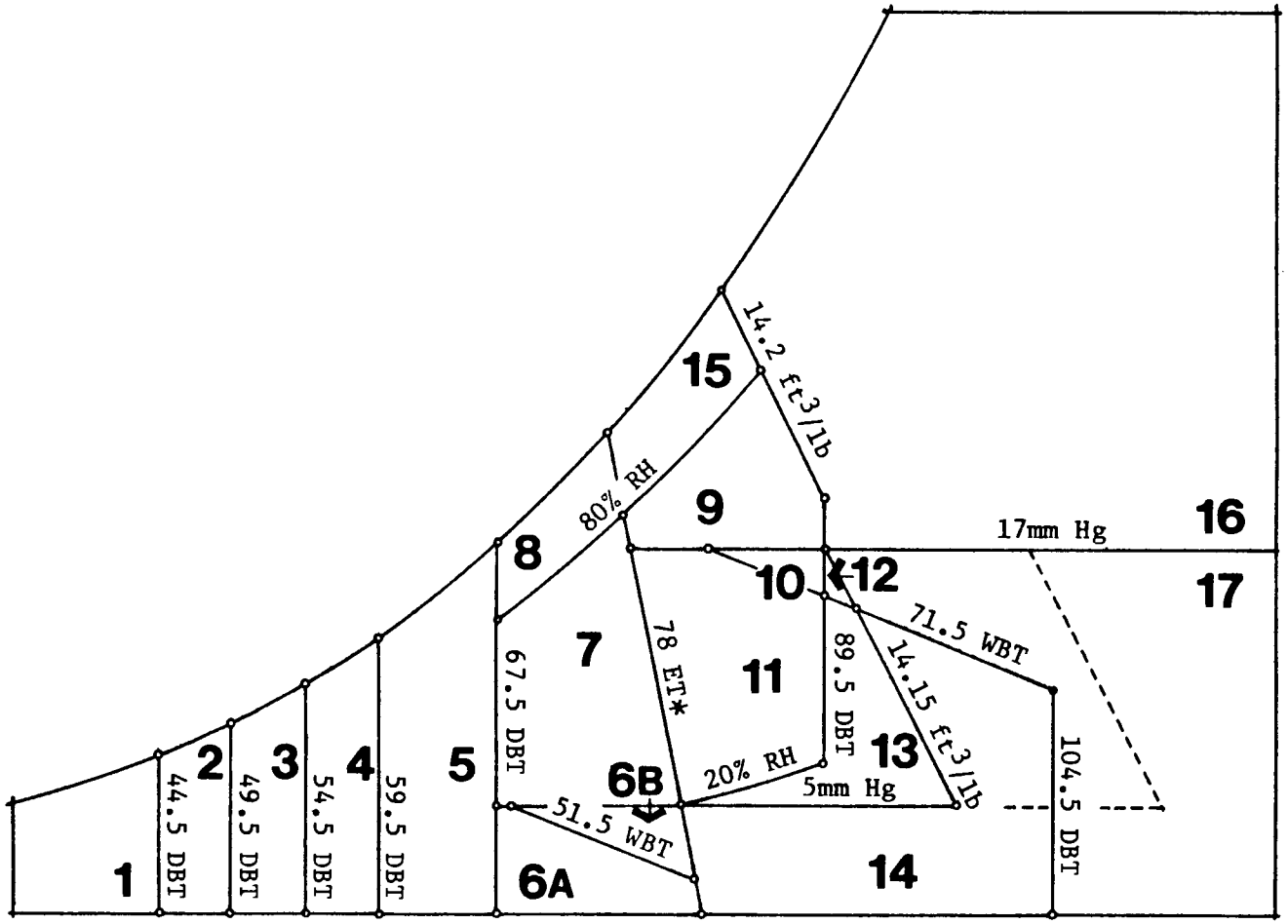


Figure D. Building Bioclimatic Chart (after Givoni).

Identification of climate control strategies on the Building Bioclimatic Chart (adapted after Givoni).

BIOCLIMATIC NEEDS ANALYSIS	
Total heating (< 68F)	1-5
Total cooling (> 78ET*)	9-17
Total comfort (68F - 78ET*, 5mm Hg - 80% RH)	7
Dehumidification (> 17 mm Hg or 80% RH)	8-9, 15-16
Humidification (< 5 mm Hg)	6A, 6B (14)
STRATEGIES OF CLIMATE CONTROL	
Restrict conduction	1-5; 9-11, 15-17
Restrict infiltration	1-5; 16-17
Promote solar gain	1-5
Restrict solar gain	6-17
Promote ventilation	9-11
Promote evaporative cooling	11, 13-14 (6B)
Promote radiant cooling	10-13
Mechanical cooling	17
Mechanical cooling & dehumidification	15-16

TABLE A. Ground profile versus air temperatures, January 21.

Location	Ground Temperature (0 - 6)	Ground Temperature (2-12)	Air Temp (Daily Avg)	Grnd - Air*
Minneapolis	33	42	7	35
Kansas City	42	50	26	24
Salt Lake City	41	50	26	24
Windsor Locks	38	47	24	23
Oklahoma City	48	57	34	23
Chicago	38	46	24	22
Denver	42	50	28	22
Indianapolis	42	50	28	22
Albuquerque	49	57	35	22
Midland	58	65	43	22
Dallas	58	65	43	22
San Antonio	65	71	50	21
Little Rock	52	59	39	20
Houston	66	72	53	19
Tucson	61	67	49	18
Nashville	48	55	38	17
Jackson	56	63	46	17
Phoenix	61	67	50	17
Boston New York	40	47	31	16
New York	41	49	33	16
Atlanta	52	59	43	16
Raleigh	50	57	42	15
Washington, DC	43	51	37	14
Medford	45	51	37	14
Seattle	44	48	36	12
San Francisco	56	60	48	12
New Orleans	60	66	54	12
Los Angeles	61	66	54	12
Miami	68	72	69	3

* "Grnd" refers to 2-12' profile

TABLE B. Air versus Earth Heating Degree Days (base 65F).

Location	Air HDD	Earth (2-12) HDD		Earth (0-6) HDD	
		annual	as % air	annual	as % air
Minneapolis	8119	6388	79	6393	79
Windsor Locks	6727	4927	73	5017	75
Denver	6417	4196	65	4373	68
Chicago	6307	4926	78	5064	80
Salt Lake City	6230	4194	67	4420	71
Boston	5845	4927	84	4951	85
Indianapolis	5798	3466	60	3968	68
Seattle	5690	4926	87	4931	87
Medford	5468	4197	77	4199	77
New York City	5162	4196	81	4375	85
Kansas City	5035	3466	69	3968	79
Albuquerque	4578	2100	46	2713	59
Washington, DC	4408	3466	79	3829	87
Oklahoma City	4005	1809	45	2502	62
Nashville	3918	2212	56	2792	71
Raleigh	3713	1677	45	2272	61
San Francisco	3705	956	26	1399	38
Little Rock	3281	1284	39	1947	59
Atlanta	3127	1284	41	1947	62
Midland	2993	358	12	1011	34
Dallas	2567	315	12	925	36
Jackson	2546	539	21	1151	45
Tucson	2086	64	3	579	28
Los Angeles	1985	590	30	590	30
Phoenix	1864	64	3	579	31
San Antonio	1765	0	0	141	8
New Orleans	1539	128	8	546	35
Houston	1163	0	0	0	0
Miami	285	0	0	0	0

TABLE C. Severe winter temperature indicators.

Location	%HR < 50F	50F HDD	ASHRAE Design Temp	
			97½%	99%
Minneapolis	53.3	4584	-12	-16
Windsor Locks	50.0	2971	4	0
Chicago	47.8	2954	0	-4
Salt Lake City	49.8	2648	8	3
Denver	48.9	2592	1	-5
Indianapolis	44.6	2511	2	-2
Kansas City	39.5	2417	6	2
Boston	47.4	2374	9	6
Washington, DC	36.9	2004	17	14
New York City	43.9	1931	15	11
Medford	48.7	1576	23	19
Albuquerque	38.5	1497	16	12
Seattle	51.5	1397	26	21
Oklahoma City	32.6	1232	13	9
Nashville	32.0	1195	14	9
Raleigh	31.0	990	20	16
Little Rock	27.9	984	20	15
Atlanta	26.2	758	22	17
Midland	24.9	627	21	16
Dallas	21.3	505	22	18
Jackson	21.1	471	25	21
Tucson	17.1	214	32	28
San Antonio	13.9	213	30	25
San Francisco	20.7	202	38	35
New Orleans	11.3	197	33	29
Phoenix	14.9	187	34	31
Houston	7.3	161	32	27
Los Angeles	7.4	64	43	41
Miami	1.1	3	47	44

TABLE D. January Solar: Heating Degree Day Ratio

Location	Jan VS[a] Solar	Jan[b] HDD	$\frac{\text{Solar}}{\text{HDD}}$ ratio[c]
Minneapolis	921	1637	17
Seattle	559	831	21
Windsor Locks	869	1246	22
Chicago	921	1262	23
Indianapolis	850	1150	23
Boston	878	1110	25
Medford	752	880	26
New York City	884	1017	27
Kansas City	1098	1175	29
Washington, DC	959	1020	29
Salt Lake City	1129	1147	31
Nashville	900	828	34
Denver	1440	1088	41
Oklahoma City	1220	874	43
Little Rock	1092	791	43
Raleigh	1071	760	44
Atlanta	1041	701	46
Albuquerque	1530	924	51
Jackson	1053	569	57
Dallas	1164	608	59
San Francisco	1145	518	69
Midland	1496	663	70
Houston	1014	416	76
San Antonio	1160	451	80
New Orleans	1097	403	84
Tucson	1529	442	107
Phoenix	1472	428	107
Los Angeles	1353	331	127
Miami	1236	53	723

a Normal daily insolation on vertical south surface, Btu/sq ft(day)
b Base 65 monthly Heating Degree Days
c Total monthly vertical south surface insolation/Jan. HDD

TABLE E1. Base 65F Cooling Degree Day Ratios

Location	CDD 65F (Air)	CDD 65F (0-6)	(0-6)[a] / Air	CDD 65F (2-12)	(2-12)[a] / Air
Medford	927	0	0	0	0
Minneapolis	860	0	0	0	0
Seattle	246	0	0	0	0
Boston	790	23	3	0	0
Windsor Locks	817	88	11	0	0
Chicago	1144	132	12	0	0
Denver	927	168	17	0	0
Salt Lake City	1273	221	17	0	0
New York City	927	176	19	0	0
Washington, DC	1474	360	24	0	0
Kansas City	1791	496	28	0	0
Nashville	1824	784	43	205	11
Indianapolis	1155	496	43	0	0
Albuquerque	1576	706	45	92	6
Phoenix	3957	2220	56	1707	43
Oklahoma City	2015	1223	61	532	26
Raleigh	1596	994	62	402	25
Little Rock	2207	1399	63	737	33
Tucson	3265	2220	68	1707	52
Midland	2578	1923	75	1275	49
Atlanta	1786	1399	78	737	41
New Orleans	2763	2188	79	1772	64
Jackson	2440	2063	85	1454	60
Dallas	2967	2567	86	1958	66
Miami	4022	3829	95	3834	95
San Antonio	3111	3242	104	3103	100
Houston	3029	3832	127	3834	127
Los Angeles	581	1501	258	1071	184
San Francisco	207	848	410	410	198

[a] expressed as a percentage

TABLE E2. Base 78ET* Cooling Degree Day Ratios.

Location	CDD 78ET* (Air)	CDD 78F (0-6)	(0-6)[a] / Air	CDD 78F (2-12)	(2-12)[a] / Air
San Francisco	13	0	0	0	0
Seattle	19	0	0	0	0
Los Angeles	28	0	0	0	0
New York City	125	0	0	0	0
Boston	127	0	0	0	0
Windsor Locks	141	0	0	0	0
Denver	145	0	0	0	0
Minneapolis	160	0	0	0	0
Medford	214	0	0	0	0
Indianapolis	228	0	0	0	0
Chicago	241	0	0	0	0
Salt Lake City	275	0	0	0	0
Albuquerque	295	0	0	0	0
Washington, DC	322	0	0	0	0
Raleigh	374	0	0	0	0
Atlanta	397	0	0	0	0
Nashville	486	0	0	0	0
Kansas City	496	0	0	0	0
Oklahoma City	593	0	0	0	0
Little Rock	674	0	0	0	0
Phoenix	1554	140	9	0	0
Midland	731	81	11	0	0
Tucson	987	140	14	0	0
New Orleans	772	117	15	0	0
Jackson	714	164	23	0	0
Dallas	1051	415	39	0	0
San Antonio	972	577	59	63	1
Miami	1045	690	66	269	26
Houston	988	834	84	361	37

[a] expressed as a percentage

TABLE F. July 21 air versus (2-12') profile earth temperature.

Location	(2-12)	DBT	(2-12) - DBT
Salt Lake City	56	78	-22
Minneapolis	53	74	-21
Kansas City	60	81	-21
Washington, DC	60	80	-20
Chicago	56	77	-19
Phoenix	72	91	-19
New York City	58	76	-18
Denver	56	73	-17
Boston	56	73	-17
Medford	56	73	-17
Windsor Locks	56	73	-17
Oklahoma City	66	82	-16
Nashville	64	80	-16
Albuquerque	62	78	-16
Indianapolis	60	75	-15
Little Rock	68	82	-14
Tucson	72	85	-13
Midland	70	83	-13
Dallas	74	87	-13
Raleigh	66	78	-12
Seattle	54	65	-11
Jackson	72	82	-10
Atlanta	68	78	-10
New Orleans	73	82	-9
San Antonio	76	84	-8
Houston	79	84	-5
Miami	78	82	-4
Los Angeles	68	69	-1
San Francisco	66	60	+6

TABLE G. Condensation index.

Location	(2-12)[a]	DPT[b]	Cond Indx[c]
San Francisco	66	55	11
Los Angeles	69	61	8
Tucson	72	64	8
Albuquerque	62	55	7
Phoenix	72	66	6
Midland	70	65	5
Salt Lake City	56	51	5
Denver	56	51	5
Houston	79	76	3
San Antonio	76	73	3
Miami	78	76	2
Dallas	74	72	2
Medford	56	55	1
Jackson	72	74	-2
Seattle	54	56	-2
Atlanta	68	72	-4
Oklahoma City	66	70	-4
New Orleans	73	77	-4
Little Rock	68	75	-7
Raleigh	66	73	-7
Nashville	64	72	-8
Boston	56	65	-9
Washington, DC	60	71	-11
Kansas City	60	71	-11
Indianapolis	60	71	-11
New York	58	69	-11
Windsor Locks	56	68	-12
Chicago	56	69	-13
Minneapolis	53	68	-15

a Earth profile temperature (approx. same for 6' depth), July 21 (F)
b Average daily maximum dew point temperature, July 21 (F)
c Condensation index is the difference between (2-12) and DPT

TABLE H. Ventilation effectiveness

Location	Overheatedness % Year > 78ET*	Vent Effect % annual hrs	Vent Effect % ovrhtd hrs
Phoenix	35.7	13.6	38
Tucson	29.5	11.6	39
Denver	7.1	3.1	44
Salt Lake City	10.2	4.5	44
Albuquerque	12.4	6.1	49
New Orleans	33.5	19.2	57
Houston	40.4	22.9	57
San Antonio	34.0	21.1	62
Midland	23.7	15.2	64
Medford	7.4	5.0	67
Little Rock	23.3	15.7	67
Dallas	31.9	21.5	67
Jackson	25.3	17.2	68
Miami	50.2	35.4	70
Oklahoma City	20.1	14.8	74
Los Angeles	2.0	1.5	75
Nashville	18.4	14.2	77
Washington, DC	14.2	10.9	77
Windsor Locks	6.9	5.4	78
Raleigh	15.1	11.9	79
Kansas City	17.9	14.1	79
New York City	7.1	5.7	80
Atlanta	17.2	14.2	83
Chicago	10.0	8.5	85
Indianapolis	10.6	9.0	85
San Francisco	0.8	0.7	88
Minneapolis	7.2	6.3	88
Boston	6.0	5.3	88
Seattle	1.2	1.1	92

TABLE I. Dehumidification and ventilation need (% annual hours).

Location	Dehum only (zone 8)	Dehum + Clg (zone 15)	Vent + Dehum (8 + 15)
San Francisco	0.0	0.0	0.7
Seattle	0.0	0.0	1.1
Los Angeles	1.4	0.0	2.9
Denver	0.0	0.0	3.1
Salt Lake City	0.0	0.0	4.5
Medford	0.0	0.0	5.0
Albuquerque	0.0	0.0	6.1
Boston	3.4	0.4	9.1
Minneapolis	2.5	0.6	9.4
Windsor Locks	4.5	0.9	10.8
Chicago	3.5	0.8	12.8
Tucson	1.3	0.0	12.9
New York City	6.7	1.2	13.6
Phoenix	0.5	0.5	14.6
Indianapolis	6.1	1.3	16.4
Midland	2.4	0.0	17.6
Washington, DC	6.7	2.3	19.9
Kansas City	3.9	1.9	19.9
Nashville	8.6	3.0	23.1
Oklahoma City	6.9	2.2	23.9
Raleigh	10.7	2.5	25.1
Atlanta	10.7	2.0	26.9
Little Rock	9.1	6.1	30.9
Dallas	5.9	5.1	32.5
Jackson	12.7	6.6	36.5
San Antonio	10.6	6.5	38.2
New Orleans	15.5	14.1	48.8
Houston	14.0	17.5	54.4
Miami	15.9	14.7	66.0

TABLE J. Thermal mass effectiveness.

Location	Overheatedness % Year > 78ET*	Mass Effect % annual hrs	Mass Effect % ovrhtd hrs
Seattle	1.2	1.2	100
San Francisco	0.8	0.8	100
Medford	7.4	7.2	97
Midland	23.7	21.6	91
Los Angeles	2.0	1.6	80
Phoenix	35.7	27.6	77
Salt Lake City	10.2	7.8	76
Boston	6.0	4.3	72
Albuquerque	12.4	8.8	71
Tucson	29.5	20.5	69
Chicago	10.0	6.8	68
Minneapolis	7.2	4.9	68
Denver	7.1	4.6	65
Windsor Locks	6.9	4.1	59
Oklahoma City	20.1	11.7	58
Kansas City	17.9	10.4	58
Indianapolis	10.6	5.8	55
Atlanta	17.2	9.2	53
New York City	7.1	3.7	52
San Antonio	34.0	17.3	51
Dallas	31.9	15.6	49
Washington, DC	14.2	6.9	49
Nashville	18.4	8.8	48
Raleigh	15.1	7.1	47
Jackson	25.3	9.1	36
Little Rock	23.3	8.1	35
Miami	50.2	8.9	27
New Orleans	33.5	5.4	16
Houston	40.4	1.4	3.5

TABLE K. Evaporative cooling effectiveness.

Location	Overheatedness % Year > 78ET*	Evap Cooling % annual hrs	Evap Cooling % ovrhtd hrs
Salt Lake City	10.2	10.2	100
Denver	7.1	7.1	100
Seattle	1.2	1.2	100
San Francisco	0.8	0.8	100
Albuquerque	12.4	12.3	99
Medford	7.4	7.3	99
Tucson	29.5	28.2	96
Midland	23.7	21.8	92
Los Angeles	2.0	1.8	90
Phoenix	35.7	26.2	73
Boston	6.0	3.7	62
Minneapolis	7.2	4.2	58
Windsor Locks	6.9	4.0	58
Chicago	10.0	5.6	56
Indianapolis	10.6	4.9	46
Kansas City	17.9	8.1	45
Washington, DC	14.2	6.2	44
New York City	7.1	3.1	44
Atlanta	17.2	6.9	40
Oklahoma City	20.1	7.9	39
Raleigh	15.1	5.6	37
Nashville	18.4	6.7	36
San Antonio	34.0	10.2	30
Dallas	31.9	8.9	28
Jackson	25.3	6.5	26
Little Rock	23.3	5.7	24
Miami	50.2	7.4	15
New Orleans	33.5	4.0	12
Houston	40.4	1.2	3

TABLE L. Compatibility Ratio.

Location	Compatibility Ratio
Houston	-28.64
New Orleans	-5.87
Miami	-5.56
Little Rock	-2.38
Jackson	-2.34
Raleigh	-1.92
New York City	-1.84
Nashville	-1.83
Indianapolis	-1.72
Washington, DC	-1.72
Atlanta	-1.71
San Antonio	-1.51
Dallas	-1.51
Kansas City	-1.41
Oklahoma City	-1.35
Minneapolis	-1.34
Windsor Locks	-1.32
Chicago	-1.31
Boston	-1.28
Seattle	+1.09
San Francisco	+1.14
Los Angeles	+1.20
Medford	+1.48
Midland	+1.53
Albuquerque	+2.02
Salt Lake City	+2.27
Denver	+2.29
Phoenix	+2.30
Tucson	+2.48

DISCUSSION AND CONCLUSIONS

Limitations

Although the details and limitations of the analysis techniques used in obtaining data for this summary are discussed in detail in the technical section of this report, some of the limitations of the procedures and analysis should be mentioned here. These involve 1) validity of the data available for analysis, and 2) the applicability of the analysis methods.

The weather data procured for analysis were recorded at airport weather stations and consist of hourly or tri-hourly readings taken over (in most cases) 30 year periods. This data only truly portrays the climate of the airport location, and does not necessarily represent the climate of the broader region. Caution must be exercised in extending the data beyond the airport station, and in interpolating between different cities for which data is given. Microclimatic effects can be responsible for significant differences within a geographic region, and many airports themselves are characterized by conditions atypical of the broader region (location along bodies of water, for example). Air quality conditions (dust, odors, etc.) are not recorded, and these are not considered in the analyses even though they may affect the desirability of ventilation.

The bioclimatic analysis procedure is based on a model devised by Givoni which applies to residential scale buildings devoid of appreciable internal heat gains. The analysis of appropriate strategies, therefore, is not directly relevant to the design of large offices or industrial buildings where lighting and other processes contribute significantly to the cooling load. The use pattern of the building

can also alter the usefulness of the data: high mass construction is of value in suppressing indoor temperature rise during the daytime, but it does so at the expense of retarding the rate of nighttime cooling. A low mass structure might, consequently, be preferred for a house which is unoccupied during the daytime but which is intensively used in the evening and at night. The analysis procedure used here considers 24 hour data.

There exists no body of recorded ground temperatures that is useful to the building industry. In order to fill this void, an extensive set of ground temperature tables has been synthesized for this study through use of a mathematical temperature model. The model applies strictly only to homogeneous soils (i.e., without layering) which posses constant thermal properties over time. Although these conditions rarely truly exist, the model has been shown to provide reasonably accurate estimations of ground temperature by numerous experimenters in the U.S. and abroad. Data has been selected from the tables to represent expected regional average values for each of the 29 study areas. Such a method is always subject to some error, but for most purposes related to climate design, the data is felt to be quite adequate. It may also be noted that the data selected for discussion here pertains to ground climate near the surface; temperatures at greater depths and for deeper profiles have been modeled and are presented in the tables.

Heat exchange between buildings and the soil is not well understood, especially during the cooling season. It is known that any device which exchanges heat with the soil must unavoidably alter its initial or undisturbed temperature; the undisturbed temperatures predicted by the tables must, therefore, be regarded as lower limits of likely temperatures to be found in the vicinity of a building, and not the actual disturbed temperatures themselves. The undisturbed temperatures cannot be used to calculate heat flux in and out of the structure in their present form.

The final limitation of this study is that its scope is restricted to identifying strategies for climate control in design, whereas the actual performance of the building will depend upon the specifics of its physical design, or the details of the execution of these strategies. Other publications describing design aspects of various strategies are already available, and these can provide insights into the climatic detailing of the interface between the surface and the subsurface. Building underground does not automatically simplify climatic design, and the practice should not be viewed as an isolated alternative to above ground passive design techniques. A major aim of this report, therefore, is to identify consonance and conflict between above and underground alternatives.

General trends

Comparison of the various indicators of summer advantages of earth tempering reveals a general trend that the favorability of ground climate increases with aridity. The value of earth covered roofs increases with aridity, and conflict with the need for natural ventilation diminishes at the same time. Mapping of the favorability of below ground versus above ground climate (based on temperature differences) also shows increasing benefit with aridity within the same latitude range. This is related to both the greater diurnal air temperature range characteristic of arid zones, as well as the smaller thermal diffusivity (and, therefore, faster temperature damping with depth) of dry soil.

While the need for all available controls on reducing heat gain and promoting heat loss are greatest in the South, the ability of earth tempering to contribute significantly to climate control in summer increases with decreasing soil temperature, or with movement northward. Overall, it may be said that earth tempering techniques

are ideally and most uniquely suited to regions of cloudy, cold winters, and dry, overheated summers. These conditions are typical of the northwest cities of Seattle and Medford. Earth sheltering and earth covered construction is also ideally—although less uniquely-suited to regions of cold, sunny winters and hot, dry summers. Typical of these are Salt Lake City, Denver, and Albuquerque. Earth tempering practices of all kinds offer substantial advantages and no discernible disadvantages in these five areas, except for the fact that extraordinarily high winter rainfall rates in the Northwest increase soil conductivity (and, therefore, winter heat loss from underground structures) when this is least desirable.

Northern states

Very important winter advantage is to be had for underground construction throughout the entire middle and eastern northern section of the United States. Significant summer advantages exist here, too, although with 1) the likelihood of condensation, and 2) an expected sacrifice in ventilating ability. Ventilation and dehumidification are the most important summer strategies of climate control throughout the Midwest and Northeast, so these issues remain to be addressed in earth tempered design; the suitability of earth tempering in the north central and northeastern states ultimately depends upon how successfully they are addressed. Roof mass is less important in these areas than in the West. If it is necessary to uncouple the interior from the surrounding soil to reduce the potential of condensation, then earth sheltering offers no unique climate control benefit compared to other heat conservation strategies, such as superinsulation. It is possible to design a superinsulated house to ventilate more effectively than an earth sheltered house, so earth tempering is not necessarily the best overall strategy for humid northern zones. On the other hand, mechanical ventilation can be provided at small energy cost, so ventilation alone need not be a decisive factor.

Sunbelt

The southern Sunbelt requires little in the way of heat conservation, so the value of earth tempering must be judged primarily on its summer usefulness. The "compatibility ratio" gives very poor scores for southern Florida and the Gulf Coast as a whole; roof mass here is of little value and subgrade placement is likely to interfere with the most important strategy of natural ventilation. Condensation may be a problem throughout much of the Southeast, although not so persistently as in its northern counterpart. Ground temperatures are too high to actually serve as a sink for indoor heat except at undesirably high temperatures, so the value of below grade placement must be judged on whether it offers significant reductions over outdoor temperatures, and on reductions in overall cooling load.

From the indices examined here, it is felt that earth tempering offers little on its own merit along the Gulf and southern Atlantic Coasts, and that it is likely to interfere with the more important strategy of natural ventilation. Overhangs, exterior shade panels, landscaping, and insulation are means of restricting heat gain for above grade structures, and the former two of these can be used to enhance the usefulness of natural breezes. Earth sheltering, therefore, may be viewed as offering no unique nor superior advantage, and a very possible disadvantage along southern coasts. These disadvantages diminish, and the advantages begin to increase, with movement northward. There is no way at present at judging where in the Southeast earth sheltering begins to offer unqualified positive advantage; ultimately, this is always a matter of design and site specifics. Probably, the region extending from North Carolina through Arkansas may be considered marginal in terms of both positive and negative value.

Structures of deep placement present a more complex thermal problem which cannot readily be evaluated within the methodology of this

study. Additional theoretical and empirical data will be required before the thermal interactions between the earth and structures with more than 5 or 10 feet of earth cover are well understood.

Texas and Southwest

The benefits of earth tempering do not appreciate greatly with increasing aridity, but its drawbacks disappear with decreasing humidity. This is nowhere more apparent than with movement across Texas: while there is nothing to recommend earth sheltering in Houston, Dallas and San Antonio show less need for ventilation relative to the value of mass, and in west Texas, earth tempering is fully consonant with competing passive design alternatives. In the arid West, earth sheltering is an effective way of removing sidewalls from the extreme heat of the day, and earth covered roofs—with or without planting-provide desirable thermal mass facing the sky. Still, ground temperatures are high throughout southern California, Arizona and New Mexico, so special care should be taken in making the best use of insulation and design form to maximize the benefits of earth climate. The cooling degree day analyses do show major reductions in cooling load as a result of full subgrade placement. Moreover, ground temperature modification techniques are most effective in arid climates, so the ground may be made to have greater advantage than indicated by studies of undisturbed ground temperatures.

California coast

The remaining region considered in this study is the California coast. The climate of California is complex and varies greatly both north and south and east and west; the conclusions made concerning the coastal regions should not be inferred to apply very far inland. The state as a whole deserves its own detailed study of climate, a

task beyond the scope of this paper.

The most remarkable thing about the California coast is its temperature stability throughout the year, and the nearness of these conditions to comfort zone levels. Neither Los Angeles nor San Francisco have severe heating or cooling requirements compared to much of the rest of the country. While San Francisco has the largest percentage of annual hours below comfort level, it ranks among the lowest in base 65F heating degree days. Most indicators of the suitability of earth tempering practices show these as favorable; the cooling degree day ratios are an exception, suggesting that the ground presents a much warmer summer thermal environment than the air. Due to the dryness of summers in both cities, however, roof mass is favorable, and the ground temperatures themselves are not high. One can conclude that the comfort control problem is not difficult here, and earth tempering fits into a range of suitable climate control techniques.

SUMMARY

Climate control ordinarily is a very complex problem which defies simple conclusions. This is particularly true of earth sheltering, where the complexities of both above and below ground climate must be evaluated simultaneously. At the risk of oversimplification and possible future misinterpretation, however, it is felt that the major design-related issues of ground versus above ground climate are most vividly summarized in a single map, which immediately follows.

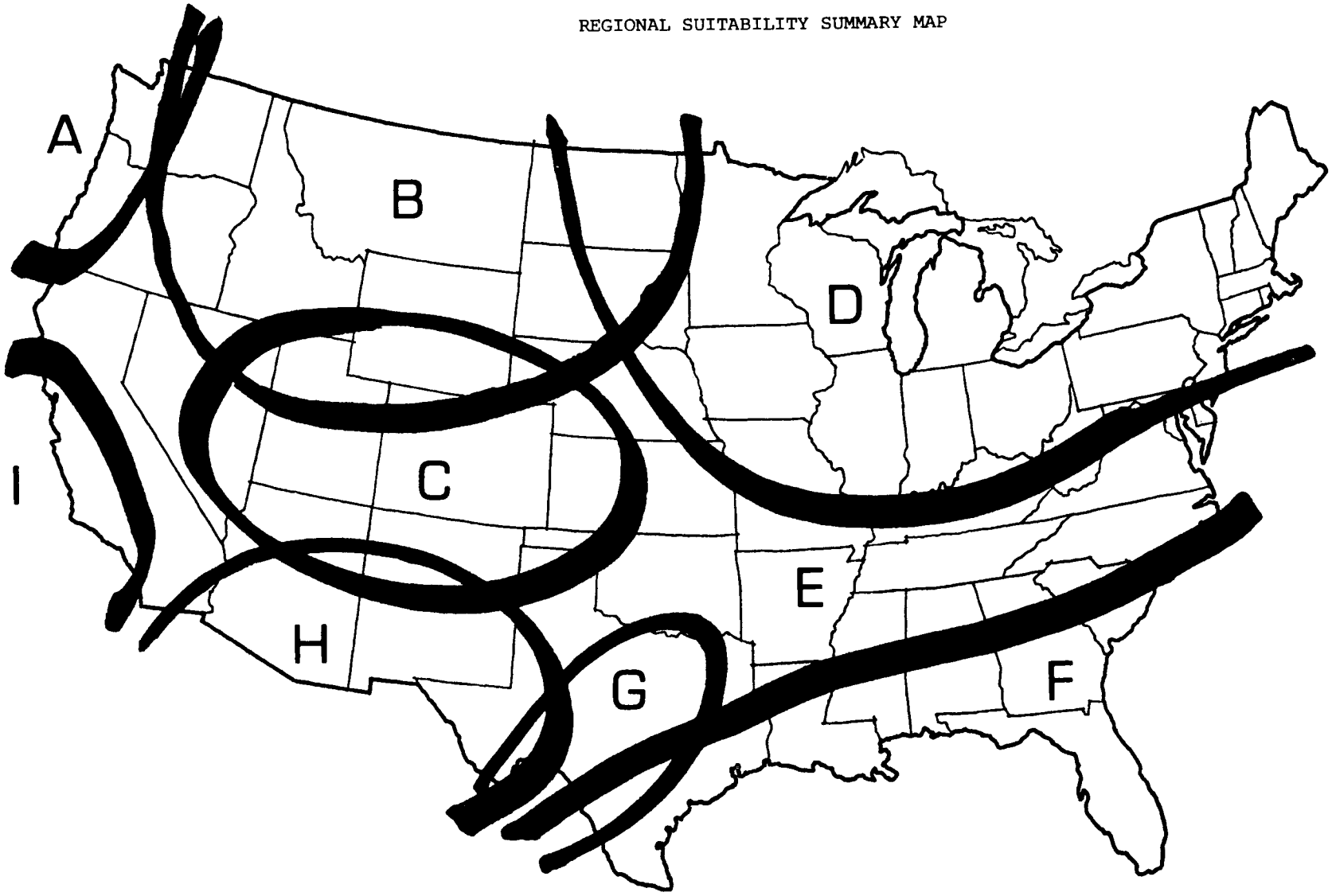
There are numerous nonthermal climatic benefits and nonclimatic advantages of underground construction that equal or supercede the importance of thermal issues alone. Among these are regional threats of hurricanes, tornadoes, and firestorms, and such site specific issues as noise control, preservation or scenic landscapes, and nature conservation. Whether initially considered for energy conservation or for other reasons, the climatic data contained in this report can be used in "tuning" the earth tempered structure to its region. Additional local climatic data should also be considered in this process.

Earth tempering offers benefits on its own terms for most areas of the United States. When compared to the appropriateness of other passive design techniques, however, some of these benefits are outweighed by the potential disadvantages. The real measure of this value cannot be found in analyses of raw data: the climate control successfulness of any structure ultimately depends not upon whether it is above or below grade, but upon how it is designed.

SYNOPSIS OF REGIONAL EARTH TEMPERING ISSUES

A	Cold, cloudy winters maximize value of earth tempering as a heat conservation measure. Cool soil and dry summers favor subgrade placement and earth cover, with little likelihood of condensation.
B	Severely cold winters demand major heat conservation measures, even though more sunshine is available here than on the coast. Dry summers and cool soil favor earth covered roofs and ground coupling.
C	Good winter insolation offsets need for extraordinary winter heat conservation, but summer benefit is more important here than in zone B. Earth cover is advantageous, the ground offers some cooling; condensation is unlikely, and ventilation is not a major necessity.
D	Cold and often cloudy winters place a premium on heat conservation. Low summer ground temperatures offer a cooling source, but with possibility of condensation. High summer humidity makes ventilation the leading conventional summer climate control strategy. An above ground superinsulated house designed to maximize ventilation is an important competing design approach.
E	Generally good winter sun and minor heating demand reduce the need for extreme heat conservation measures. The ground offers protection from overheated air, but not major cooling potential as a heat sink. The primacy of ventilation and the possibility of condensation compromise summer benefits. Quality of design will determine actual benefit realized here.
F	High ground temperatures. Persistent high humidity levels largely negate value of roof mass and establish ventilation as the only important summer cooling strategy. Any design that compromises ventilation effectiveness without contributing to cooling may be considered counterproductive.
G	This is a transition area between zones F and H, comments concerning which apply here in degree. The value of earth tempering increases moving westward through this zone, and diminishes moving southward.
H	Summer ground temperatures are high, but relatively much cooler than air. Aridity favors roof mass, reduces need for ventilation, eliminates concern about condensation. Potential for integrating earth tempering with other passive design alternatives is high.
I	Extraordinary means of climate control are not required due to relative moderateness of this zone. Earth tempering is compatible with other strategies, with no strong argument for or against it.

REGIONAL SUITABILITY SUMMARY MAP



TECHNICAL DOCUMENT

CLIMATOGRAPHY AND ARCHITECTURE

Climatography refers to the description of climate. It has been common practice in discussions of climate and architecture to partition geographic areas into climatic zones which are supposed to share similar climatic conditions. The purpose of this partitioning is to permit generalized design guidelines to be made on a regional basis. Climatography as related to architectural design is poorly developed, however; as a result, regional delineations are often arbitrary, or borrowed from other disciplines, thereby having little or no meaning for architectural practice.* The few principal climatic studies related to architectural design are briefly discussed below.

Climate Control Project

House Beautiful magazine's "Climate Control Project" [44] was the earliest and remains the most extensive description of various regional climates and their individual implications for design. The original intent of the Climate Control Project was to subdivide the United States into housing zones. This approach was quickly abandoned, as it became clear to the authors [80] "that either there had to be hundreds of zones, or that simplified larger zones, based primarily upon temperature and precipitation, would be unreliable because of other factors such as sunshine, wind, humidity, and so forth." Finally, it was decided to select fifteen population centers on a more or less arbitrary basis and to delineate primary and secondary zones (of 5% and 10% variation from the norm) of similarity enveloping the weather station center (Figure 1).

*Many different schemes of climatic classification are presented in Visher's Climatic Atlas of the United States [88].

Climatic data based on 5 years of hourly records were published for each of the fifteen zones in the Bulletin of the American Institute of Architects, while articles describing prototypical house designs for each region were concurrently published in House Beautiful. The overall emphasis of the Climate Control Project was placed on the diversity of the nation's climates, and the unsuitability of transposing any design from one region to another. The fifteen cities ultimately selected were not purported to represent specific climatic regions, nor was the decision to publish fifteen regions intended to indicate the existence of only fifteen climatic regions in the United States.

Four Zone System

Despite the effort of the Climate Control Project to discredit the simplification of the climate of the United States into four zones [81], probably the most familiar partitioning of the country is into "cool," "temperate," "hot-humid" zones (Figure 1). This scheme apparently was popularized by Victor Olgyay [71], who simplified Koeppen's global classification of climate. Although Victor and Aladar Olgyay introduced the important concept of "bioclimatic analysis"—or relating climatic conditions to human comfort—the Koeppen classification itself is based on mapping of vegetation, and has nothing to do with human thermal comfort factors. The Olgyays chose the cities of Miami, Phoenix, Minneapolis, and New York to represent the four zones. The former three of these are probably more representative of the extremes of their respective regions than the means, and New York, as a coastal city, can be viewed as a poor indicator of all the temperate inland regions it is intended to represent.

Six Zone System

A six zone macroclimatic classification of the United States was

delineated by geographer Paul Grogger [40] in a paper describing the relationship of microclimates to building design (Figure 2). Guidelines were offered on the suitability of different housing types to the six regions (Table 1), although the discussion emphasized the importance of microclimatic influences within each zone (Table 2). Grogger's six zones are designated "cold," "cool/humid," "cool/humid-arid," "cool/arid," "hot/arid," and "hot/humid." The temperature partitioning limits are given in Table 3. The humidity index is based on the precipitation/potential evapotranspiration ratio: if the ratio is greater than one, the area is designated humid, and if less than one, it is considered arid. On the West Coast, seasonal variations in moisture availability leads to a humid-arid combination. It can be argued that the P/PE ratio is a poor index of moisture conditions with respect to building design. Givoni [32], instead uses mean vapor pressure as an indicator of the suitability of thermal mass and evaporative cooling as climate control strategies.

AIA/RC-HUD-DOE Regional Guidelines

A sixteen zone map (Figure 3) serves as the basis for identifying regional design approaches in a report prepared by the American Institute of Architects Research Corporation for the U.S. Department of Housing and Urban Development and the Department of Energy [2]. These regions are "based on heating and cooling needs, solar usefulness in a 50° to 65°F range, wind usefulness in a 75° to 85° range, diurnal temperature impact, and low humidity impact for natural heating and cooling of homes." Although the zones presumably are derived from a series of maps published in an earlier AIA Research Corporation report [64], the precise method of delineating the zones is described in neither publication.

Terjung's Physioclimatic Regimes

Perhaps the most ambitious and comprehensive climatographic analysis of the United States was made during the 1960s by geographer Werner Terjung [84]. Terjung analyzed weather data from 260 stations with respect to eight groupings of temperature-humidity conditions, which can be depicted on the psychrometric chart (Figure 5). These were designated "cold," "keen," "cool," "mild," "warm," "hot," "sultry," and "extremely hot." The "mild" category corresponds loosely to the human thermal comfort zone by more recent criteria. Daytime data only was analyzed, from which were plotted Dominant Regimes, where a single physioclimatic type occurs more frequently than others, and Transitional Regimes, where several types vie with one another. A simplified version of Terjung's map appears as Figure 4. A related paper by Terjung [85] contains an extensive review of comfort factors and previous mapping schemes.

Among many conceived uses, it was stated that "maps of this nature would simplify knowledge regarding housing needs, building materials and heating and cooling requirements." Although often acknowledged as one of the most useful of analyses with respect to human needs and responses, Terjung's procedure nevertheless has been criticized for using independent, rather than correlated, monthly average data [59], and for describing only daytime conditions.

Discussion of Climatic Regions

Although some similarities exist among the climatic classification schemes reviewed, it is clear that overall agreement is not good. No consensus exists as to the necessary number, delineation, or even the appropriateness of describing geographic zones for building design.

One can argue that climatic differences are infinitely variable, so that the number of possible climatic zones is limitless. Taken

further, this view contends that delineation of geographic zones can be more misleading than helpful. Most detailed (hourly) weather data is collected only at airport weather stations, which themselves are often atypical of their respective regions (Philadelphia International, Boston-Logan, New York-LaGuardia, e.g.); data supposed to represent a region, in fact, only truly represents the site at which it was collected. Extrapolation of data collected at a single station to a broader region can, therefore, be questioned, especially if conditions surrounding the instruments themselves are unknown.

In many metropolitan areas, significant microclimatic variation occurs as a result of changes in elevation, proximity to bodies of water, and the "heat dome" effect characteristic of large cities. Such intraregional differences may exceed the inter-regional differences assumed in some studies. A detailed comparison of hourly weather data from several stations within one or more selected standard Metropolitan Statistical Areas would be of great interest. These could be conducted by the bioclimatic analysis method applied to the 29 stations examined elsewhere in this report.

A large scale bioclimatic analysis of weather data would permit delineation of effectiveness limits for individual climate control strategies. These could be mapped in percentile ranges for which various passive design measures are theoretically capable of establishing indoor comfort. Findings of the analyses performed in this study are mapped in the Bioclimatic Analysis section.

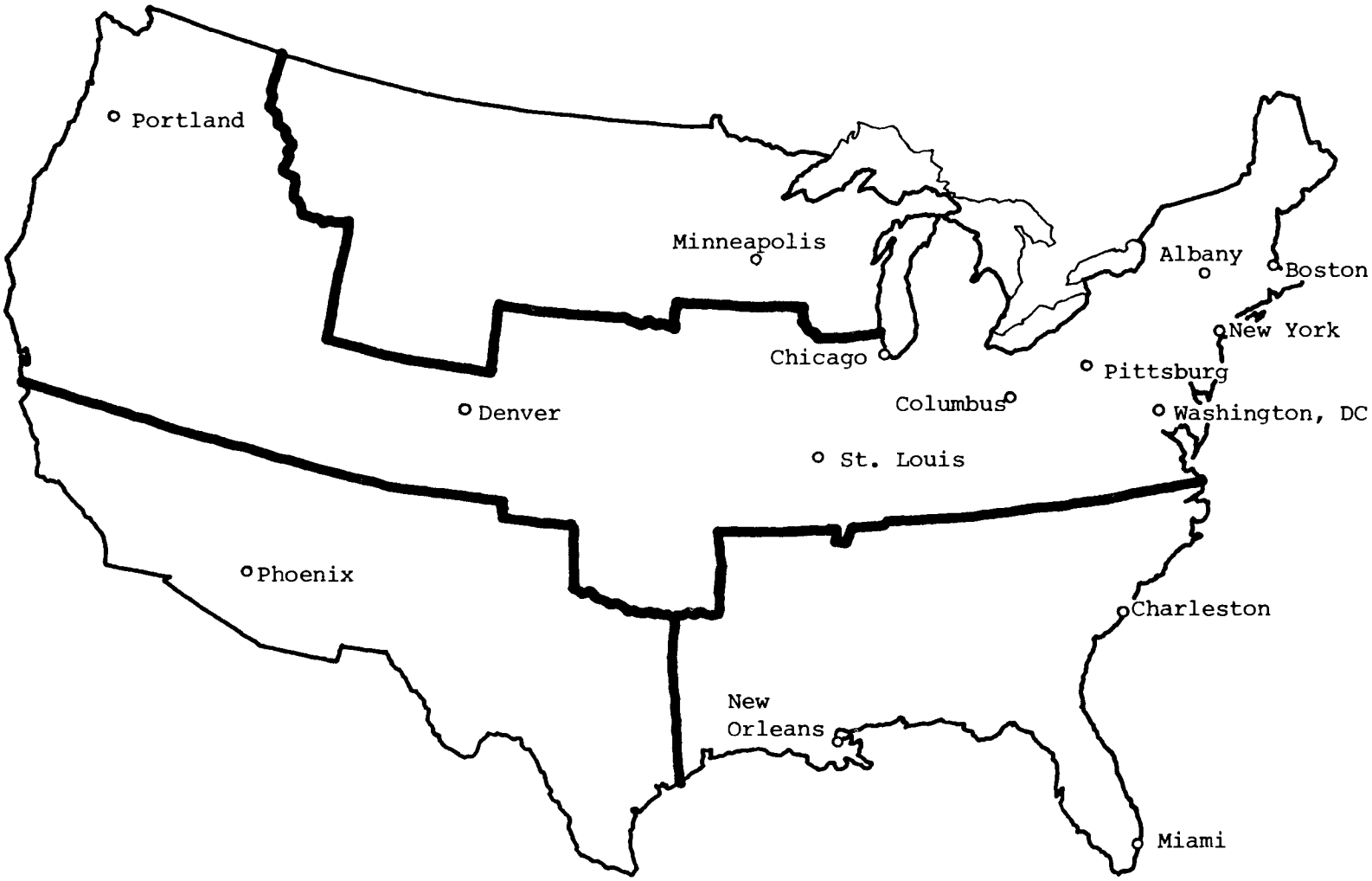


Figure 1. The familiar four zone climatic classification of the United States, and identification of the fifteen cities analyzed in the House Beautiful Climate Control Project.

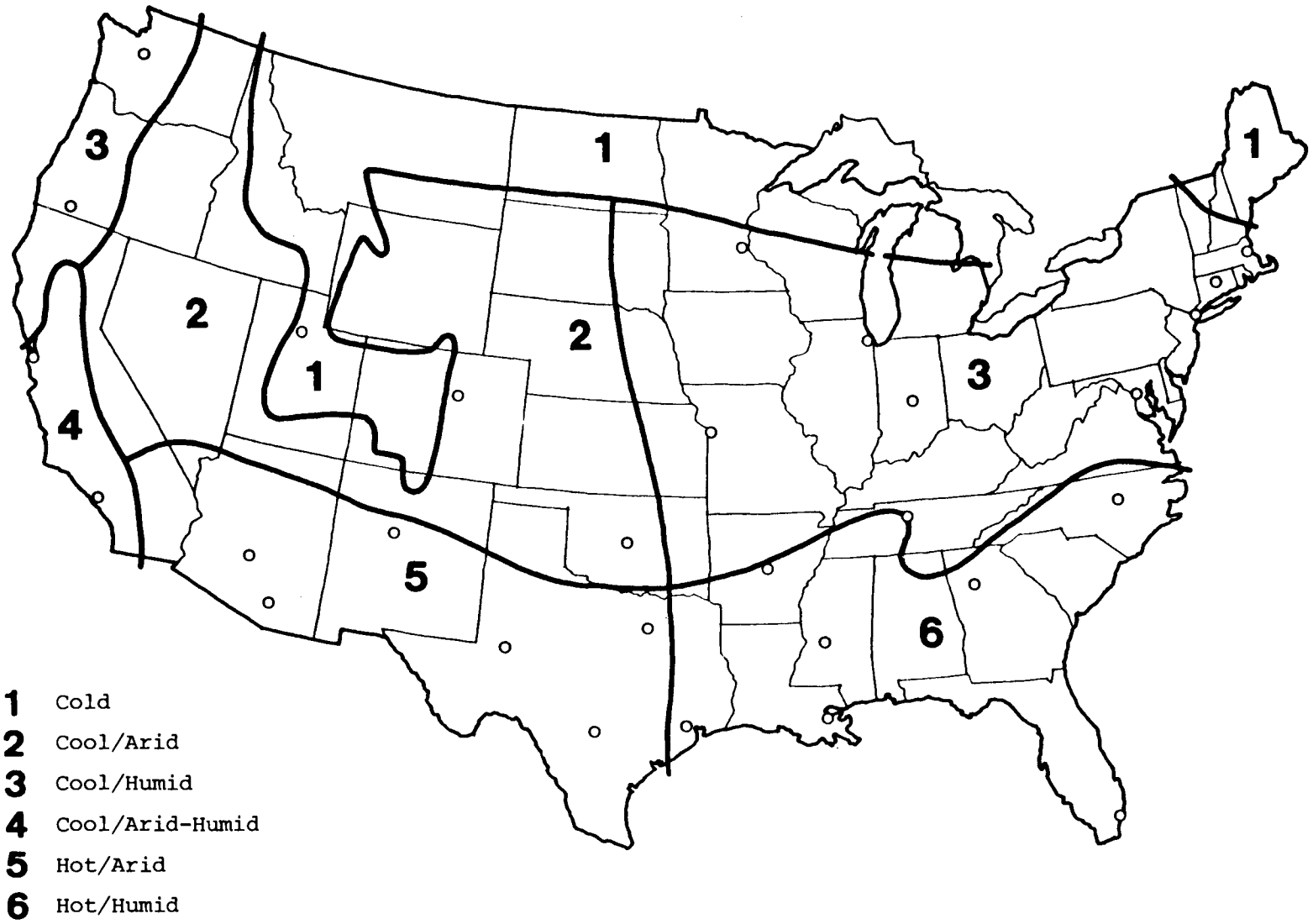


Figure 2. Grogger's classification of macroclimatic regimes.

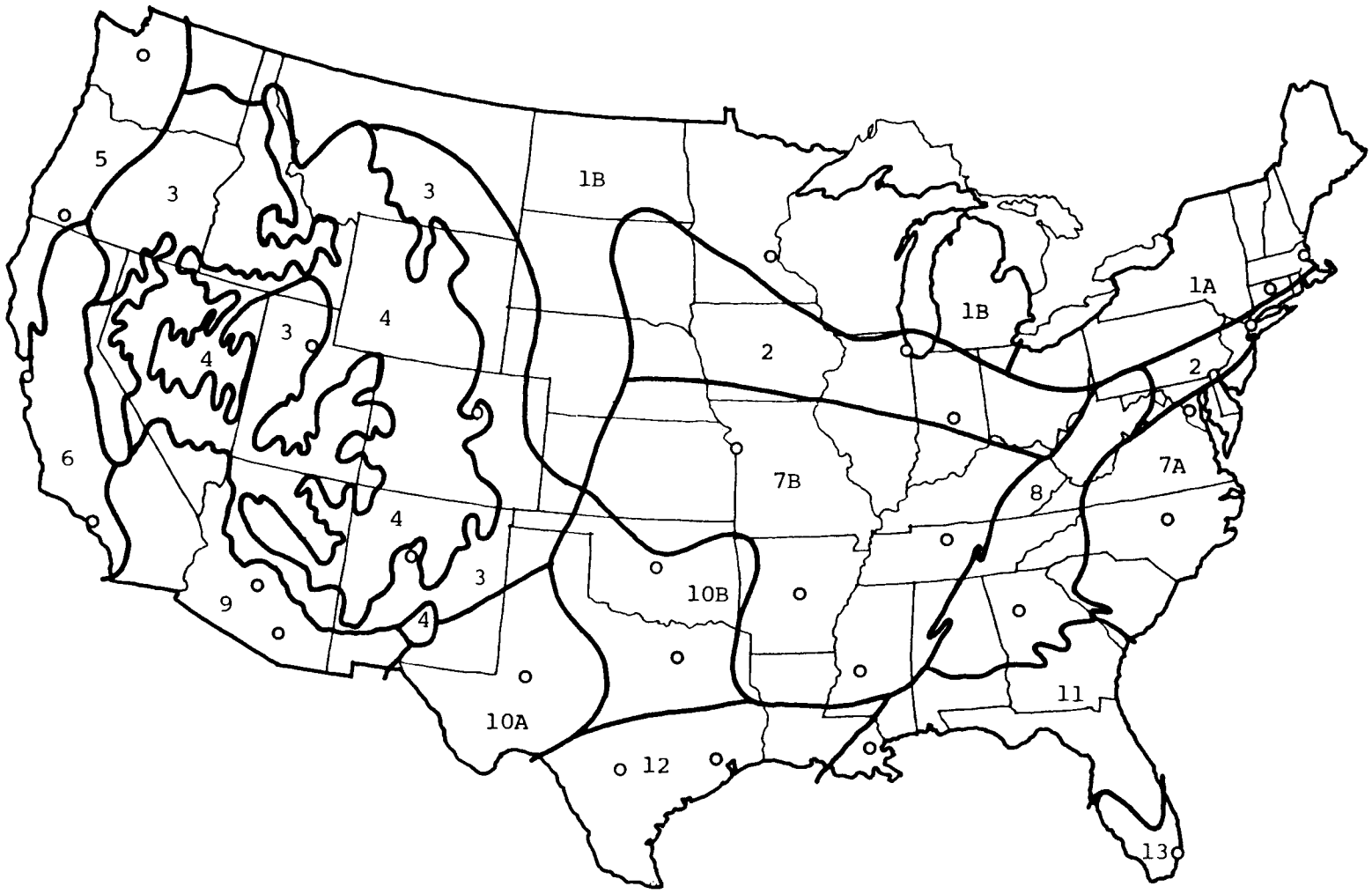


Figure 3. Thirteen region map (with 3 subregions) devised by the AIA Research Corporation.

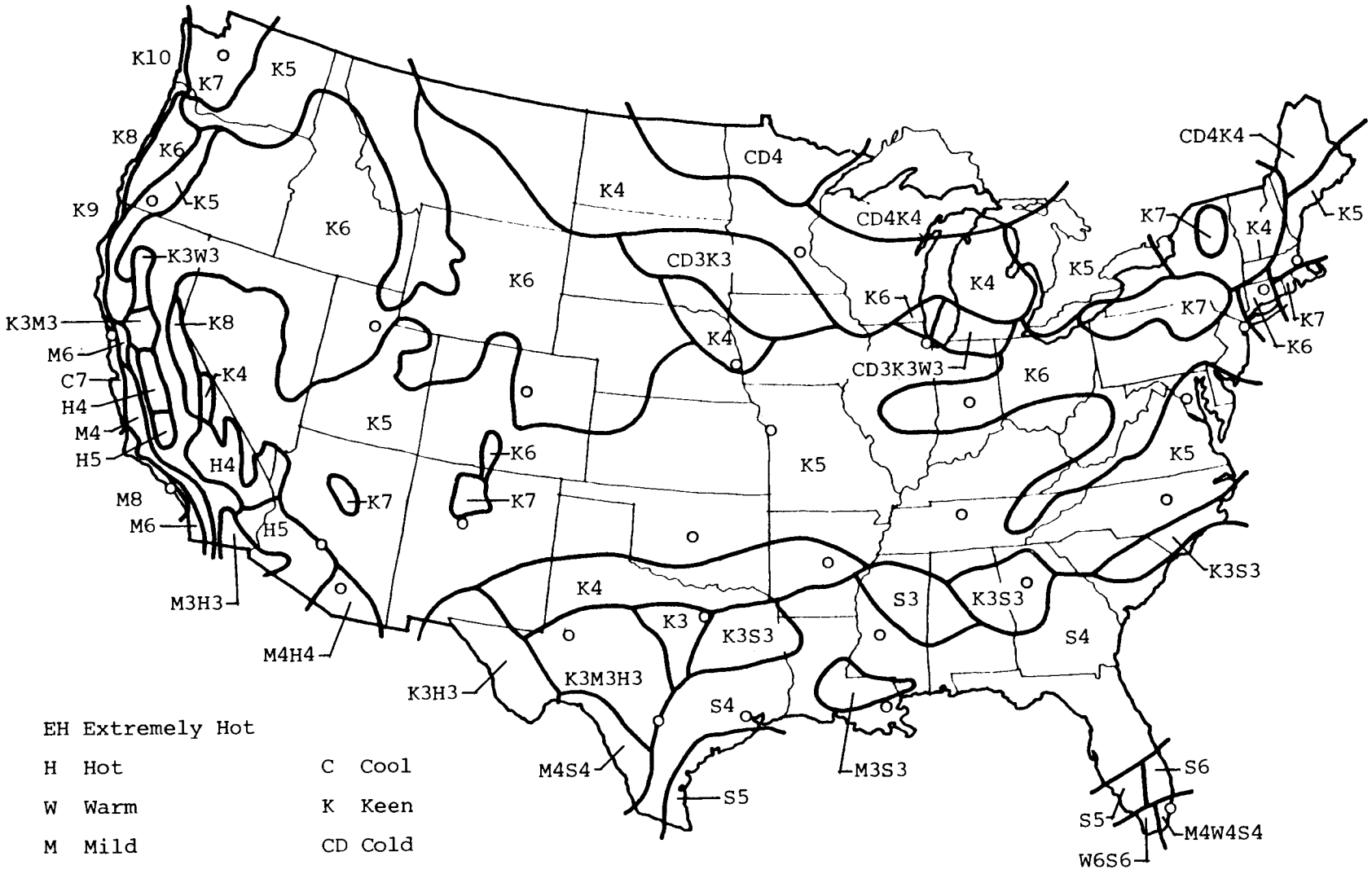


Figure 4. Terjung's Annual Physioclimatic Regimes, based on daytime conditions. Dominant regimes are indicated by letter codes; multiple letters indicate transitional regimes; numerals indicate number of annual months that dominant regime prevails.

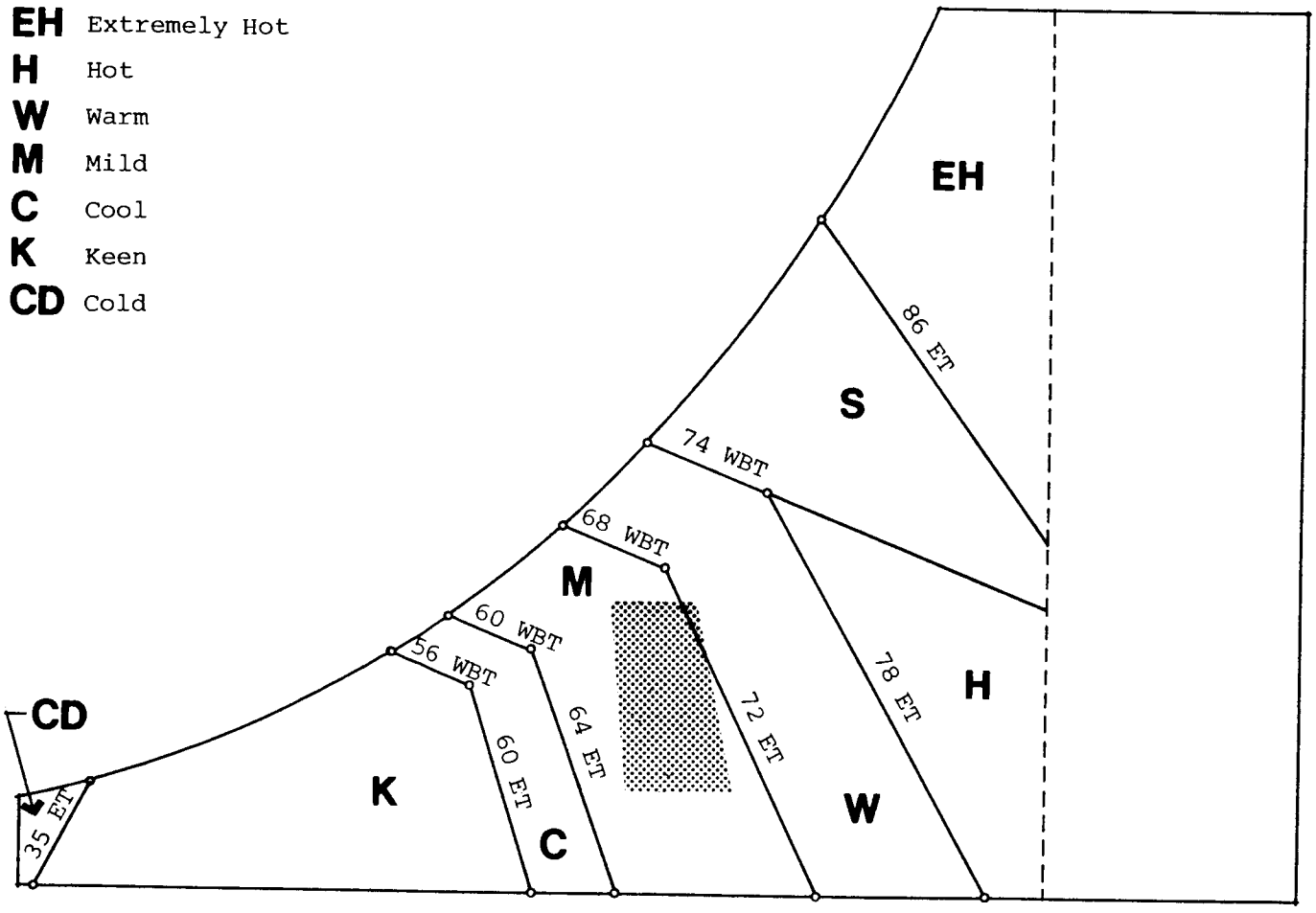


Figure 5. Partitioning of psychrometric chart for Terjung's climate classification.

TABLE 1. Grogger's assesment of the relative usefulness of seven different housing types to six macroclimatic regions of the United States.

	Cold	Cool/Arid	Cool/Humid	Cool/Arid-Humid	Hot/Arid	Hot/Humid
Split Level	L	L	U	L	U	B
Ranch	L	U	U	U	B	B
Bi-Level	U	U	U	U	U	U
Tri-Level	U	U	U	U	U	U
Two-Story	B	B	U	B	U	U
Townhouse (2 Story)	B	U	U	U	U	L
Multi-Level	B	U	U	U	U	L

Key: B = Best
U = Useful
L = Less useful

TABLE 2. Synopsis of Grogger's description of the interaction and importance of microclimatic elements with specific non-climatic elements.

Climatic Elements	Latitude	Elevation	Relief	Topography	Distance from water	Vegetation	Human Structures	Total
Cloud Cover	8	5	9	2	6	3	6	39
Sunshine	8	4	6	6	5	10	8	47
Solar Radiation	9	5	6	8	5	10	8	51
Airflow	5	5	8	7	7	7	7	46
Temperature	11	6	5	6	8	9	9	54
Rel Humidity	7	2	5	7	8	9	9	47
Evapotrans.	8	4	1	5	5	7	10	40
Albedo	2	1	2	5	4	6	7	27
Precipitation	7	4	8	1	9	5	4	38
Total	65	36	50	47	57	66	68	

Note: Individual categories are rated on a scale of 0 (not important) to 12 (very important).

TABLE 3. Characterizations of the temperature portion of Grogger's climate classification

Temperature Characterization	Solar radiation from December to and including February (in langleys)	Annual Heating Degree Days	Sunshine, annual in hours
Cold	350 to 550	7000 to 10000+	1800 to 2600
Cool	300 to 900	4000 to 8000	1800 to 2800
Hot	700 to 1000+	100 to 6000	1900 to 3000

GROUND CLIMATOGRAPHY AND ARCHITECTURE

The history of mapping and analysis of ground climate for reasons related to architectural design and mechanical engineering is extraordinarily brief. A synopsis of previous work follows, given in chronological order.

Climate Control Project: "Lithosphere Buildings"

The format of the House Beautiful Climate Control Project (CCP) "Regional Climate Analyses and Design Data" published in the Bulletin of the AIA [44] contained comments on the desirability and design of foundations and basements with respect to thermal, sun and wind, and moisture analysis for each of its fifteen study areas. Excerpts from these notes are given in Table 4.

Overall, semi-underground construction was viewed as an attractive climate control technique in many parts of the country. An entire article about the benefits of underground construction was published in House Beautiful magazine [61] in August 1950. This article contained a map prepared by Dr. Paul Siple, a military geographer and consultant to the CCP. The map (Figure 6) identifies three zones of suitability of subsurface construction: a large northern area of greatest advantage, an intermediate area of moderate advantage, and a southern zone of minor advantage. No reference was made as to the criteria used in preparation of the map. Said Siple in an address to the 1950 conference, Weather and the Building Industry [80]:

> For example, in much of the country our homes make us suffer unnecessarily from heat in summer and cold in winter, when only a few feet downward or into the sides of hills is a

permanently uniform temperature within a few degrees of the ideal living temperature.

Siple went on to discuss the problem of moisture and condensation in basements,

> It is amazing that so many regions of our country are cursed with the malady of moisture-sick basements in summer. Moisture accumulates in the basement because the temperature of the walls is lower than external dew point temperature. Erroneously, the attempt to dry out basements by opening windows to ventilate only serves to let in more moisture. The basement could be vapor-sealed and the air dried mechanically, but there is a much simpler way. By heating the basement floor and walls to about 70° or 75° , which will be above dew point temperature, the basement will dry. And it won't be necessary to burn fuel to do this. During the summer there is an overabundance of sun which we must shade ourselves from. Let in some of this sunshine; or put one end of a coil of radiant heating tubing capable of carrying a liquid into the floor and walls of the basement, and the other end of the coil under a sunstruck pavement, court of pavement. You may even cool an undesirably hot paved court and warm the basement to a usable temperature at the same time.

Characteristically ahead of its time, the CCP spawned the first euphemism for underground construction, and expressed other concerns still poignent 30 years later (again from Siple):

> . . . Of course, no one likes to live in basements or caves. Every word associated with underground is distasteful, so we propose the new term "lithosphere buildings." Some day, if we don't solve world problems without wars, our only safe places to live and work may be in lithosphere buildings. But bombing safety is only minor, considering the comforts that might be derived by taking natural advantage of lithosphere possibilities. Excavation costs would be high but fuel costs low. Moisture could be controlled. Through periscopic windows one could choose his outdoor views and even let sunshine in from all four sides of the house simultaneously.

NBS Earth Temperature and Thermal Diffusivity Analysis

The most influential ground climate work has been performed by T.

Kusuda and P.R. Achenbach of the National Bureau of Standards [54]. The work was commissioned by the Department of Civil Defense in order to obtain a method for estimating seasonal conditions surrounding fallout shelters. The authors collected available ground temperature records from 47 different locations in the U.S. The data for each station were analyzed by a least squares procedure to obtain a best fit to a simplified sinusoidal temperature model (described elsewhere in this report). The input parameters thereby obtained were used to generate theoretical predictions of temperatures for each station. This served 1) to test the validity of the theoretical model for a variety of soil and geographic conditions, 2) to determine the likely range of input parameters, in particular of the thermal diffusivity of soil in situ, and 3) to examine relationships between air and ground temperature. A subsequent report by Kusuda [53] refined the methodology of the first paper.

The results of the analysis of various ground temperature records performed by Kusuda and Achenbach have been discussed elsewhere in this report, and will not be itemized here. The end product of the work was a set of estimates of the average temperature of a soil profile ranging from the surface to a depth of 10 feet. This "integrated average" temperature was computed for the 47 locations for which the proper input parameters were assessed from field records; this data subsequently appears in ASHRAE Applications [8]. The Federal Construction Council extended this work to synthesize 0-10 foot integrated average temperatures to over 400 stations in the U.S. [25]; these are reported on a seasonal basis only, using air temperature data as estimates of the input parameters. A major contribution of the NBS work is its compilation of most known ground temperature records in the U.S. and its detailed analysis of this data as an evaluation of the suitability of a theoretical model of ground temperature prediction.

Ground Temperature Degree Day Analysis

K. Labs [56] and R. Goetz [33] both in 1975 performed degree day analyses of soil environments for making regional evaluations of the benefit of building underground. Labs subtracted from 65F the integrated average earth temperatures for the 0-10 foot profile published by Kusuda and Achenbach [54]. This was done for the profile's annual minimum temperature; this difference was multiplied by 31 to yield approximate monthly degree days for a 31-day one month period.* These "underground degree days" were then compared to published air heating degree day normals for the (coldest above ground) month of January. A percentage savings was then computed by the relation, % savings = (Jan. DD-UDD)/Jan. DD. The data was both tabulated (Table 5) and mapped (Figure 7).

Goetz approached the problem in much the same way, but with greater rigor and for the entire year. Instead of average temperature for the 0-10 foot profile, he used monthly average temperature at the 10 foot depth alone for his ground temperature index. These monthly averages were converted to degree days for each month of the year by means of a formula devised by Thom. Ground temperatures at the 10 foot level were synthesized values, obtained either directly from T. Kusuda at NBS, or were snythesized by Goetz in the same manner. Both heating and cooling degree days were computed to base 65F, for a total of 65 stations in the U.S. Percent savings based on heating degree days alone, cooling degree days alone, and combined energy savings (assuming each cooling degree day requires four times as much energy as one heating degree day to offset) as compared to air temperature

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*The profile average will vary little during the months of minimum and maximum temperature; the annual minimum temperature, therefore, closely approximates the average temperature of the coldest 31 day period. Given the grossness of other assumptions, the simplification can be justified for this application. Error inherent in the method will overestimate underground degree days and lead to a conservative estimate of the moderateness of ground climate as compared to the air.

degree day normals were computed by the same relationship as Labs and mapped (Figures 8-12). The results are interesting, although the validity of extrapolating data from only 65 stations to country-wide maps can be questioned. Goetz's thesis overall is an excellent review of ground climate phenomena; unfortunately it is virtually unknown among researchers in the field.

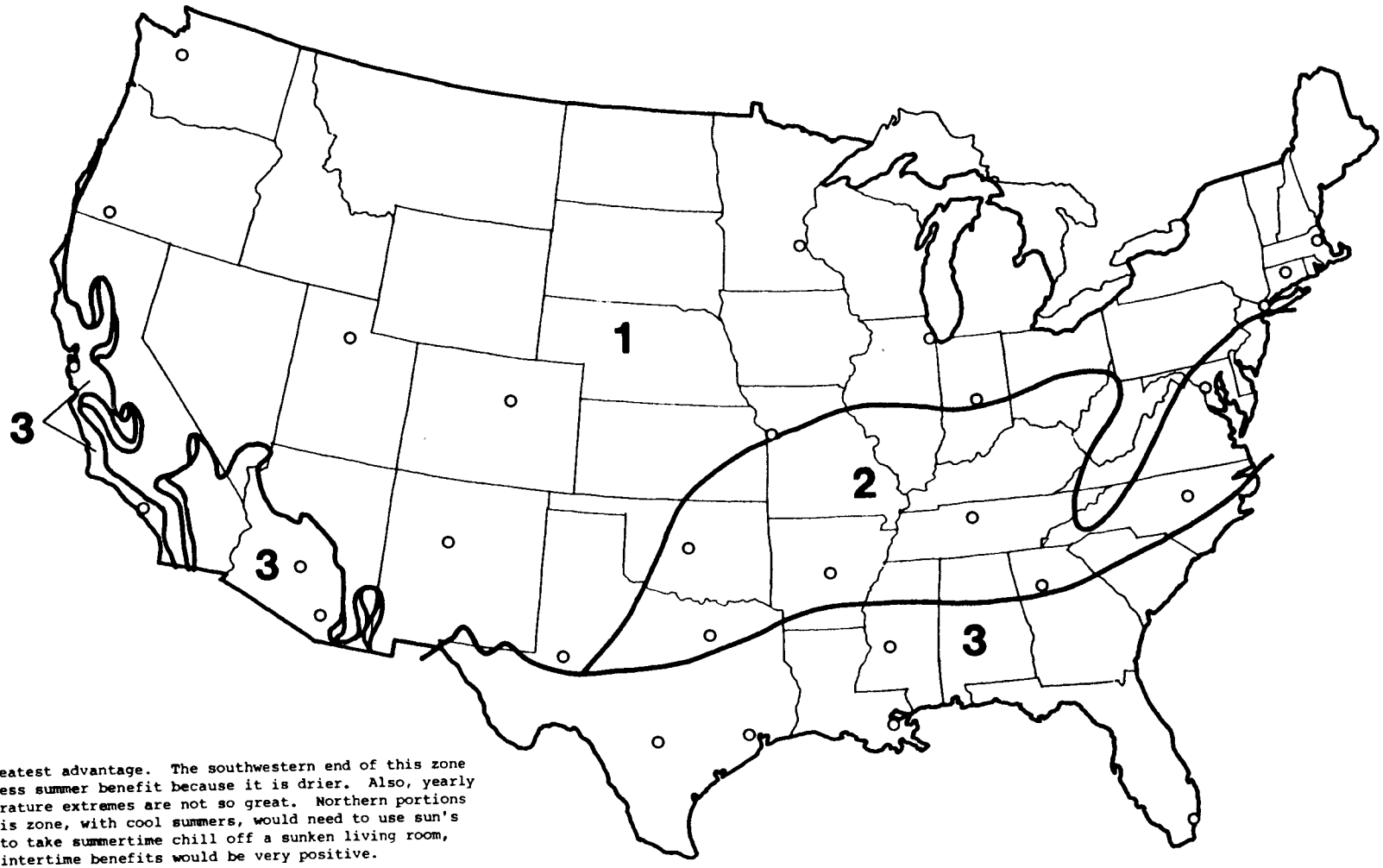
At present, degree day analyses of ground climate are mostly of academic interest only, since there is no known way of relating underground degree days of any kind to heating or cooling demand. Unlike flowing, fluid air, soil has both high heat capacity and is fixed in place. Soil stores heat lost from subgrade spaces; this elevates its own temperature above that of undisturbed soil, upon which degree day computations are made. As a result, degree day methods based on undisturbed woil temperature significantly overestimate heat loss if used to calculate heating demand in the conventional way.

Perhaps future work will determine correction factors which could account for heat storage in the soil. Priestly [75] indicates that the conductive capacity of "stirred air" ranges from nearly equal to, to over 20 times greater than soils (Table 6). By such reasoning, an underground degree day could be expected to be much "smaller" than a conventional air degree day. Such correction factors would probably have to be linked both to detph and to month, and perhaps to mean annual ground temperature as well. The problem abounds with uncertainties for actually computing fuel consumption, but as an index of regional climatic differences, degree day comparisons are simple and conservative.

Seasonal Severity Index

Labs [56] also proposed a simple comparison between the severity of above and below surface climates, again using data published by

Kusuda. The difference in range between monthly mean air and ground temperatures was computed by the relation, $(Air_{max} - Air_{min}) - (Earth_{max} - Earth_{min})$. The earth temperatures used were snythesized values for the integrated average 0-10 foot depth (Table 5). It was reasoned that earth tempering practices would be of greatest value for regions where the difference in range weas greatest. The results were listed in descending rank order, arbitrarily grouped in 5F increments (Table 7).

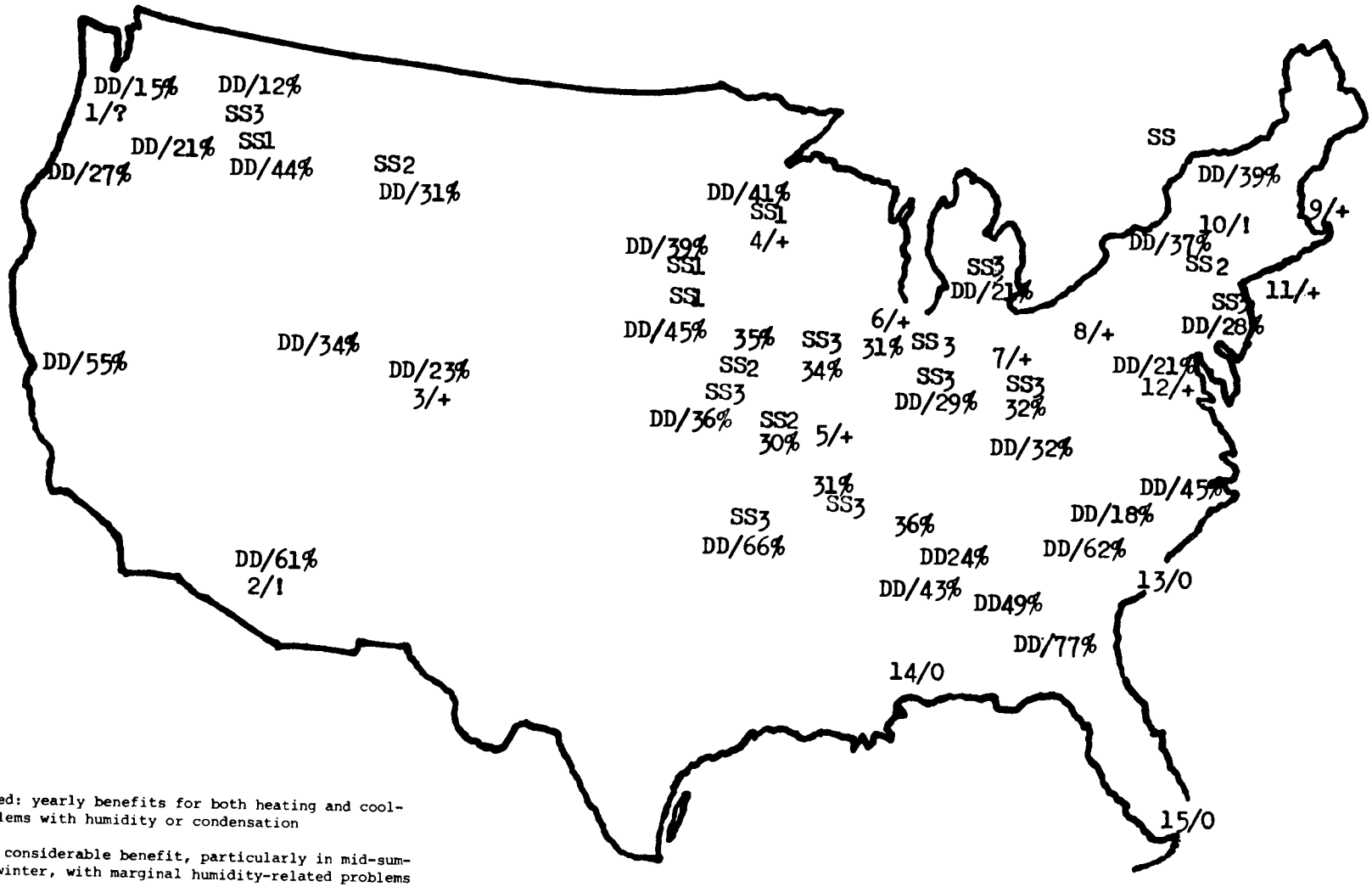


1 Greatest advantage. The southwestern end of this zone has less summer benefit because it is drier. Also, yearly temperature extremes are not so great. Northern portions of this zone, with cool summers, would need to use sun's heat to take summertime chill off a sunken living room, but wintertime benefits would be very positive.

2 Summer and winter advantages. But due to high relative humidities, a sunken room in this zone would require some mechanical air-drying to prevent condensation on walls, floors, etc. It is in this zone that complete, or partial, air conditioning would be most economical, and within the range of most people.

3 Area where underground living offers minor advantages — for the following reasons: because climate above ground is pleasant and without great extremes, or because the underground temperatures are not different enough to correct the above-ground climate, or because of the complications of extreme humidities.

Figure 6. Siple's map of the regional climatic suitability of underground living areas.



1 Ideally suited: yearly benefits for both heating and cooling, no problems with humidity or condensation

+ Well suited: considerable benefit, particularly in mid-summer and mid-winter, with marginal humidity-related problems

0 Poorly suited: benefits are either few or limited to a short season, or other inherent conflicts exist (high humidity, e.g.)

? Inconclusive: insufficient information to make judgments regarding overall performance throughout the year.

Figure 7. Summary of near-surface (0-10' depth) subsurface climatic benefit evaluated by Labs.

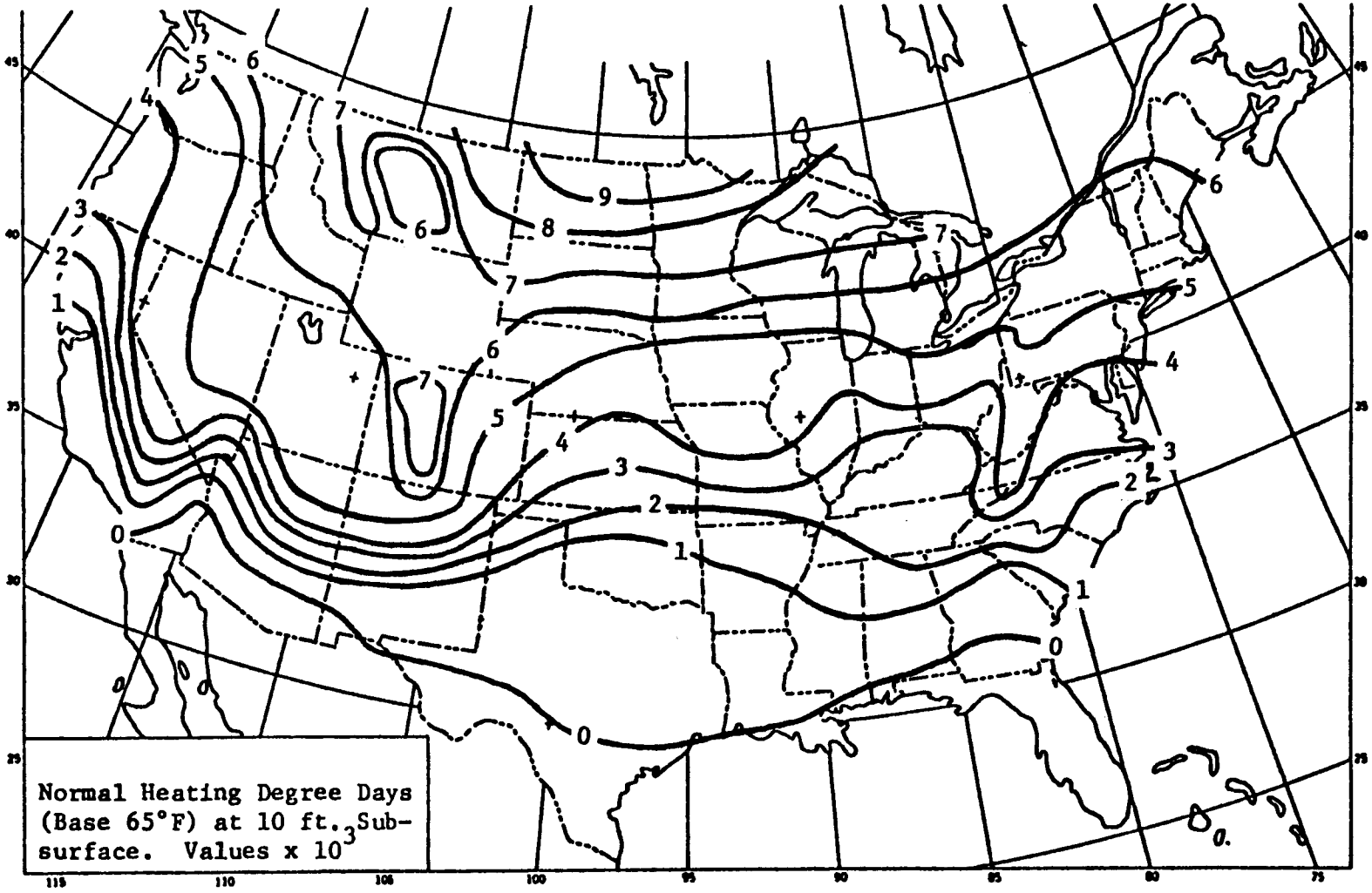


Figure 8. Goetz's analysis of normal annual heating degree days at the 10' depth.

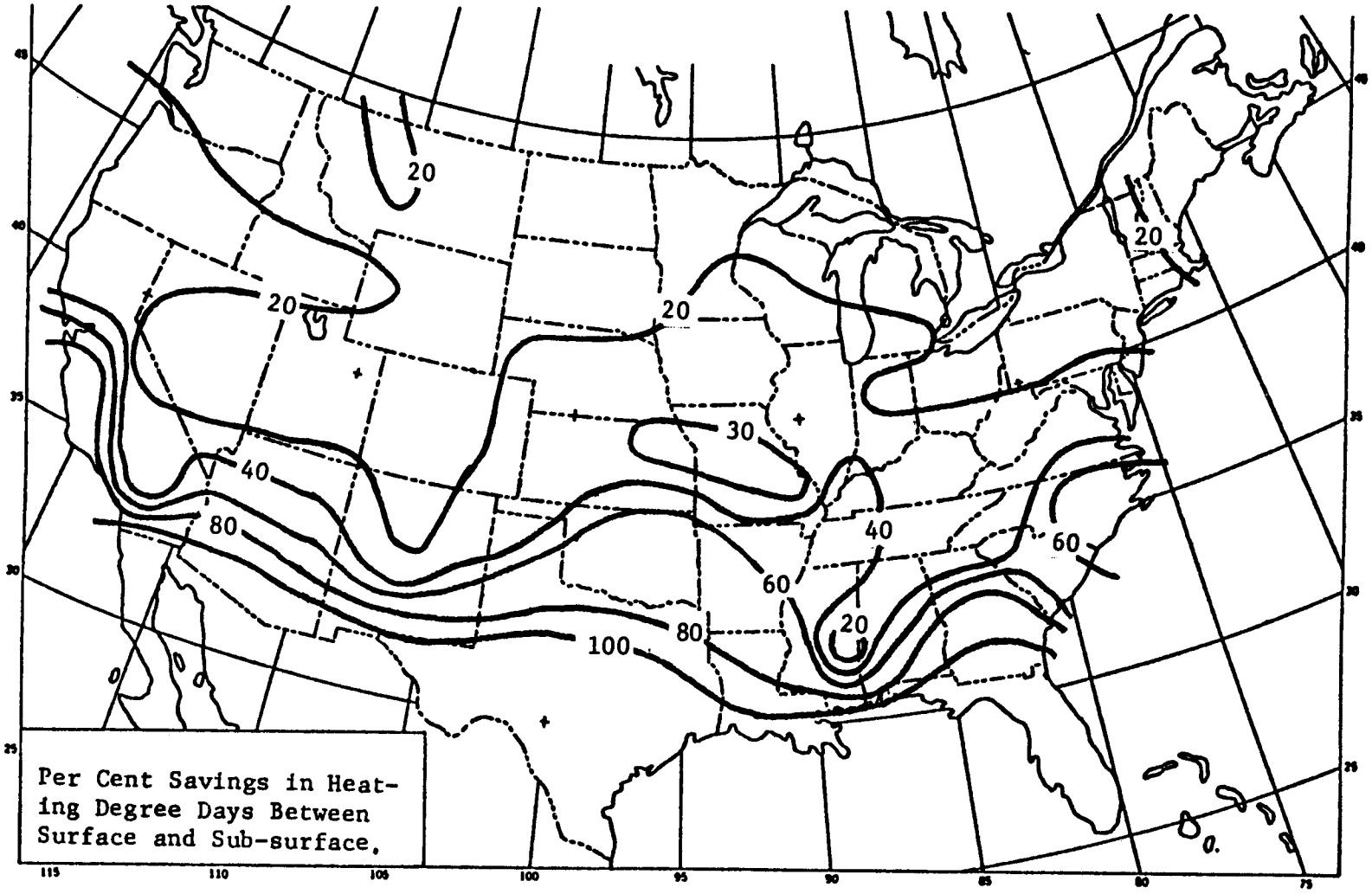


Figure 9. Goetz's analysis of heating degree day savings for the 10' depth vs. the surface (air).

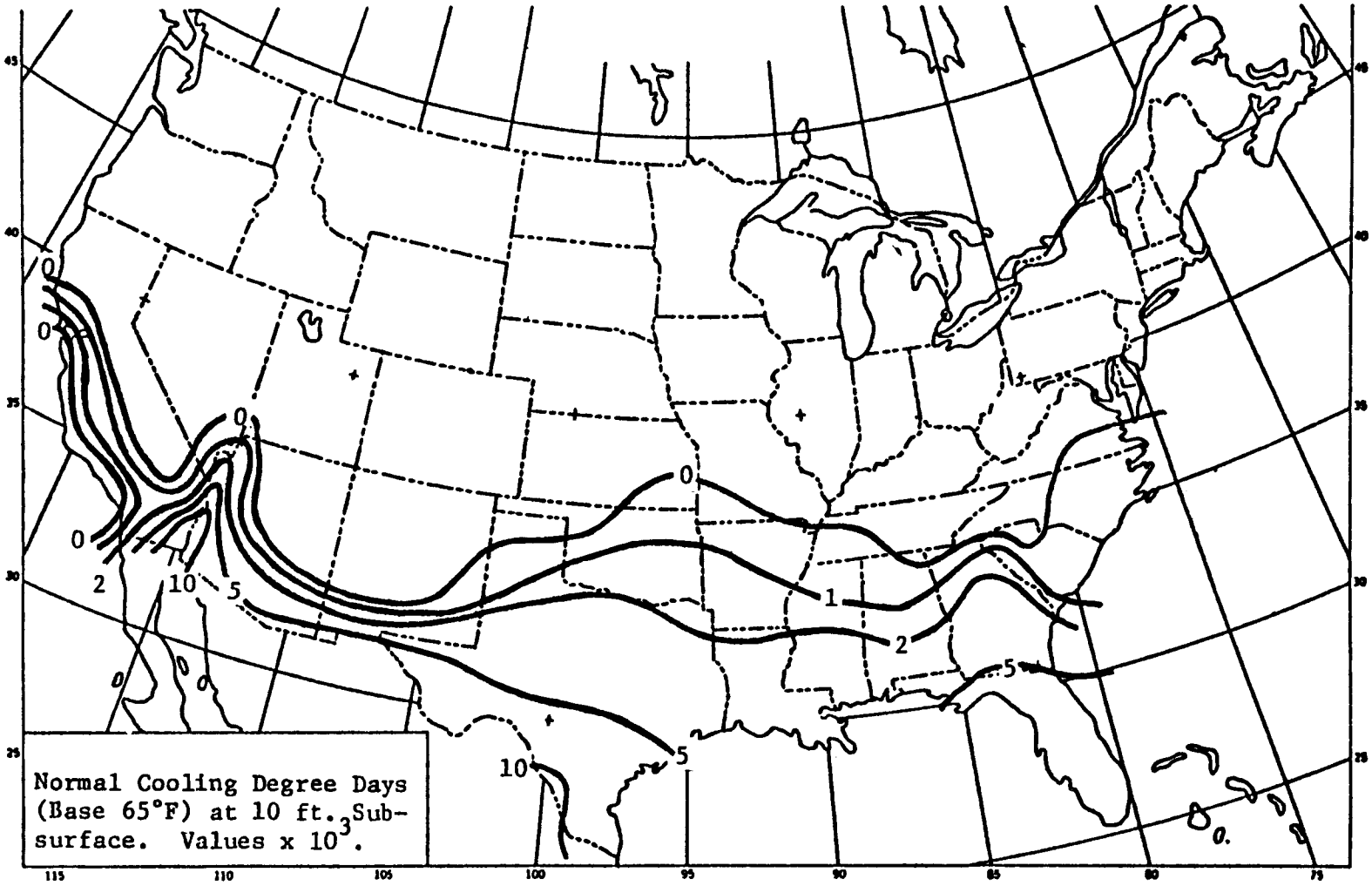


Figure 10. Goetz's analysis of normal annual cooling degree days at the 10' depth.

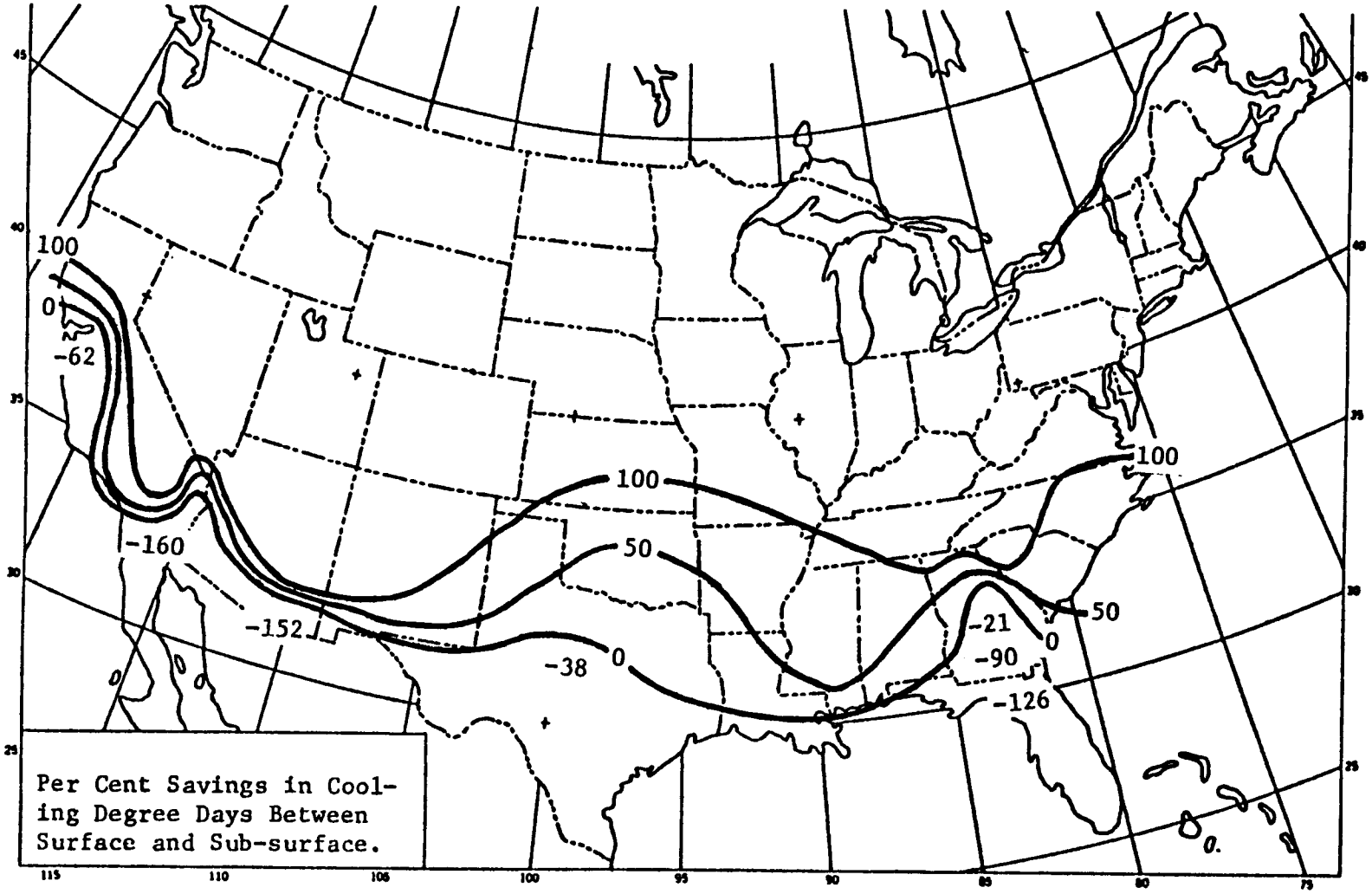


Figure 11. Goetz's analysis of cooling degree day savings for the 10' depth vs. the surface (air).

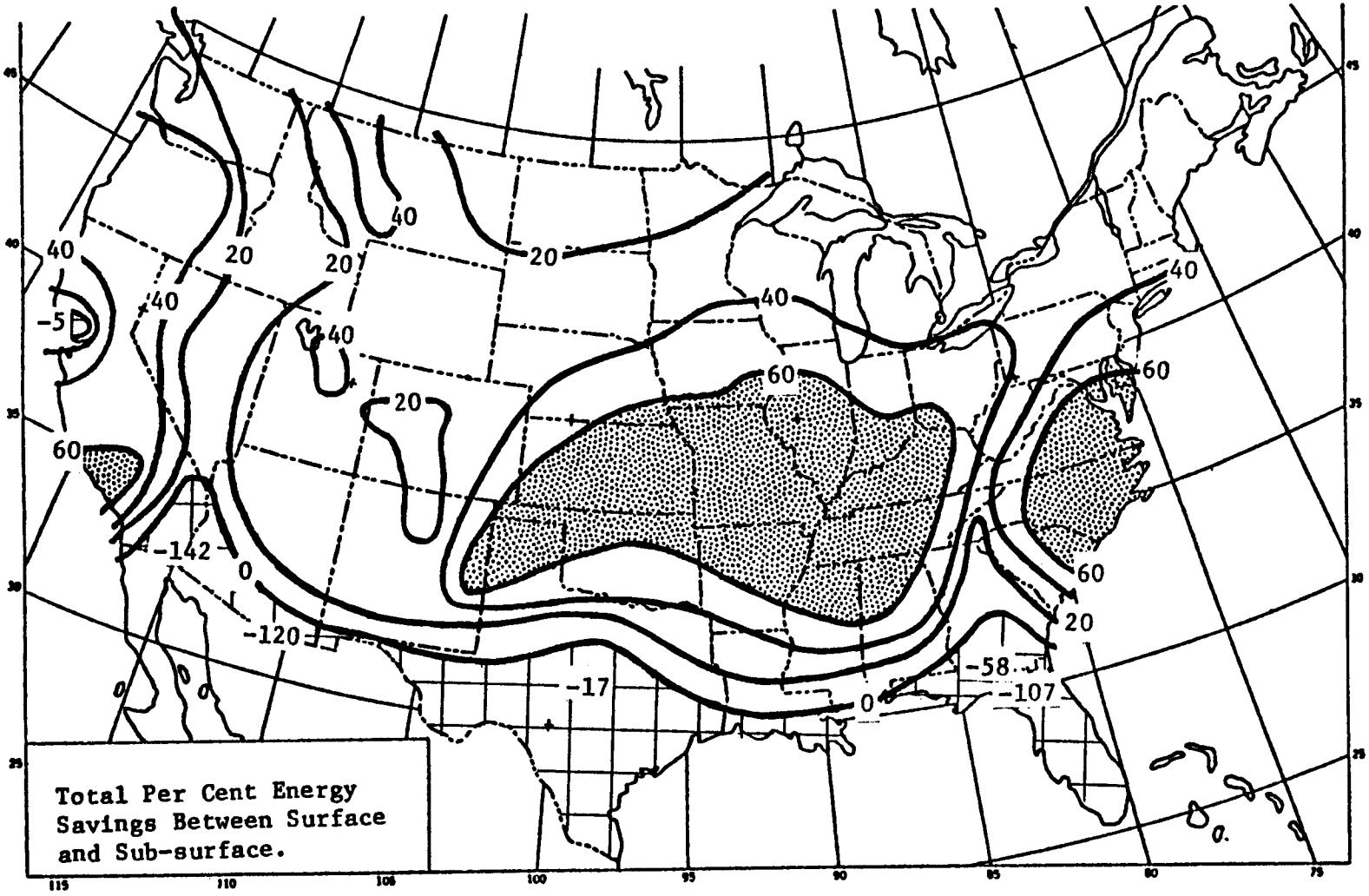


Figure 12. Goetz's analysis of energy savings for below vs. above ground climate.

TABLE 4. House Beautiful Climate Control Project's description of climatic implications for basement living areas in 15 regions of the United States.

PORTLAND, OREGON: Basement floor temperatures are reported to range from 46F to 60F, requiring some heating (solar heating described as "adequate") for comfortable summer use. "Basements on slope exposing wall on sunny side are suitable for living quarters." (No specific reference to winter)
PHOENIX (ARID SOUTHWEST): Atmospheric seasonal design temperature range is 16F to 106F, pointing out desirability of ameliorating devices. "In this region, basement might prove to be most comfortable living portion of the house. Several feet below surface mean annual temperature of 70F is present both day and night in winter and summer. This is an ideal living temperature and by building down into the ground this temperature should prove to be an asset in maintaining constant living conditions."
DENVER, COLORADO: Basement described as desirable, i.e., cool in summer with no humidity problems and easily heated in winter. Optimum condition would include sloping site with southern elevation fully exposed to sun.
MINNEAPOLIS-ST. PAUL: Atmospheric winter design temperature reported to be -12F, compared to minimum basement design temperature of +31F. Southern exposed wall is recommended, largely in response to the relatively high summer humidity level.
MID-MISSISSIPPI BASIN (ST. LOUIS-KANSAS CITY): "Subsurface rooms, with ground temperature constantly at 55F, will conserve considerable fuel in winter because floor slab will always be 24-40F warmer than outside air." "Subsurface rooms, if properly dehumidified and ventilated, will be most comfortable part of house during hot months."
CHICAGO, ILLINOIS: "If properly dehumidified, basement rooms will be attractive retreat during summer months." (Severe Chicago cold and wind are not discussed, but are plain benefits of winter relative advantage)
COLUMBUS, OHIO: Minimum basement design temperature is given as 30F, vs 8F for outdoor air, indicating obvious winter benefit. Humidity is indicated as a concern in summer, but "if humidity is controlled, basement will be most comfortable part of house during summer months."
PITTSBURG, PENNSYLVANIA: "Basement living quarters would cut fuel requirements for heating degree days approximately in half during winter, but would require additional vapor sealing and air circulation." "Normal summer temperature in basement too low for comfortable living conditions." Some summer heating required, so southern exposure is recommended.
BOSTON, MASSACHUSETTS: Humidity and condensation problems are cited, which may be at least partially alleviated with solar exposure of south walls. Ventilation alone said to be inadequate remedy for dampness. Cold winters mean obvious heating season benefits.

ALBANY (BUFFALO-MONTREAL): "Potentially a basement in this area has superior advantages for living facilities, for which it is cooler in summer and warmer in winter, and if these lithosphere rooms were made attractive and spacious, they would probably be preferable to living quarters normally planned for floors above the ground." Solar heating — by means of conservatories and light wells — is suggested, both for winter warmth and as a means of dealing with occasionally high summer humidity.

NEW YORK METRO AREA (INCL. PHILADELPHIA): A basement design temperature of 30F in winter is contrasted to an atmospheric design temperature of 12F, and it is stated that "unheated basements will be warmer and drier than the outside atmosphere," 47F and less than 65% RH being present during winter.

WASHINGTON, DC AND CHESAPEAKE BAY AREA: Basement areas are said to provide maximum summer comfort if properly dehumidified, and a relative source of heat in the winter. Solar heating methods are advocated, particularly as a means of dealing with high summer humidity; summer ventilation may only exacerbate the humidity/condensation problem.

CHARLESTON, SOUTH CAROLINA: High humidity and relatively high summer soil temperatures make basement living areas unsuitable for use during the predominant warm seasons. No comment made on winter advantages (but the generally moderate climate makes few rigorous demands on the building as a whole; it might be noted that elevating the structure on stilts is recommended as a means of increasing natural ventilating capability).

GULF COAST (FLORIDA TO TEXAS): Basements are generally omitted in conventional design; "high humidity, combined with high ground temperatures (70F in summer) make underground areas unsuitable for living or storage." Instead, "the higher the living quarters are placed, the more comfortable they are likely to be."

MIAMI, SOUTHERN FLORIDA: High ground water and ventilation requirements exclude basements from consideration: "a basement would be a liability because of high humidity during most of the year."

TABLE 5.

EARTH TEMPERATURE STATION/1	AIR TEMPERATURE STATION/2	MAXIMUM E	MAXIMUM A	MINIMUM E	MINIMUM A	SPREAD E	SPREAD A	SPREAD DIFF	JAN DD (1)	UDD (2)	%SAVINGS (3)
Auburn, Ala.	Montgomery, Ala.	74	81	56	49	18	32	14	543/2	279	49
Decatur, Ala.	Huntsville, Ala.	71	81	48	43	23	38	15	694/2	527	24
Tempe, Ariz.	Phoenix, Ariz.	81	90	59	50	22	40	18	474/2	186	61
Tucson, Ariz.	Tucson, Ariz.	85	86	65	50	20	36	16	471/1	0	-
Brawley, Cal.	Yuma, Ariz.	90	95	68	55	22	40	18	363/2	-93	
Davis, Calif.	Sacramento	76	75	56	44	20	31	11	614/2	279	55
Ft. Collins, Col.	Denver, Col.	63	72	37	29	26	43	17	1128/2	868	23
Gainesville, Fla.	Orlando, Fla.	80	82	69	62	11	20	9	220/2	-124	-
Athens, Ga.	Athens, Ga.	77	81	57	45	20	36	16	642/1	248	62
Tifton, Ga.	Albany, Ga.	80	83	62	51	18	32	14	400/4	93	77
Moscow, Idaho	Idaho Falls	57	69	37	16	20	53	33	1550/2	868	44
Argonne, Ill.	Chicago, Ill.	64	75	38	25	26	50	24	1209/2	837	31
Lemont, Ill.	Chicago, Ill.	65	75	39	25	26	50	24	1209/2	806	33
Urbana, Ill.	Springfield, Ill.	67	76	39	27	28	49	21	1135/2	806	29
Urbana, Ill.	Springfield, Ill.	68	76	42	27	26	49	23	1135/2	713	37
W. Lafayette, Ind.	S. Bend, Ind.	66	71	38	25	28	46	18	1221/2	837	32
Burlington, Iowa	Burlington, Iowa	71	77	38	24	33	53	20	1259/1	837	34
Manhattan, Kans.	Concordia, Kans.	69	80	41	28	28	52	24	1163/2	744	36
Lexington, Ky.	Lexington, Ky.	68	76	42	33	26	43	17	946/1	651	32
Lexington, Ky.	Lexington, Ky.	70	76	46	33	24	43	19	946/1	589	38
Up. Marlboro, Md.	Washington, DC	70	77	42	36	28	41	13	900/4	713	21
E. Lansing, Mich.	E. Lansing, Mich.	63	71	37	24	26	47	21	1262/1	868	21
St. Paul, Minn.	Minneapolis	62	74	34	15	28	59	31	1631/2	961	41
State U., Miss.	Meridian, Miss.	79	81	55	48	24	33	9	543/2	310	43
Faucett, Mo.	Springfield, Mo.	65	78	43	33	22	45	23	973/2	682	30
Kans. City, Mo.	Kans. City, Mo.	66	81	42	30	24	51	27	1032/1	713	31

EARTH TEMPERATURE STATION/1	AIR TEMPERATURE STATION/2	MAXIMUM E	MAXIMUM A	MINIMUM E	MINIMUM A	SPREAD E	SPREAD A	SPREAD DIFF	JAN DD (1)	UDD (2)	%SAVINGS (3)
Sikeston, Mo.	Springf'd, Mo.	71	78	43	33	28	45	17	973/2	682	30
Bozeman, Mont.	Billings, Mont.	56	73	33	23	23	50	27	1296/2	992	24
Huntley, Mont.	Billings, Mont.	64	73	36	23	28	50	22	1296/2	899	31
Lincoln, Nebr.	Lincoln, Nebr.	69	79	39	24	30	55	25	1237/1	806	35
Norfolk, Nebr.	Norfolk, Nebr.	66	76	40	19	26	57	31	1414/1	775	45
New Brunswick,N.J.	Newark, N.J.	65	75	42	32	23	43	20	983/2	713	28
Ithaca, N.Y.	Syracuse, N. Y.	59	73	39	26	20	47	27	1271/2	806	37
Raleigh, N.C.	Raleigh, N.C.	73	79	52	41	21	38	17	725/1	403	45
Columbus, Ohio	Columbus, Ohio	65	74	41	30	24	44	20	1088/1	744	32
Barnsdall, Ok.	Oklahoma City	74	82	54	37	20	45	25	1165/2	341	70
Pawhuska, Ok.	Oklahoma City	74	82	50	37	24	45	21	1165/2	465	60
Corvalis, Oreg.	Eugene, Oreg.	66	67	46	38	20	29	9	803/2	589	27
Pendleton, Oreg.	Pendleton, Oreg.	67	75	39	31	28	44	16	1017/1	806	21
Calhoun, S.C.	Columbia, S.C.	76	81	52	47	24	34	10	570/2	465	18
Madison, S.D.	Huron, S.D.	61	75	33	14	28	61	33	1628/2	992	39
Jackson, Tenn.	Oak Ridge, Tenn.	71	78	49	38	22	40	18	778/2	496	36
Temple, Texas	Waco, Texas	82	86	58	47	24	39	15	536/2	186	65
Salt Lake City, Utah	(same)	63	78	40	29	24	39	15	1172/1	775	35
Burlington, Vt.	Burlington, Vt.	63	70	35	18	28	52	24	1513/1	930	39
Pullman, Wash.	Walla Walla, Wash.	60	76	36	32	24	44	20	986/2	899	9
Pullman, Wash.	Walla Walla, Wash.	58	76	38	32	20	44	24	986/2	837	15
Seattle, Wash.	Seattle, Wash.	61	65	45	39	16	26	10	738/1	620	15

(1) From Climatic Atlas of the U.S., for location of earth station (1) or air station (2), as noted, month of Jan. (coldest for atmos. DD)

(2) "Underground Degree Days": (65° - Min. Earth Temperature) x 31. Coldest Earth temp. over "integrated average" 10' depth generally occurs during Feb. Min. temp. here is assumed for duration of 31 days for comparison.

(3) Comparison of atmospheric DD and "UDD" is calculated for respective min. & max. of each.

TABLE 6 Thermal properties of different media[a]

Medium	ρc	α	k[b]	$\sqrt{\rho c k}$
	$\frac{Btu}{ft^3(F)}$	$\frac{ft^2}{hour}$	$\frac{Btu}{ft(hr)F}$	$\frac{Btu}{ft^2\sqrt{hr}F}$
New snow	1.9	.02	.04	.25
Old snow	14	.01	.16	1.5
Dry sand	19	.005	.1	1.3
Wet sand	25	.04	1.0	4.9
Sandy clay[c]	37	.014	.5	4.5
Organic soil	36	.02	.7	4.9
Wet marshy soil	44	.01	.5	4.7
Still air	.019	.77	.014	.016
Stirred air:				
very stable	.019	3.9×10^3	72.5	1.2
neutral	.019	3.9×10^5	7.2×10^3	12.0
very stable	.019	3.9×10^7	7.2×10^5	120

[a]from Priestly [75], values rounded off

[b]computed from the relation $k = \rho c \alpha$; "apparent" conductivity for air

[c]15% moisture

TABLE 7. Difference between annual range in air temperature and earth temperature average for the 0-10 foot profile.

Difference	Geographical region	Designation
30F+	Minnesota (St. Paul) South Dakota Madison) Idaho (Moscow) Nebraska (Norfolk)	SS1
25F-29F	Missouri (Kansas City) Montana (Billings) Nebraska (Linclon) New York (Ithaca) Oklahoma (Barnsdall)	SS2
20F-24F	Illinois (Chicago; Urbana) Kansas (Manhattan) Michigan (East Lansing) Missouri (Faucett) Iowa (Burlington) New Jersey (New Brunswick) Ohio (Columbus) Oklahoma (Hominy; Pawhuska) Washington (Pullman)	SS3
15F-19F	Kentucky (Lexington) Tennessee (Jackson) Indiana (West Lafayette) Arizona (Tempe; Tucson) California (Brawley) Colorado (Fort Collins) Missouri (Sikeston) North Carolina (Raleigh) Oregon (Pendleton) Georgia (Athens) Alabama (Decatur) Texas (Temple) Utah (Salt Lake City)	
14F-	Alabama (Montgomery) Georgia (Tifton) Maryland (Upper Marlboro) California (Davis) Washington (Seattle) South Carolina (Calhoun) Oregon (Corvallis) Mississippi (Oxford) Florida (Gainesville)	

GROUND CLIMATOGRAPHY: DATA BASE

Existing Literature and Records

Geographic distribution of ground climate has received little attention from the building industry, which historically has concerned itself only with depth of frost penetration for foundation design. Since no private or public agency has ever sponsored a national program of ground temperature measurement and reporting, existing ground temperature records are scattered and few, for the most part having been collected by individual researchers for their own work, or by state agricultural research stations at their own initiative. Many observations have been made to depths of only 18 inches or less. In many instances, too, observations were made for the duration of a single year. Details about surface cover, soil type, and other site specific factors (such as concurrent air temperature, snow cover, and precipitation) are often not noted, and methods of instrumentation and frequency of reading vary widely.

Compilations of records have been published by Fitton and Brooks [27], Chang [17], and Kusuda and Achenbach [53]. In 1961, the U.S. Weather Bureau published its History of Soil Temperature Stations in the United States [43], a directory of known sources of soil temperature records. The former Canadian Meterological Branch of the Department of Transport (now the Atmospheric Environment Service of the Department of Environment) initiated a ground monitoring program in 1958. A fifteen year summary of data has been published [10] which gives monthly average temperatures for a range of depths extending from 1 to 300 cm. This excellent data is of particular interest because many of the reporting stations are located near the U.S. border, and because there are so few records in the U.S. from this area.

Several reviews of ground temperature research have been published. Richards et al [76] have emphasized near-surface observations with reference to plant growth. Gold and Lachenbruch discuss ground climate especially relating to permafrost [36], and Crawford [20] summarizes the findings of various researchers with respect to various factors affecting ground temperature. The most extensive published review of ground temperature work was prepared by Chang [17] in 1958. Most recently, Labs [57] has discussed a selection of papers with particular reference to the environment of underground buildings.

An extensive bibliography of international research is contained in the report previously cited by Chang. A selected annotated bibliography on soil thermal properties was published in 1962 by A. Peters of the Franklin Institute [74]. A bibliography containing 207 references on earth tempering, earth coupling, and other aspects of underground engineering has recently been made available by J.M. Akridge and C.C. Benton [3] through the Southern Solar Energy Center. An unpublished file of references is being collected by the DOE-sponsored Passive Cooling Program of the Lawrence Berkeley Laboratory [72], and an extensive annotated bibliography of ground temperature and ground heat transfer literature is expected to be prepared at a future date by the Underground Space Center of the University of Minnesota [87].

Existing Data Base: Mean Annual Ground Temperature (T_m)

Since air is closely coupled to the ground surface, the average daily, monthly, and annual air temperatures take on values very near those of the ground surface. The steady state temperature of the ground represents an average of the annual course of surface temperatures. In the absence of other data, therefore, deep ground temperatures are often estimated by an empirical relation of the form, $T_m = (x + T_a)$, where x is +1 to +5F, and T_m and T_a are the mean annual

ground and air temperatures, respectively. W.D. Collins [18] prepared his familiar well water isothermal map of 1925 in this way, allowing that T_m typically exceeds T_a by 2 to 3F. Correlations of this type are useful only in areas devoid of significant seasonal snow cover, as the insulative effect of snow uncouples the ground surface from the air. In areas of deep and continuous snow cover, T_m may exceed T_a by as much as 9F [93]. Collins was unable at his time to estimate the magnitude of the seasonal insulation effect; as a result, his well water temperature estimates fall significantly below actual observed annual average ground temperatures in the northern states and Canada (see Figure 13). The effect of seasonal insulation is an interesting subject in itself. It has been studied experimentally [34, 35, 69] and by numerical simulation [30, 31]. Stephenson [82] has proposed a mathematical method of estimating necessary depths of mulch to prevent the ground from freezing in northern climates.

The best estimates of steady state ground temperatures are obtained by taking the temperature of water from nonthermal wells between depths of 20 and 200 feet. The National Water Well Institute has collected well water temperature records and from these and has prepared a map plotting isothermal distribution (Figure 14). This is believed to be the best available map of its kind (superseding the Collins map); it is sufficiently accurate for most regional ground temperature studies. Average annual ground temperature at any given site may depart from the regional norm for a host of reasons, including variation in slope, aspect, elevation and ground cover. These are discussed further by Labs [57].

Existing Data Base: Surface Temperature Amplitude (A_s)

Like average annual ground temperature, the annual surface temperature amplitude can be estimated approximately from air temperature data, provided that the air temperature station is located over a

ground cover similar to that at the surface of the site being considered. Sellers [78] quotes de Vries as relating annual surface temperature amplitude to that of the air by the expression, $A_s = 1.25A_a$, over short grass, where A_s is the soil surface temperature amplitude and A_a is the dry bulb air temperature amplitude measured at a height of 2 meters. Over bare soil, the multiplying factor is said to range from 1.1 to 2.0, averaging 1.3. Overall, these values appear high when compared to data analyzed by Kusuda and Achenbach [54]; their plotting of A_s versus A_2 for two dozen pairs of stations* shows 1.25, for instance, to represent a likely upper limit rather than a normal relationship (Figure 15).

Values of A_s computed by Kusuda and Achenbach with a least squares technique for a number of stations with grass or other herbaceous ground cover have been plotted on Figure 16 along with long term annual air temperature amplitudes redrawn from Visher [88]. Since the number of data points is so small, few conclusions can be made; however, there generally appears to be good correlation between the two sets of data.

Chang [16, 17] has prepared global maps of estimated ground temperature amplitudes at depths of 4 inches, 12 inches, and 4 feet. The annual amplitude at the 4 inch depth is practically identical with that of the surface, so Chang's map of North America has been used in a method for calculating heat loss from basements [9, 13]. It is reproduced here as Figure 17. Chang had even less data available for preparing his map than exists at present, so much of the actual plotting was guided by patterns observed elsewhere in the world. For instance, he remarks [16],

> At Ithaca, Resolute Bay, and Anchorage the annual ranges of air temperature exceed those in soil temperature in the

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*Air temperature data was obtained from the nearest reporting weather station, often at considerable distance from the site of ground temperature observation.

top layers. This is the result of the insulating effect of snow cover in winter, preventing the lowering of soil temperature.

On the contrary, the soil temperature range of shallow depths exceeds air temperature range in deserts; for example, Cairo, Tiflis, and along the mid-latitude west coasts having dry summers, for example, Seattle and Santiago. Dry, sandy soils with low heat capacity are more subject to temperature extremes than wet, heavy soils. At Seattle and Santiago the difference is caused by the relative coolness of the ocean air which is brought in by prevailing westerlies.

Since air temperature is closely coupled to ground surface temperature, the two are governed by the same climatic factors. Consequently, Visher's climatic laws for annual air temperature range (range is twice the amplitude) serve to explain and provide further insight into the distribution of surface temperature amplitude [89]:

22. Annual or seasonal range in temperature increases with latitude to the region of persistent snow and ice because of the increased significance of the changes in the angle of insolation and the increased contrast in length of day and night. Long days in summer tend to produce high maxima. Long nights in winter tend to produce low minima. There is a rapid lowering of minima with increase in latitude and a less rapid lowering of maxima. As minus departures from the normal temperature are usually greater, and often twice as great as the plus departures, low minima are more important than high maxima in producing great seasonal range. The regions of extreme range are therefore on the continents in high latitudes where the winters are long but where snow does not persist throughout the year and thus prevent high maxima; i.e., in the interiors of northern Asia (range 170F; 94C), and in northern North America (range 160F; 89C).

23. Annual or seasonal range in temperature becomes greater with decreases in the influence of the oceans, in the amount of moisture present in the air, soil or on the surface, and with reduction in vegetation, because conditions favorable for high temperatures by day, favor high summer averages and maxima, and conditions favorable for low temperatures at night favor low winter averages and minima. Marine climates have little range compared with continental climates. The average annual range in marine climates is 15F (8.3C) for latitude 35N., and 14.8F (8.2C) for latitude 60. For continental climates, latitude 40 has a range of 52F

(29.5C) and latitude 60 a range of 88F (48.6C).

American examples of seasonal range follow: Western Oregon has a normal seasonal range of only about 18F (10C), while South Dakota has a range of 60F (33C). . . . Because of the increased dominance of continental conditions, seasonal range commonly increases toward the est on land areas in the westerly wind belt, although the eastward increase in humidity, as in the eastern United States, tends to counteract this influence. Examples of the increase in range toward the east are: Southwestern Arizona has a monthly range of 30F (17C) and Northwestern Georgia, one of 35F (19C). . . . Nevada has a monthly range of almost 5F (2.8C) less than Illinois or Pennsylvania. Some stations in southern Minnesota have less rage than some in northern New York, in spite of the tempering influence of the Great Lakes. An illustration of the influence of vegetation on annual range is the fact that in Austria the average temperature in the forest is 2F (1C) lower in summer than outside of forests, while in winter the difference is negligible.

24. Annual or seasonal range increases with altitude up to the snow line.

25. Seasonal range in temperature is affected by topography. Slopes inclined sharply toward the midday sun are warmer in summer than those not so inclined, while in winter they may be equally cold, and thus have the greater range. Favorably situated valleys are usually warmer than nearly level stretches (although they may sometimes be notably colder at night). Such valleys are normally warmer because: (1) Foehn breezes of winds often prevail; (2) the more effective heating of those portions which receive vertical insolation may more than compensate for the less effective heating of slopes not so favorably situated for heating as are level tracts. (3) Radiation from the sides of warm valleys interferes with loss of heat by radiation from the valley bottom, or in the case of a narrow valley, from the other side, probably because of the larger radiating surface in proportion to the volume of air within the valley receiving the radiated heat.

Large bodies of water and other regional physiographic features have a more direct and greater effect on air temperature than surface temperature. This follows from the general observation that the ground is stationary and has large heat capacity, whereas air is mobile and has comparatively negligible heat capacity. The air, therefore, both sees and is more sensitive to reginal influences than the ground.

Kusuda and Achenbach have noted, with reference to Figure 15, that the points below the $A_s = A_a$ line represent inland cities such as Ithaca, NY, Salt Lake City, UT, Madison, SD, and St. Paul, MN, with the exception of Ft. Collins, CO. From this and previous observations can be inferred the general pattern,

$A_s > A_a$ for coastal areas

$A_s \leq A_a$ for inland areas

Site specific factors, especially those regarding surface cover, are discussed in references [19, 34, 51].

Existing Data Base: Surface Temperature Phase (t_o)

Knowledge of the phase of the ground temperature wave at the surface is important in mathematical modeling of ground temperatures. Empirical research has shown that ground temperatures can be estimated with reasonable accuracy by a sinusoidal function (described elsewhere in this report). A phase constant is some time value which correctly registers the wave of surface temperature variation within the calendar year.

Ground temperatures are modeled in this report as a negative cosine wave. The phase constant here is given in days; subtracting the phase constant from the time coordinate t shifts the curve to the right or forward in time. In the format of the equation used here, the phase constant represents the number of days after midnight December 31 upon which the annual minimum temperature occurs. It is important to recognize that the sinusoidal function is an idealized model, so the date upon which the minimum temperature of the overall best fit curve occurs may not necessarily coincide with the average date of long term field observations. This is especially true of regions with seasonal snow cover, which tends to skew the shape of the curve.

A theoretical value for the phase constant can be determined from the heat flow equation developed elsewhere in this report. Assuming solar radiation as the primary driving force of heat flux at the surface, the phase of the surface temperature wave is predicted to follow one-eighth cycle behind the heat flux wave. Taking minimum heat flux on December 21, this indicates the minimum surface temperature occurs 45.6 days later, on February 4. The theoretical value of the phase constant, therefore, is 34.6 days (Figure 18).

Kusuda [53] has analyzed ground temperature records from over 60 locations in the United States by a least squares procedure. Phase constants determined by his analysis are mapped on Figure 19. The arithmetic average of 61 values is 35.6 days, or exactly one day (less than 0.3 percent of the annual cycle) off the theoretical value. The range of phase constant values found in the analysis by Kusuda falls between 26 and 45 days, although most are tightly grouped around the average.

Many of the ground temperature records were kept for only one or two years, so the values mapped on Figure 19 do not necessarily represent regional long term averages. In an earlier report, Kusuda and Achenbach [55] compared phase values of ground temperature observations against long term averages of air temperature from nearby weather stations (Figure 20). They concluded,

> The phase angles of the earth surface temperature cycles do not show a definite correlation with that of annual air temperature cycles. The annual air temperature cycles of various cities in the United States are all approximately in phase with the minimum occurring about at the beginning of February.

Additionally, it may be noted that the arithmetic average of air station phase constants almost exactly equals the average of those from earth temperature stations. This may be explained by the fact that the air is mobile and possibly exerts an equalizing effect upon the

various phases of different surfaces it sees. It is likely that variation in surface temperature phase is more site- than region specific, being influenced by factors such as topography, orientation, surface cover, drainage, and shading.

Determination of phase is probably the least explored area of ground temperature research. With respect to thermal modeling, it is one of the most critical aspects, if accurate predictions with respect to time are required: a shift in phase of a week or two can result in large differences in temperature predictions, especially during spring and fall when the temperature curve is rising and falling rapidly. Deliberate manipulation of the phase of the surface temperature wave offers promise in purposeful modification of ground temperature. Labs [57] has proposed examination of shading to uncouple the ground from the solar flux wave, so that the heat flux wave is delayed to be driven by air temperature.

Visher [89] provides some explanation of regional variations in the phase of the air temperature wave, as related to soil and other conditions:

> 14. Diurnal and seasonal lag usually increases with latitude at least in middle latitudes, and decreases with increased aridity. Lag is due to the fact that heating is delayed by the presence of ice, cold water, frozen or chilled soil and rock and that cooling is delayed by stored-up heat in water, rock, soil and water vapor. There is less lag for atmospheric temperatures in arid regions than in humid regions because: 1) There are fewer clouds and less other atmospheric moisture to intefere with radiation; 2) there is little water vapor available for evaporation or freezing; 3) there is a greater exchange of heat by conduction between the atmosphere and the land because the scanty vegetal cover is less effective than the denser vegetation of more humid lands in maintaining a layer of stagnant air between the land and the atmosphere. Another cause of more effective conduction in arid regions is the greate exposure of firm rock there than in humid regions. Rock is a much better conductor than soil.

The form of the heat flow equation discussed elsewhere does not suggest that conductivity has any influence on phase lag at the surface. Latent heat exchange and the resistance to heat flow caused by snow cover and other seasonal changes in the overall surface heat transfer coefficient (annual growth and decay of ground cover vegetation) are probably responsible for the largest departures from the norm, where the phase constant t_o = 35 days.

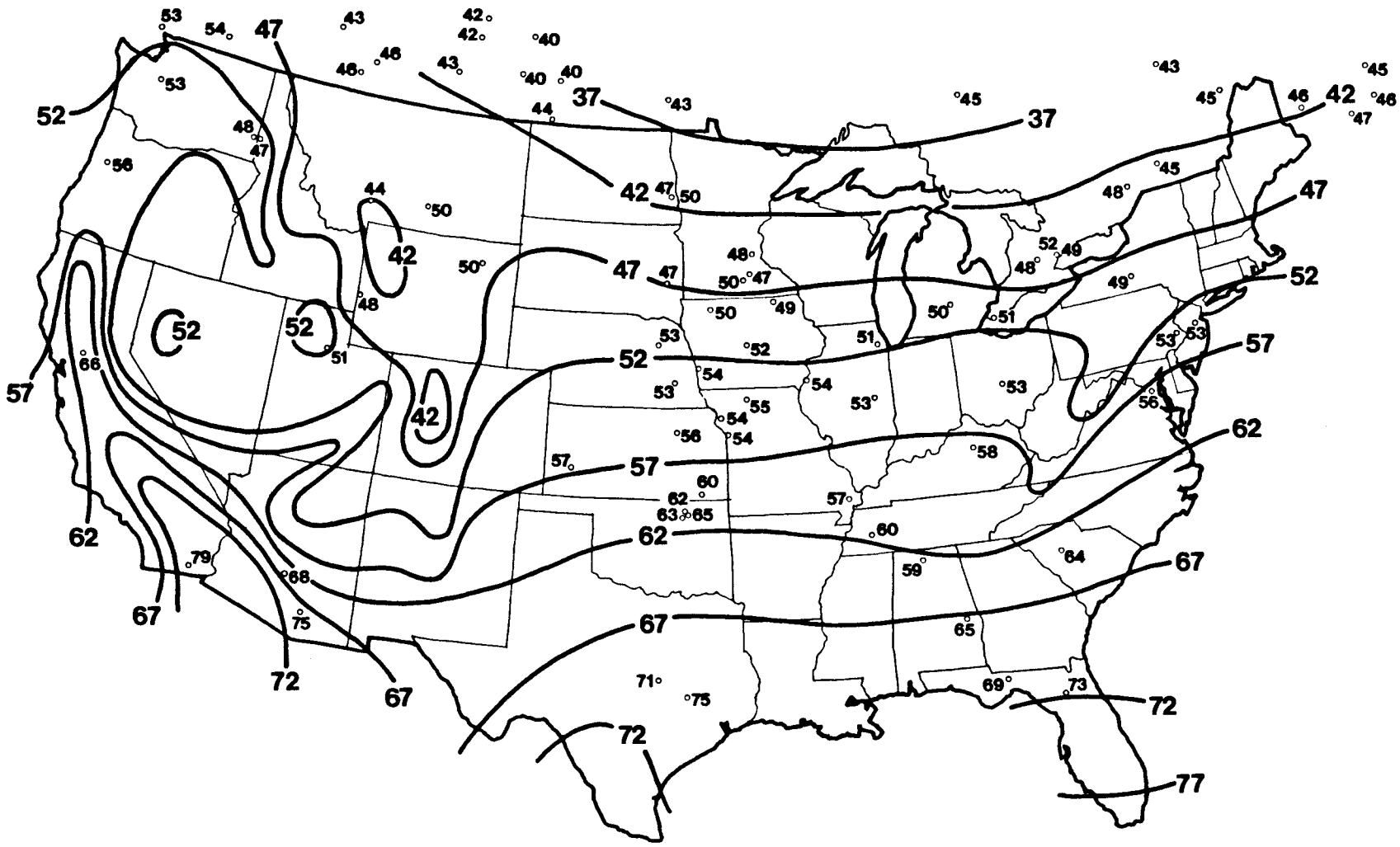

Figure 13. Values of mean annual earth temperature from observations at individual stations are superimposed upon Collins' estimated (1925) well water isotherms.

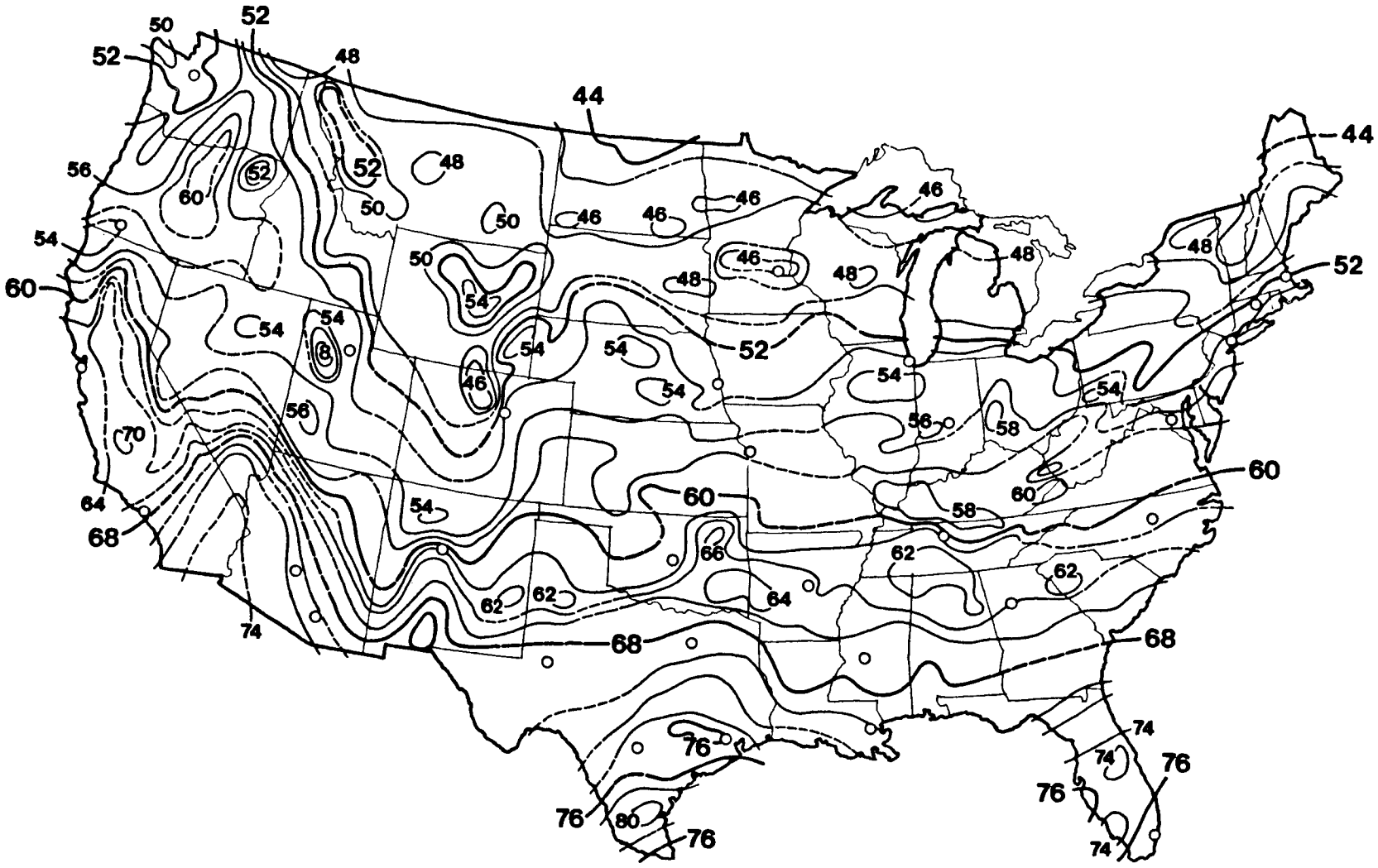

Figure 14. This map of distribution of nonthermal well water temperature can be used for making regional estimates of mean annual earth temperature (redrawn after a map prepared by the National Water Well Institute).

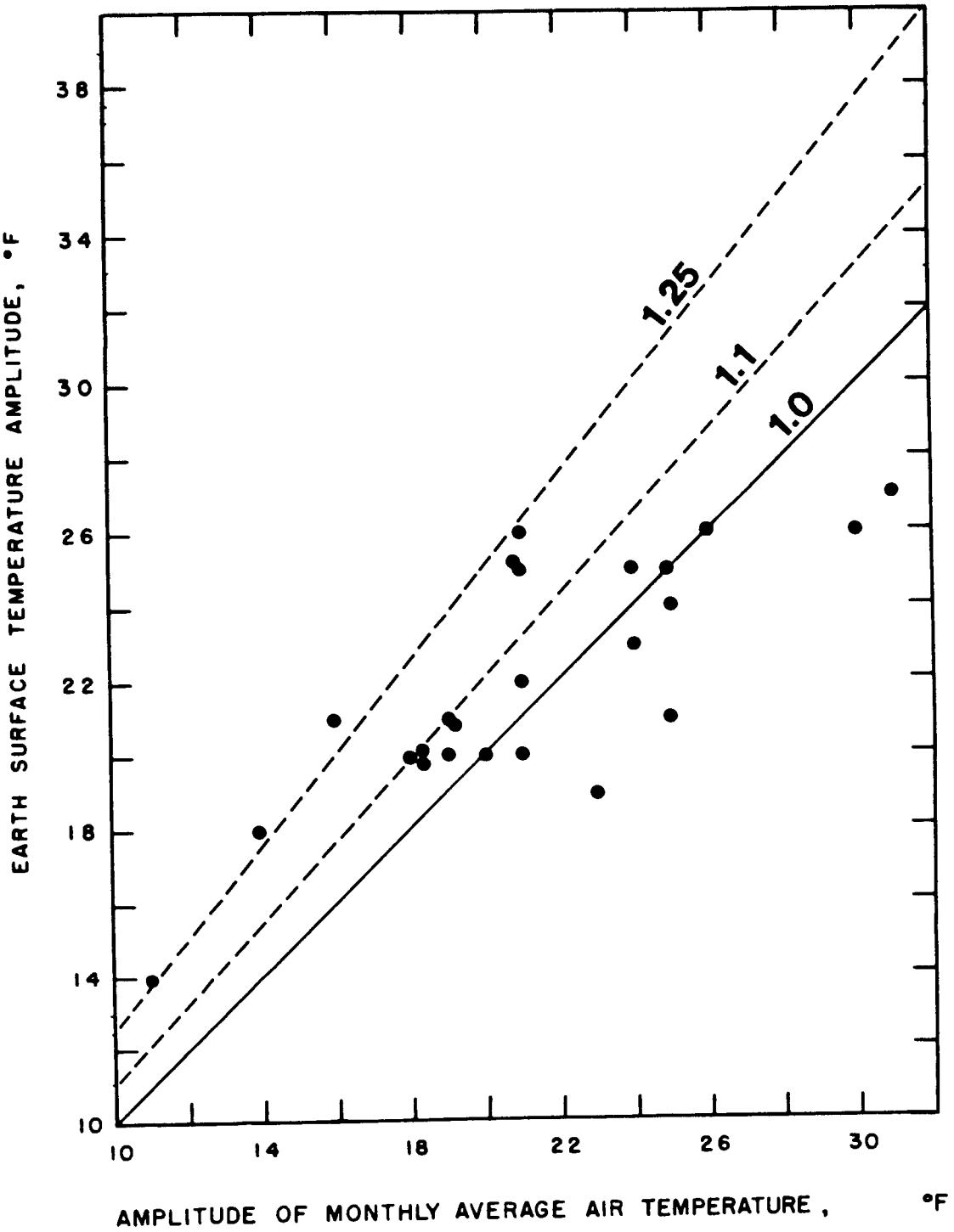

Figure 15. Relationship between earth surface temperature amplitude and of the air, according to least squares analysis by Kusuda and Achenbach.

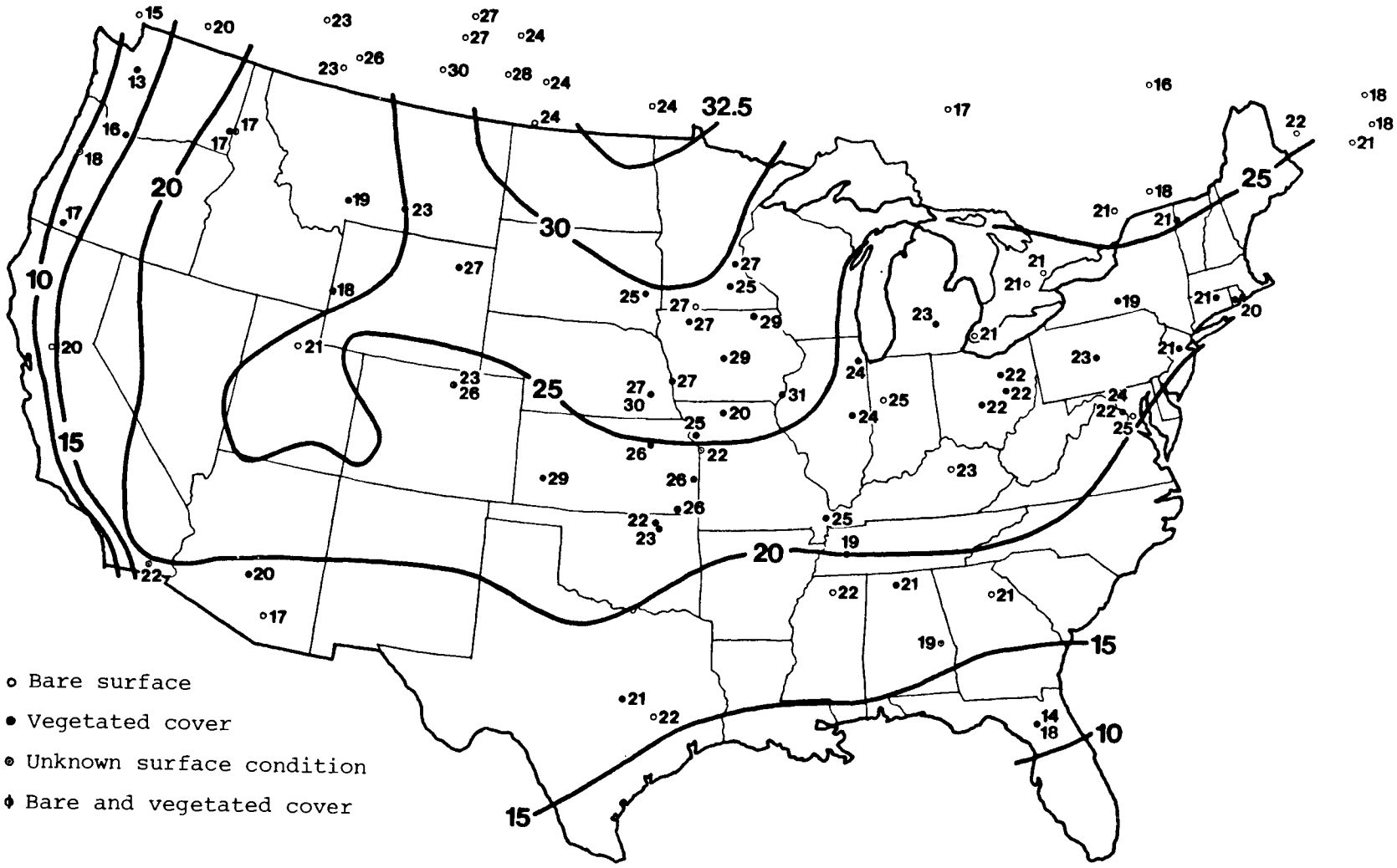

Figure 16. Earth surface temperature amplitude determined through least squares analysis by Kusuda and Achenbach of observed data is superimposed on map of annual air temperature amplitude. Canadian data obtained by taking one-half the range of annual temperature at the 10mm depth.

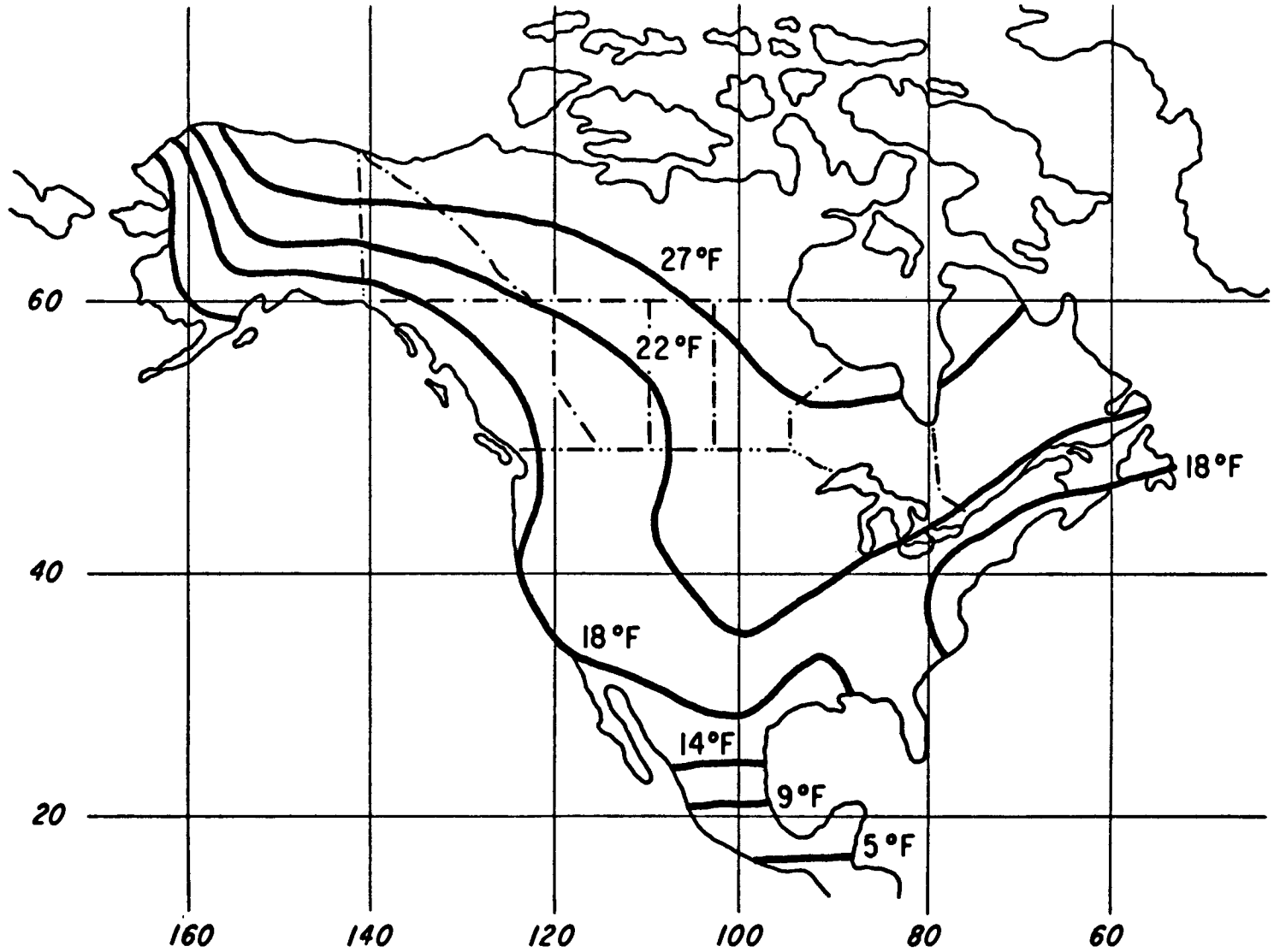

Figure 17. Earth temperature amplitude at the 4 inch depth, according to Chang.

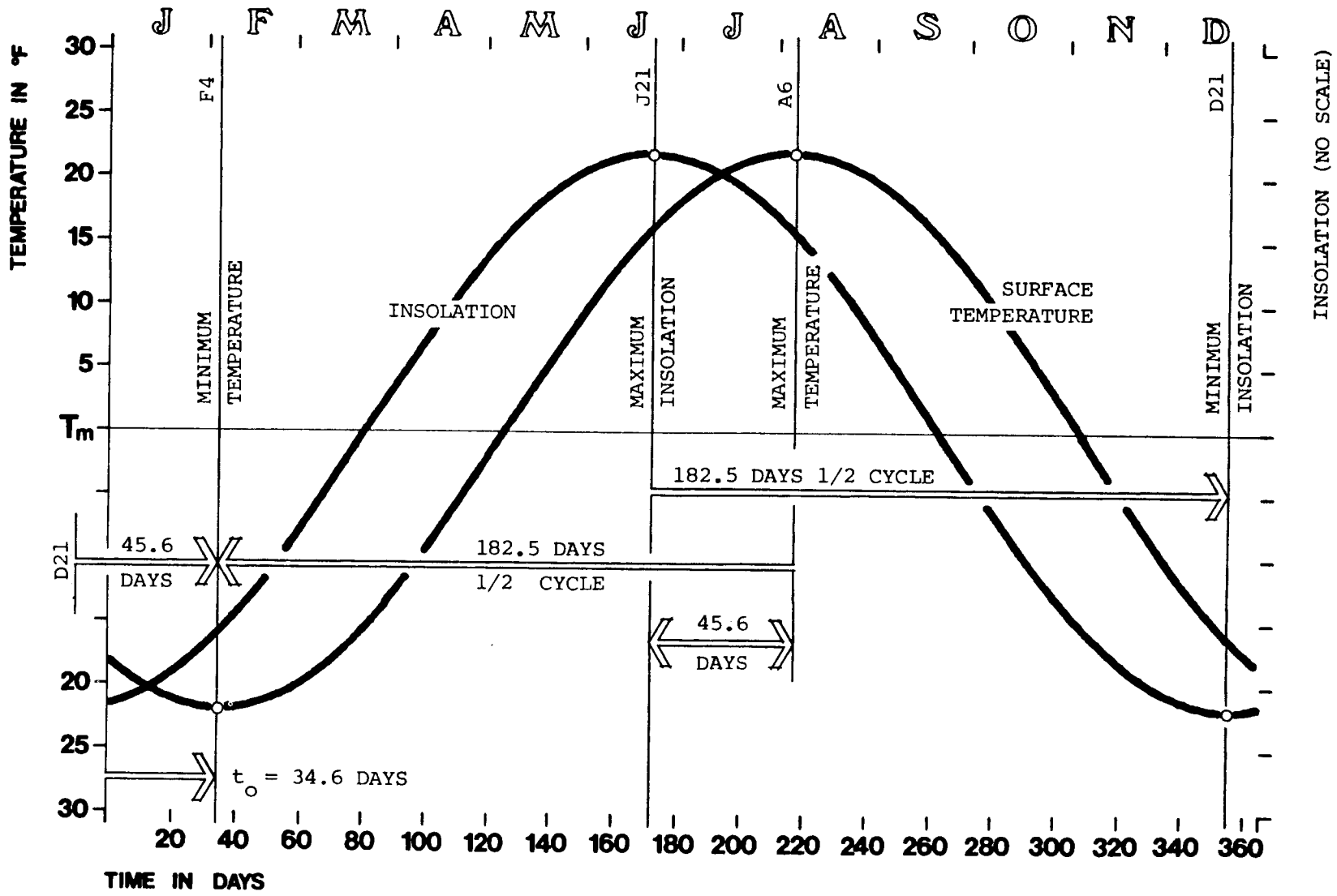

Figure 18. Surface temperature phase follows 1/8 cycle after heat flux, fixing t_o at 34.6 days.

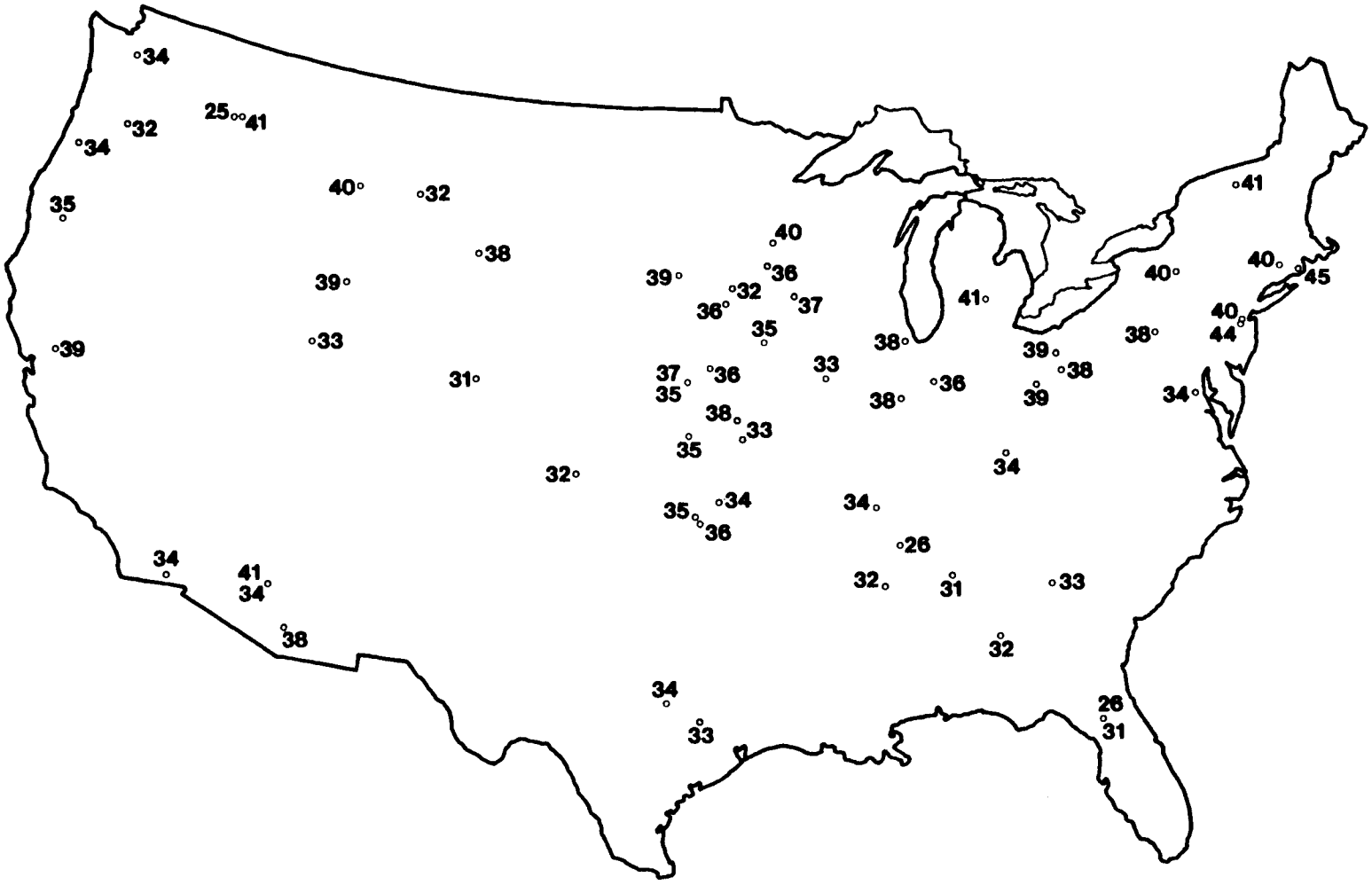

Figure 19. Phase constants of individual earth temperature stations, determined from least squares analysis performed by Kusuda and Achenbach.

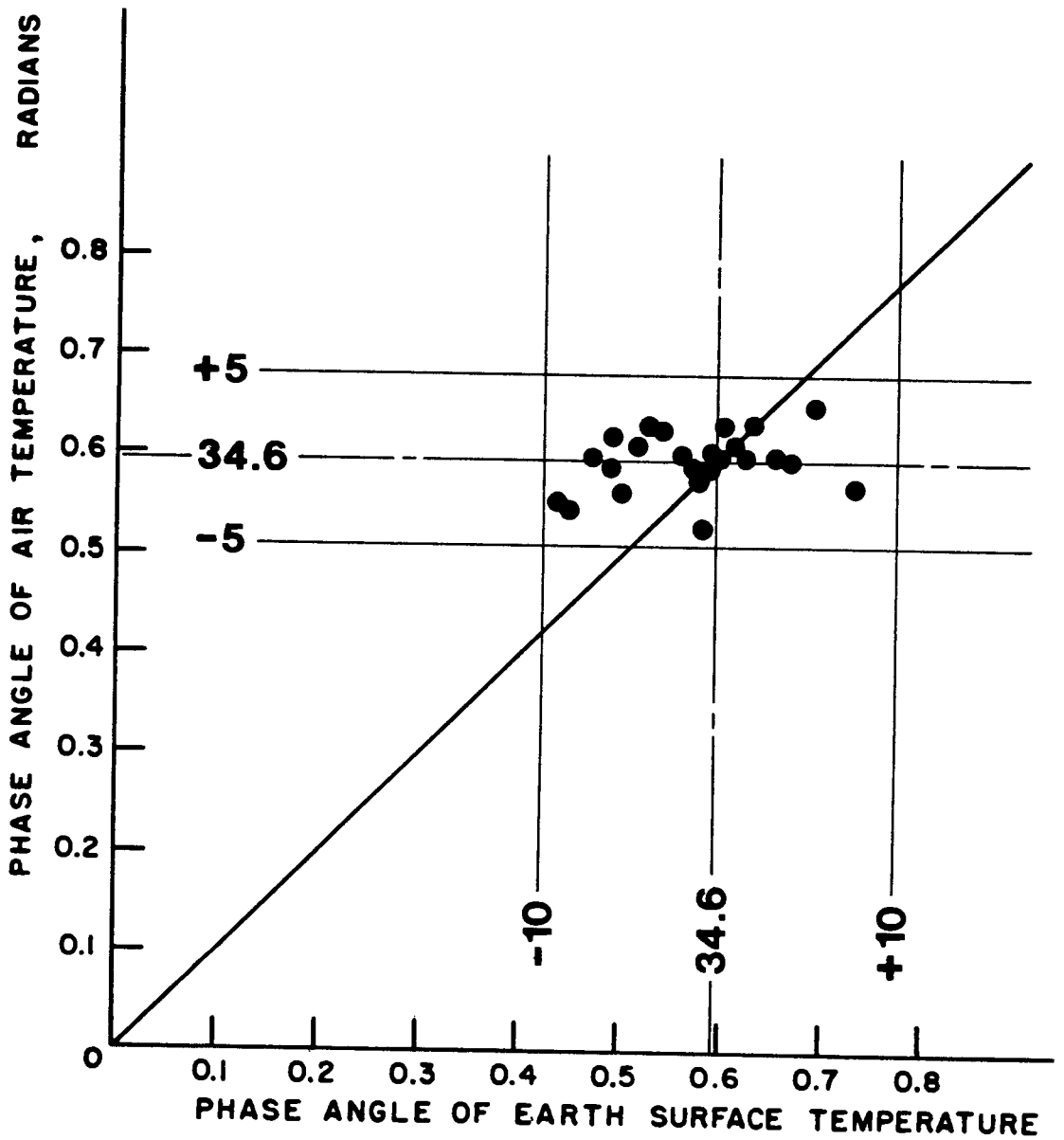

Figure 20. Relationship between phase constants of annual earth and air temperature cycles, according to least squares analysis by Kusuda and Achenbach. One day = 0.172 radians.

GROUND CLIMATE AND HEAT TRANSFER IN SOIL

The temperature of the ground is determined by a number of physical and climatic variables, few of which may be regarded as truly constant over time. These may be classified as a) geographic, including latitude, altitude, and solar radiation; b) meteorological, including snow cover, rainfall, cloud cover, local air temperature and wind flow; c) site specific, including topography (slope and aspect), surface cover, and shading effects of nearby trees and structures; d) subsurface, including the thermal and physical properties of soils, and the level and movement of ground water in the soil. In urban areas, soil temperatures can be appreciably affected by the presence of heated buildings, buried steam pipes, and a host of other disturbances.

The uppermost levels of the soil are greatly affected by the irregularities of radiation, rain, wind, and thermal effects of soil "breathing." The usual stratification of the uppper soil horizon compounds the complexity, making the thermal processes there difficult to model with accuracy. Despite the thermal irregularities of the surface regime, thermal processes in the soil below a depth of two or three feet can be described remarkably well over the course of a year by heat conduction theory alone. The application of heat conduction theory to the problem of prediction of ground temperatures has been studied by numerous researchers in the fields of geophysics, agronomy, biology, and civil and mechanical engineering. Representative literature has been reviewed in papers by Gold and Lachenbruch [36] and Labs [57], and an extensive comparison of observed ground temperatures with predictions by heat conduction theory has been conducted by Kusuda and Achenbach [53, 55]. The development of the mathematical model of temperature in a semi-infinite solid with periodic temperature variation

at the surface is described in many texts on heat transfer. Among those discussing ground temperature problems are Carslaw and Jaeger [15], Ingersoll, Zobel, Ingersoll [45], van Wijk [90, 91], and Kirkham [49].

Temperature Model

Variation in ground temperature is a process driven either directly or indirectly by solar heat flux at the surface. As a result, the fluctuation is fundamentally sinusoidal, and an approximation can be written, in which time is expressed in days (Figure 21),

for the surface,

$$T_{(s,t)} = T_m - A_s \cos\left[\frac{2\pi}{365}(t - t_o)\right] \qquad \text{Eq 1}$$

for depth x below the surface,

$$T_{(x,t)} = T_m - A_s\, e^{-x\sqrt{\frac{\pi}{365\alpha}}} \cos\left[\frac{2\pi}{365}\left(t - t_o - \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right] \qquad \text{Eq 2}$$

where

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

The term t_o is necessary to register the model in proper phase within the calendar year. The (-cos) function begins with the surface temperature minimum occurring on the first hour of the new year; subtracting the pahse constant t_o from t shifts the curve forward to coincide with the actual predicted minimum. The term $(2\pi/365)$ expresses the year of 365 days as a cycle of 2π radians. Alternatively, (360/365) may be substituted within the argument of the cosine, if it is found more convenient to compute the angle in degrees rather than radians. The term $(2\pi/365)$ itself is known as the <u>angular</u> or <u>radial frequency</u>. In the general case, angular frequency $\omega = (2\pi/P)$, where P is the period of the fluctuation. The temperature model $T_{(x,t)}$ can be used to describe diurnal temperature variations in the soil, although with considerably less accuracy than the annual variation. When used to describe the daily temperature cycle, the period P is changed to 24 hours, t and t_o are expressed in hours, and thermal diffusivity α must be expressed in (ft^2/hr).

The <u>amplitude</u> is defined as the maximum excursion from the mean temperature. The temperature <u>range</u> is twice the amplitude. From the form of Equation 2 it is apparent that the mean annual temperature is condsidered constant at all depths.

<u>Thermal diffusivity</u> α is defined as thermal conductivity k divided by the heat capacity (ρc), where ρ is density and c is specific heat. While the rate of heat transfer within a body is dependent upon thermal conductivity, the rise in temperature which this heat will produce depends upon its heat capacity. Thermal diffusivity, therefore, is an index of the facility with which a substance will undergo a temperature change. Thermal diffusivity has sometimes been referred to as "temperature conductivity," although this latter term is not in common usage.

Time Lag

The temperature wave in the soil lags behind the surface wave as a result of the time expended in heating the soil itself. Time lag is given mathematically by the expression (for L in days/ft),

$$L = \frac{1}{2}\sqrt{\frac{365}{\pi\alpha}} \qquad \text{Eq 3}$$

Time lag is solely dependent upon thermal diffusivity for a given period. For the annual cycle, lag time is nearly 11 days per foot for very light, dry soils (α = .25 ft^2/day), and 5 1/2 to 6 days per foot in wet, heavy soils (α = .85 ft^2/day). Soils of average diffusivity (α = .5 to .6 ft^2/day) possess lag times of 7 to 7 1/2 days per foot, or roughly, one week per foot. This linear relationship to depth can be graphed easily (Figure 22), and the effect of the lag is evident in the phase displacement of the graph of temperatures at different depths (Figure 23).

Amplitude Decrement

Temperature amplitude decays at an exponential rate with depth. Amplitude at depth x is given by the relation,

$$A_x = A_s\, e^{-x\sqrt{\frac{\pi}{365\alpha}}} \qquad \text{Eq 4}$$

which may also be written

$$A_x = A_s\, e^{-\left[\frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right]\frac{2\pi}{365}} = A_s\, e^{-xL\frac{2\pi}{365}} \qquad \text{Eq 4a}$$

where the term in brackets can be recognized as the expression for time lag at depth x; amplitude is, therefore, inextricably linked to time lag.

The attenuation or damping of amplitude with depth is known as amplitude decrement. The ratio of the amplitude at variable depth x to the surface temperature amplitude is termed the decrement factor ϕ and its reciprocal is the amplitude ratio:

$$\text{decrement factor } \phi = \frac{A_x}{A_s} = e^{-x\sqrt{\frac{\pi}{365\,\alpha}}} \qquad \text{Eq 5}$$

$$\text{amplitude ratio } \frac{1}{\phi} = \frac{A_s}{A_x} = e^{x\sqrt{\frac{\pi}{365\,\alpha}}} \qquad \text{Eq 6}$$

For convenience, the quantity under the radical sign is sometimes replaced by the single term r, called the logrithmic decrement,

$$r = \sqrt{\frac{\pi}{365\alpha}} \qquad \text{Eq 7}$$

Equation (5) therefore can be written, simply,

$$\phi = e^{-xr} \qquad \text{Eq 5a}$$

Because decrement is related to thermal diffusivity, the magnitude of damping effect varies with soil type and moisture content. The decay is most pronounced in light, well drained soils (small α), whereas in heavy, wet soils, the fluctuations are conducted to a greater depth. The influence of diffusivity is great enough that the range of fluctuation in a wet soil can be more than twice that of a

dry soil at some depths (see Figure 24). For a soil of near average diffusivity (α = .6 ft^2/day), the temperature amplitude of the surface is almost exactly halved at a depth of 6 feet.

Depth of Steady State

It is evident from Equation 4 that the magnitude of temperature variation at depth x is a simple function of surface temperature amplitude, thermal diffusivity, and the period (365 days). The depth at which appreciable temperature fluctuations disappear is easily found by rearranging Equation 5 and solving for x:

$$x = \frac{-\ln (A_x/A_s)}{\sqrt{\frac{\pi}{365\alpha}}} \qquad \text{Eq 8}$$

or, isolating thermal diffusivity,

$$x = -\sqrt{\alpha}\ (10.78 \ln \phi) \qquad \text{Eq 8a}$$

The depth at which the steady state occurs depends on how one defines the "steady state." If for instance, steady state is defined as the depth at which temperature variation exceeds no more than 1 percent of the surface amplitude (less than 1/2F in most cases), then for a soil of average thermal diffusivity (α = .52 ft^2/day),

$$x = -\sqrt{.52}\ (10.78)\ \ln 0.01 = 35.8 \text{ ft}$$

If one regards 90 percent damping as acceptably steady, then

$$x = -\sqrt{.52}\ (10.78)\ \ln 0.1 = 17.9 \text{ ft}$$

A decrement factor of 0.1 represents a subsurface variation of about ± 2F for most regions of the United States. For light, dry (α = .33 ft^2/day) and heavy, wet (α = .75 ft^2/day) soils, 90 percent damping occurs at depths of 14.2 and 21.5 feet, respectively. In all cases, decrement factors of 0.01 and 0.1 correspond to 4.6 and 2.3 times the damping depth D, as defined in the following paragraphs.

Thermal Inertia, Damping Depth

The exponential term $(-x\sqrt{\pi/365\alpha})$ or (-xr) is described by some writers [7] as the <u>thermal inertia</u> of a specified thickness x of a wall, floor, or other building mass. An increase in thermal inertia indicates an increase in damping and in time lag.

It is common in some disciplines to represent the quantity under the radical sign as a reciprocal, i.e.,

$$D = \sqrt{\frac{365\alpha}{\pi}} \qquad \text{Eq 9}$$

D is known by several terms, including <u>damping depth</u>, <u>relaxation distance</u>, and <u>thermal penetration depth</u>. Small damping depths indicate rapid decay of the temperature wave, and correspondingly large lag times.

Maxima and Minima

The minimum of the surface temperature wave occurs on day t_o,

by assignment. Accordingly, the surface temperature maximum occurs one-half cycle later, on day (t_o + 182.5). The extrema at any given depth x follow behind that of the surface by the lag time (xL), that is, on (t_o + xL) and (t_o + 182.5 + xL) for minima and maxima, respectively. These follow from the requirement that the argument of the cosine equal 1 and -1 at the time of occurrence of the extrema. In termas of thermal diffusivity,

$$t_x \text{ minimum} = t_o + \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}} \text{ days after midnight Dec 31} \qquad \text{Eq 10}$$

$$t_x \text{ maximum} = t_o + \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}} + 182.5 \text{ days after Dec 31} \qquad \text{Eq 10a}$$

Velocity of Temperature Wave, Wavelength

The time rate at which the maximum and minimum temperatures are propagated into the soil may be described as the <u>apparent velocity</u> <u>V</u> of the temperature wave. It is defined by the expression (in ft/day),

$$V = \frac{x}{L} = 2\sqrt{\frac{\pi\alpha}{365}} \qquad \text{Eq 11}$$

The quantity $\sqrt{\pi/365}$, or $\sqrt{\pi/P}$ in the general case, is referred to as the <u>coefficient of spatial damping</u> [47]. The velocity may be visualized as the distance travelled by the wave during a unit time.

The wavelength is the velocity times the period, or equivalently, the period divided by the lag rate:

$$\text{wavelength} = VP = 2\sqrt{\alpha\pi P} = \frac{P}{L} \text{ (ft)} \qquad \text{Eq 12}$$

For a soil of average thermal diffusivity (α = .52 ft^2/day), the length of the annual wave is 49 feet, the time lag is 7.5 days/foot, and the apparent velocity is 0.13 feet/day. From the relations given above, it is clear that the velocity is simply the reciprocal of the time lag rate.

Wavelength like the damping depth, is a function of the period. For the diurnal cycle, its value is $1/\sqrt{365}$ = 1/19.1 that of the annual cycle:

$$\frac{VP_{diurnal}}{VP_{annual}} = \frac{2\sqrt{\alpha\pi\,(1)}}{2\sqrt{\alpha\pi\,(365)}} = \frac{1}{\sqrt{365}}$$

Average Temperature of Soil Profile

The undisturbed temperature distribution in the ground at any moment can be determined by holding t constant and computing $T_{(x,t)}$ for a range of depths. The graphic display of temperature distribution at time t is termed a <u>tautochrone</u>, meaning, literally, "same time." Tautochrones at one-eighth cycle increments (45.6 days) are illustrated in figures 25a and b. See also figure 26.

For purposes of ground climatological analysis related to buildings, it is of interest to consider the average temperature of a specified profile ranging from some depth a to depth b. This is

accomplished by integrating Equation (2) with respect to depth x, and dividing by the height of the profile in question, (b-a), as illustrated in figure 27:

$$\bar{T}_{(a-b,t)} = \frac{1}{(b-a)} \int_a^b T_{(x,t)}\, dt \qquad \text{Eq 13}$$

$$\bar{T}_{(a-b,t)} = T_m - \frac{A_s}{(b-a)} \left[e^{-xr} \left\{ \frac{-r \cos \frac{2\pi}{365}(t - t_o - xL)}{(-r)^2 + (-r)^2} - \frac{r \sin \frac{2\pi}{365}(t - t_o - xL)}{(-r)^2 + (-r)^2} \right\} \right]_a^b \qquad \text{Eq 13a}$$

which can be simplified through use of the trigonometric identity, $\cos\theta + \sin\theta = 2\cos(\theta - \pi/4)$:

$$\bar{T}_{(a-b,t)} = T_m + \frac{A_s}{(b-a)r\sqrt{2}} e^{-xr} \cos\left[\frac{2\pi}{365}(t-t_o-xL-45.6)\right]\Bigg|_a^b \qquad \text{Eq 13b}$$

where

a = upper bounds of profile (ft)

b = lower bounds of profile (ft)

$\pi/4$ = 1/8 cycle = 45.6 days

Profile Temperature Degree Day Analysis

Profile temperatures can be examined for severity and duration of extremes in a degree day format similar to conventional heating and

cooling degree days. Ground temperature degree days to any base can be computed with use of the ground temperature model. While this can be done analytically, it is most easily performed through numerical integration on a digital computer. A graphical solution may also be employed as illustrated in Figure 28 for underground heating degree days (UGHDD) to base 65F and underground cooling degree days (UGCDD) to base 78F.

Profile Lag Time

The form of Equation (13b) reveals that the temperature average of any designated soil profile is sinusoidal. From the form, also, it can be seen that the average temperature curve will equal the mean (i.e., cross the time axis) for t when

$$e^{-xr} \cos \frac{2\pi}{365} (t - t_o - xL - 45.6) \Big|_a^b \qquad \text{Eq 14}$$

Therefore,

$$e^{-br} \cos \frac{2\pi}{365} (t - t_o - bL - 45.6) = e^{-ar} \cos \frac{2\pi}{365} (t - t_o - aL - 45.6) \qquad \text{Eq 14a}$$

solving for t_m, the date of mean temperature occurrence, (Eq 14b)

$$t_m = \frac{365}{2\pi} \arctan \left[\frac{\cos \frac{2\pi}{365} (Lb + t_o + 45.6) - e^{br-ar} \cos \frac{2\pi}{365} (La + t_o + 45.6)}{e^{br-ar} \sin \frac{2\pi}{365} (La + t_o + 45.6) - \sin \frac{2\pi}{365} (Lb + t_o + 45.6)} \right]$$

The minimum of the average profile temperature will occur either 1/4 cycle before or after t_m given by Equation (14b), that is, (t_m + 91.25 days). Accordingly, the lag of the profile tempeature can be found by subtracting the time of surface temperature minimum t_o from the calculated profile temperature minimum:

$$\text{profile lag time} = (t_m + 91.25) - t_o. \qquad \text{Eq 15}$$

As an example, the average temperature of a profile extending from 2 feet to 12 feet below the surface is found to lag 42 days behind the surface wave if a thermal diffusivity of 0.6 ft^2/day is assumed. Similarly, the lag time of a 0-6 foot profile is found to be 18 days.

Heat Flow in the Ground

An examination of any tautochrone reveals a continuously varying distribution of ground tempeature with depth. Between any two depths, therefore, exists a temperature gradient, and a consequent flow of heat. Further examination reveals that different depths can be identified through which, simultaneously, heat is passing either upward or downward. Also, at any time of year, a unique depth can be identified which is either gaining or losing heat to soil flanking it both above and below. Such a depth is passing from a period through which heat has been flowing upward and will soon be flowing downward, or vice versa, as the layer shifts from a period of cooling to heating, or heating to cooling (see Figure 29).

The amount of heat flowing through any layer in the soil can be determined through manipulation of the ground temperature model. From

the general Fourier formula of heat flow,

$$\frac{Q}{day} = -k\ (\Delta T)\ \text{area} \qquad \text{Eq 16}$$

In terms of the temperature gradient in the ground, ΔT can be written by differentiating Equation (2):

$$\Delta T = \frac{dT(x,t)}{dx} = d\left[T_m - A_s e^{-xr} \cos \frac{2\pi}{365}(t-t_o-xL)\right] / dx \qquad \text{Eq 17}$$

$$\Delta T = -A_s e^{-xr}(-r)\left[-\sin \frac{2\pi}{365}(t-t_o-xL) + \cos \frac{2\pi}{365}(t-t_o-xL)\right] \qquad \text{Eq 17a}$$

Using the trignometric identity $(\cos \theta - \sin \theta) = 2 \cos (\theta + \pi/4)$,

$$\Delta T = r\sqrt{2}\, A_s e^{-xr} \cos\left[\frac{2\pi}{365}(t - t_o - xL + 45.6)\right] \qquad \text{Eq 17b}$$

By substituting T from Equation (17b) into the Fourier formula Equation (16), the heat flow through any depth x can be written,

$$\frac{Q_x}{(\text{area})\,\text{day}} = -kr\sqrt{2}\, A_s e^{-xr} \cos\left[\frac{2\pi}{365}(t-t_o-xL+45.6)\right] \qquad \text{Eq 18}$$

where k = thermal conductivity of soil (Btu/ft(day)F); a negative sign indicates heat flow out of the ground.

For the special case x = 0, heat flow at the surface s,

$$\frac{Q_s}{(\text{area})\text{day}} = -kr\sqrt{2}\,A_s\cos\left[\frac{2\pi}{365}(t - t_o + 45.6)\right] \qquad \text{Eq 18a}$$

Several observations of particular interest to the problem of heat flow in soils can be made by a close examination of Equations (18) and (18a) and comparison of these with the temperature Equation (2):

1) The maximum heat flux at any depth x occurs 1/8 cycle before the maximum temperature at that depth. This is indicated by addition of 45.6 days (introduced through integration as $\pi/4$ radians) to the argument of the cosine; its effect is illustrated in Figure 19. If maximum heat flux is assumed to occur midday in June 21 (t = 171.5), then maximum temperature is expected to follow 45.6 days later, on August 5 (t = 217.1). This shows remarkably good agreement with field observations (Pearce and Gold [73] and others), despite the fact that the model considers conduction as the only mode of heat transfer in the ground.

2) The maximum heat flux for the profile occurs at the surface and is given by the expression,

$$\frac{\max Q_s}{(\text{area})\text{day}} = \sqrt{2}\,kr\,A_s = \sqrt{\frac{2}{D}}\,k\,A_s \qquad \text{Eq 19}$$

This is equivalent to the flow of heat which would occur through a layer of soil of thickness ($\sqrt{2}D$) if one face were maintained at the maximum and the other at the minimum temperature of the surface. The quantity ($\sqrt{2}D$) can, therefore, be regarded as an effective depth for heat flow [68]. For a soil of average thermal diffusivity (α = .52 ft^2/day), the effective depth equals 11 feet. For dry soils (α = .33 ft^2/day), it is slightly less than 9 feet, and it just exceeds 13 feet for a typical heavy, wet soil (α = .75 ft^2/day).

3) The quantity ($\sqrt{2}kr$) may be rearranged to group together

terms which express the thermophysical properties of soil:

$$\sqrt{2}\,kr = \sqrt{2}\sqrt{k^2}\sqrt{\frac{\pi}{365\alpha}} = \sqrt{\frac{2\,k^2\pi}{365\alpha}} \qquad \text{Eq 20}$$

Since $\alpha = k/\rho c$,

$$\sqrt{2}\,kr = \sqrt{\frac{2\,k^2\pi}{365}\left(\frac{\rho\,c}{k}\right)} = \sqrt{k\rho c}\sqrt{\frac{2\pi}{365}} \qquad \text{Eq 20a}$$

The heat flow Equation (18) may therefore be written,

$$\frac{Q_x}{(\text{area})\,\text{day}} = -\sqrt{k\rho c}\sqrt{\frac{2\pi}{365}}\;A_s\,e^{-xr}\cos\left[\frac{2\pi}{365}(t-t_o-xL+45.6)\right] \qquad \text{Eq 21}$$

It is clear from the form of Equation (21) that the rate of heat flow within the ground and exchanged at the surface is directly proportional to the quantity $\sqrt{k\rho c}$ and the amplitude A_s, and is also related (inversely) to the period, here 365 days for the annual cycle. The quantity $\sqrt{k\rho c}$ has special significance, and has variously been named the thermal admittance, the (thermal) contact coefficient the conductive capacity, and the thermal penetration property, among others.* The former two terms are most often used in reference to heat transfer across an interface between different media, while the latter two are more often used in the context of conduction within the interior of a solid. The term conductivity-capacity product is also sometimes used with reference to the quantity under the radical sign. "Conductive capacity" will be used hereafter in this discussion.

The proportional relationship between $\sqrt{k\rho c}$ and A_s with heat flux means that with any given rate of daily heat flow, an increase in conductive capacity must result in an accompanying decrease in A_s.

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*Gold and Lachenbruch [36] indicate that $\sqrt{k\rho c}$ is also called the "thermal inertia" by some writers; this differs from the way in which thermal inertia was previously defined.

Very wet soils, such as in bogs and marshes, therefore, exhibit small surface amplitudes, while very dry desert soils exhibit large surface amplitudes. Bodies of water have extraordinarily large conductive capacities, owing both to the high specific heat c of water as well as to its very great effective conductivity (due to convection); this accounts for the relative stability of air temperature over lakes, as compared to over land. According to Chang [17], the fraction of heat entering the soil is roughly proportional to the logarithm of the conductive capacity.

Heat Storage in the Ground

The amount of heat stored in the ground beneath any specified depth is represented as the area under the heat flow curve defined by Equation (21) for that depth. An expression for heat storage is found by integrating Equation (21) with respect to time:

$$\frac{Q_x}{\text{area}} = \int_{t_1}^{t_2} \frac{Q_x dt}{\text{area(day)}} =$$

$$\frac{365}{2\pi} \int_{t_1}^{t_2} - \sqrt{k\rho c} \sqrt{\frac{2\pi}{365}} A_s e^{-xr} \cos\left[\frac{2\pi}{365}(t-t_o-xL+45.6)\right] \frac{2\pi}{365} dt \qquad \text{Eq 22}$$

$$\frac{Q_x}{(\text{area})} = \sqrt{k\rho c} \sqrt{\frac{365}{2\pi}} A_s e^{-xr} \sin\left[\frac{2\pi}{365}(t-t_o-xL+45.6)\right]_{t_1}^{t_2} \qquad \text{Eq 22a}$$

which may be rewritten, using the identity $\sin\theta = -\cos(\theta - \pi/2)$,

$$\frac{Q_x}{\text{area}} = \sqrt{k\rho c}\sqrt{\frac{365}{2\pi}}\, A_s\, e^{-xr} \cos\left[\frac{2\pi}{365}(t-t_o-xL-45.6)\right]_{t_1}^{t_2} \qquad \text{Eq 22b}$$

For total heat storage beneath the surface (x = 0),

$$\frac{Q_x}{\text{area}} = \sqrt{k\rho c}\sqrt{\frac{365}{2\pi}}\, A_s \cos\left[\frac{2\pi}{365}(t-t_o-45.6)\right]_{t_1}^{t_2} \qquad \text{Eq 23}$$

A positive value of Qs/area indicates net heat is being stored in the soil (charging), while a negative sign indicates that heat is being released (discharging).

The following observations can be made about heat storage in the ground as revealed by Equations (22b) and (23).

1) The heat storage curve lags behind the temperature curve by 1/8 cycle, and behind the heat flux curve by 1/4 cycle at any given depth. Accordingly, the maximum amount of heat is held in the soil below the surface on the date at which net heat flux is zero, as the surface passes from a half cycle of net heat gain to its half cycle of heat loss (see Figure 30).

2) If t_2 and t_1 are chosen to span the half cycle of fully charged or depleted storage, the total amount of heat stored within a unit area of the soil mass half space is seen to equal,

$$\frac{Q_s}{(\text{area})} = \sqrt{k\rho c}\sqrt{\frac{365}{2\pi}}\, A_s \qquad \text{Eq 24}$$

The quantity under radical signs, $\sqrt{k\rho c 365/2\pi}$, indicates the amount of heat, per unit surface area, which is stored and released per unit temperature swing (amplitude). With reference to the daily temperature cycle, this term ($\sqrt{k\rho c/2\pi}$) has been described as the <u>diurnal heat capacity</u> by Balcomb <u>et al</u> [12]. For the general case of period P, the term may be denoted the

periodic heat capacity.

As in the case of the depth to which temperature variation penetrates, the extent of the heat storage reserve which is coupled to the surface depends upon the period. For the diurnal cycle, this depth is $1/\sqrt{365}$ that of the annual cycle.

3) Equation (24) can be rewritten in the form,

$$\frac{Q_s}{(\text{area})} = \rho c \sqrt{2}\, D\, A_s \qquad \text{Eq 25}$$

This represents the aount of heat flowing into or out of the soil surface during one-half cycle. It is the amount of heat required to raise through A_s a layer of soil equal to the effective depth $\sqrt{2}D$ [68]. The quantity $\sqrt{2}D$ can be considered an effective depth for heat storage.

4) From Equation (22b), it is apparent that heat storage diminishes exponentially with depth. The participation of deep layers is therefore relatively unimportant as compared to the layers near the surface.

Envelope house: crawl space heat storage

A simple example shows a practical application of the heat storage equation. It is alleged that the ground underlying the crawl space of a double envelope house provides thermal storage for excess heat energy passing around the "convective loop." Temperature fluctuations measured by Abrams and Akridge [1] at the surface of the ground of the crawl space of such a house were found typically ranging between 47 and 53F. If a heavy, damp soil favorable for heat storage is assumed (k = .75 Btu/(hr) ft; ρ = 131 lb/ft^3; c = .23 Btu/lb), then the total amount of heat energy stored and released during a daily cycle is found from Eq (24),

$$\frac{Q_s}{(\text{area})} = \sqrt{\frac{(131\ \text{lb})}{\text{cu ft}}\,\frac{(.23\ \text{Btu})}{(\text{lb})\text{F}}\,\frac{(.75\ \text{Btu})}{\text{hr}(\text{ft})\text{F}}}\,\sqrt{\frac{24\ \text{hr}}{2\pi}}$$

$$\frac{Q_s}{\text{area}} = \sqrt{\frac{9.3 \text{ Btu}}{\text{sq ft(F)}}} \; A_s$$

Assuming an amplitude (or one-half range) of 3F,

$$\frac{Q_s}{\text{area}} = (9.3)(3) = 27.9 \text{ Btu/sq ft}$$

This small amount of storage indicates that the crawl space does not participate in a major way in the overall storage of heat in the envelope house. The limitations of ground coupling between a periodically heateed crawl space or beneath a direct gain slab-on-grade floor are further suggested by the effective depth $\sqrt{2}D$. Since deep ground serves as a sink to interior heat in all major heating zones of the United States, it is (from the standpoint of heat conservation alone) desirable in principle to insulate beneath these. This is rarely cost effective, however, since the temperature differential is relatively small, and the insulation can usually be made better use of elsewhere. If the temperature differential is increased by using the mass as a storage medium for excess heat (i.e., exposed to temperatures much in excess of normal room temperature) then the rate of heat loss to deep ground increases, and the desirability of uncoupling the active storage mass from deep ground also increases. Little mass below the depth $\sqrt{2}D$ communicates with the surface (about 7.5 inches for the soil assumed above), so no more than a foot of soil is useful for thermal storage on a diurnal cycle. A method for determining optimum storage depths for a variety of materials is given by Balcomb et al [12]; this technique gives optimum depths of about 20 percent less than $\sqrt{2}D$. The cost effectiveness of insulating beneath the active storage layer remains a problem for economic analysis.

Two ways of increasing the storage ability of a crawl space are to 1) increase the conductive capacity $\sqrt{\rho ck}$ of the storage medium, and 2) increase the area of the heat transfer surface, so as to activate more mass in the storage proces. Rocks, jugs of water, phase change canisters and similar discrete storage units satisfy both requirements. The maximum (but not optimum) effective size of round-shaped rocks can be determined by requiring the radius not to exceed $\sqrt{2}D$; other considerations normally argue for smaller radii.

Geothermal Heat Flow

Geothermal heat flow refers to heat produced at the center of the earth which is conducted outward. By the time this heat has reached the surface, it has diffused over such an ever-widening area that its magnitude is insignificant from an engineering point of view.

Temperature gradients established by geothermal heat flow have been observed in mines, boreholes, and other shafts in many parts of the world. The gradient ranges from about 0.5F to 2F per 100 feet, with 1.4F representing an average value [47]. If the thermal conductivity of the earth's crust is assumed to equal 1.4 Btu/ft(hr)F (the ASHRAE [8] value for "average rock") and the geothermal gradient is taken as 1.4F per 100 feet, geothermal heat flow can be estimated,

$$\frac{Q}{\text{area}} = \frac{k\,(\Delta T)}{x} = \frac{1.4\ \text{Btu}\ (1.4\text{F})}{\text{ft(hr)F}(100\text{ft})} = \frac{0.0196\ \text{Btu}}{\text{(hr)sq ft}}$$

This represents an annual heat flow of only 172 Btu/ft^2. In fact, the mean geothermal heat flow for North America is reported as 1.19 microcalories/cm^{2}sec [62], which is equivalent to 138 Btu/ft^2 year. Geothermal heat received at the surface equals roughly 3/10,000 of the amount of heat received from the sun in termperate regions.

Jumikis [47] characterizes geothermal heat as "just enough to melt a layer of ice 7.4 mm thick in one year, or to thaw a frozen, saturated layer of soil about 25 mm thick."

Other Models of Ground Temperature

It has been concluded after extensive analysis of field data that the ground temperature model presented in Equation (2) is sufficiently accurate for engineering purposes, provided that the variables can be chosen to closely approximate field conditions [54]. Nevertheless, numerous refinements and alternatives to the model have been suggested by investigators exploring both theoretical and other practical aspects of ground temperature prediction. While discussion of these is beyond the scope of this work, a brief review of some of the more salient inquiries is presented.

Thermal diffusivity is closely related to moisture content, which varies throughout the year. A solution for time-dependent diffusivity has been discussed by van Wijk and de Vries [91], who assume that diffusivity varies sinusoidally. A new function expressing variable diffusivity is substituted for t in a formula similar to Equation (2). The analysis produces a distorted sine wave.

Scott [77] treats the problem of phase change effects and sudden heating of the surface (of a body of uniform temperature). The effect of a surface layer having no heat capacity, but possessing a conductance coefficient is also discussed, as are the effects of different ground covers in coupling the surface to the air.

Temperature disturbances of several sorts are discussed in an excellent review paper by Gold and Lachenbruch [36], and in an earlier, important contribution to the literature, Lachenbruch [58] develops an analytical method for calculating the temperature at any

point within the field of influence of a temperature disturbance at the surface. Jumikis [46] has prepared a set of influence charts for predicting disturbed temperatures beneath a heated slab-on-grade based on Lachenbruch's analysis technique, and Brown [14] describes a graphic technique for estimating steady state conditions due to long term surface temperatue disturbances. Frost penetration depths and sudden temperature changes at the surface are discussed in a textbook on thermal geotechnics by Jumikis [47], who also discusses problems in permafrost and insulation of roads and building perimeters to protect them from frost heaving.

A model for exploring the effect of variable surface covers ("heat valve" effects) is discussed in papers by Gilpin and Wong [29, 31]. The problem of layered soils is explored mathematically by van Wijk and Derksen [90]. A mathematical model for predicting ground temperature driven by solar radiation has been described by Khatry et al [48].

A variety of different approaches to modeling ground and surface temperatures for the daily cycle have been described. Among these are models driven by air temperatures [42], heat balance relationships [29, 30, 50, 90], and a method for calculating heat transfer when conductivity and heat capacity vary with depth [63]. Langbein [60] discusses methods of predicting the effect of irregularities in weather.

In general, much of the most advanced work at present dealing with ground temperatures and heat transfer in soil regarding the annual cycle is being performed within the geotechnical and geophysical disciplines. Most of this is oriented toward problems of permafrost and temperature disturbances. Studies of soil temperature variation on the daily cycle are presently published mostly in journals of soil science and agricultural engineering.

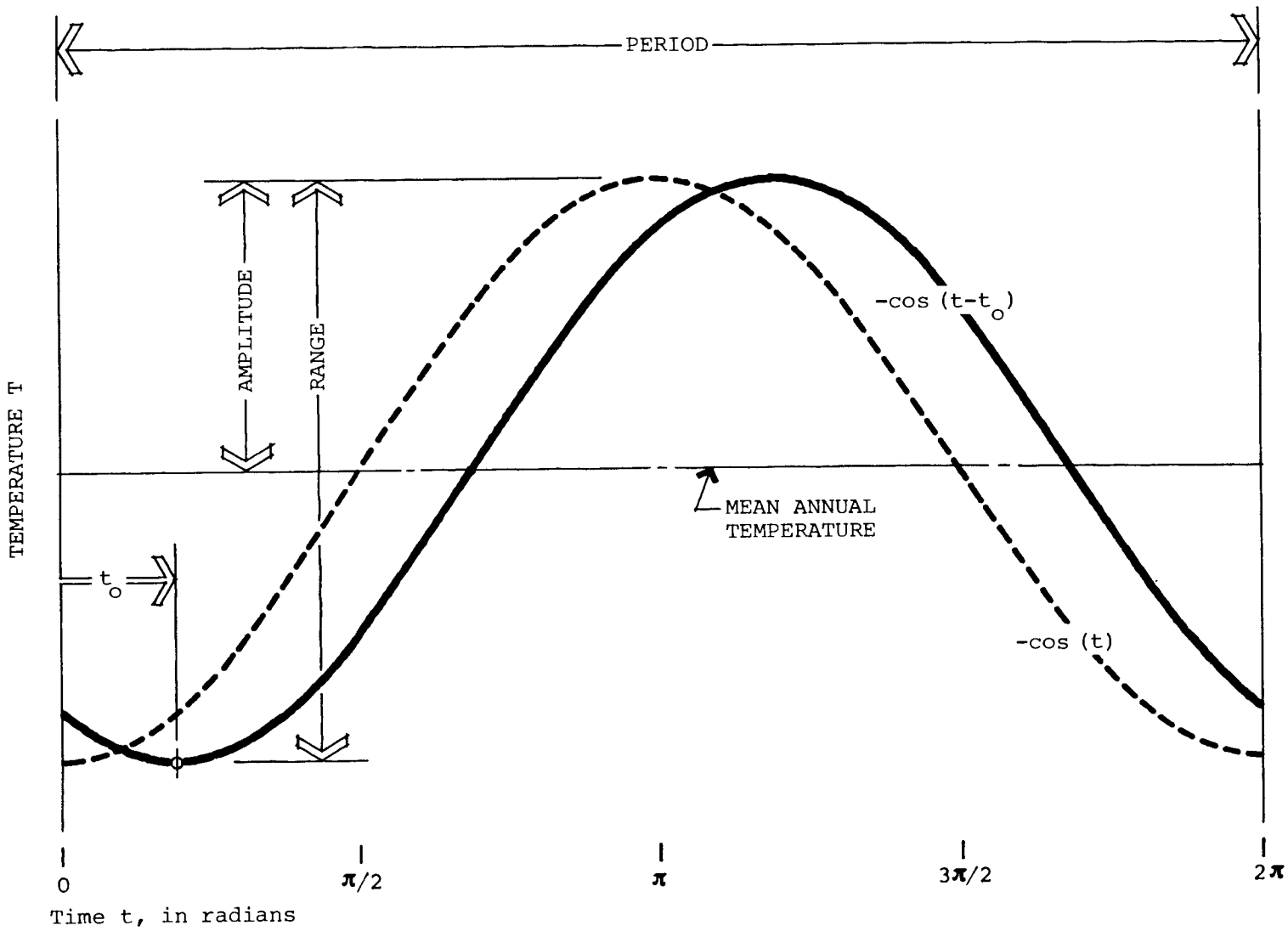

Figure 21. Temperature variation at the surface can be represented as a negative cosine wave that fluctuates about the mean annual temperature. Period of the function is 2π radians; t in days is converted to radians by multiplying by 2π/365.

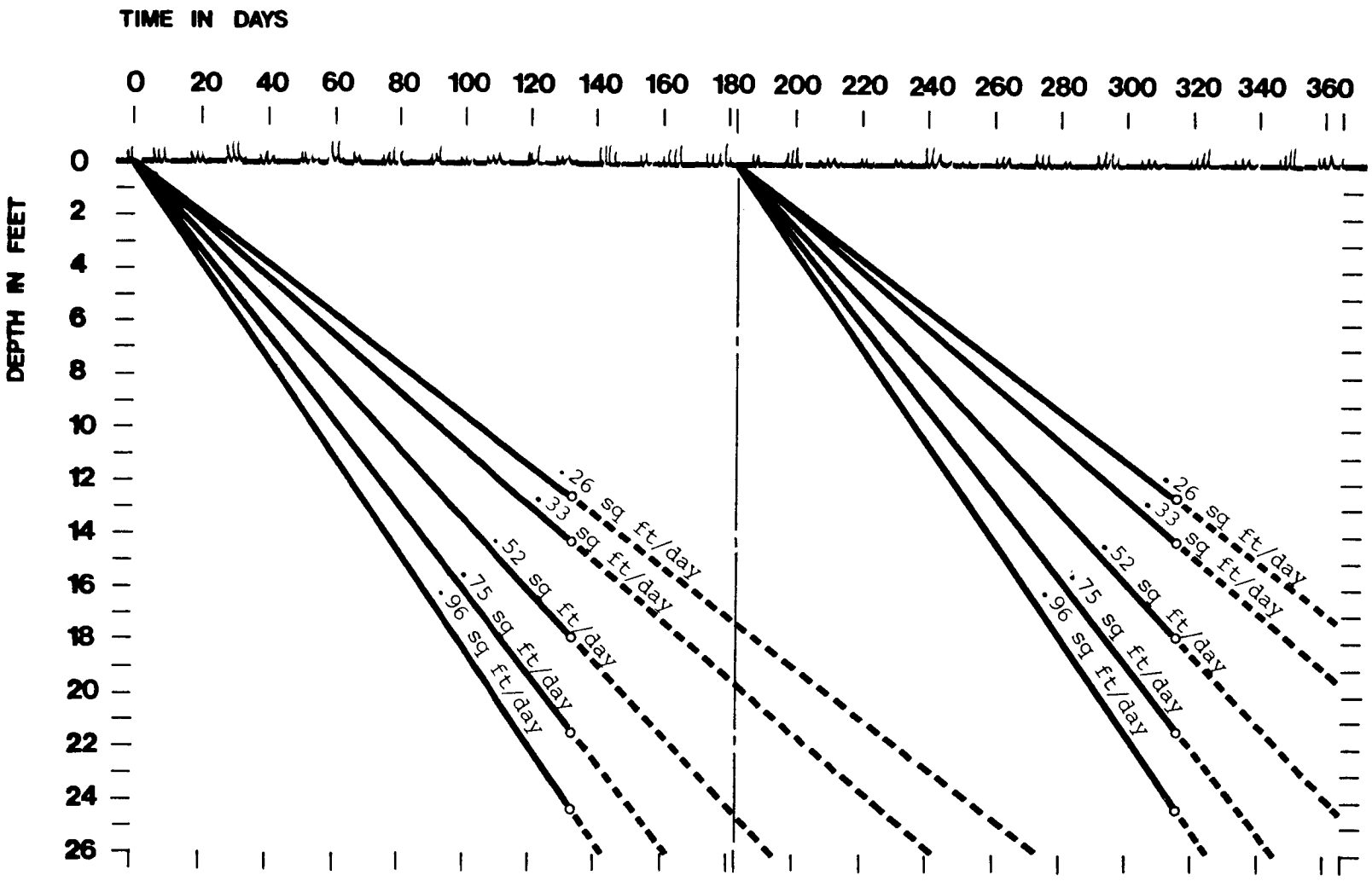

Figure 22. Time lag plotted as a function of depth and time. for different thermal diffusivity values (.26 for very light, dry soils, .96 for heavy, wet soils). Small cicles followed by broken lines indicate depths of 90% damping (2.3D) for each soil.

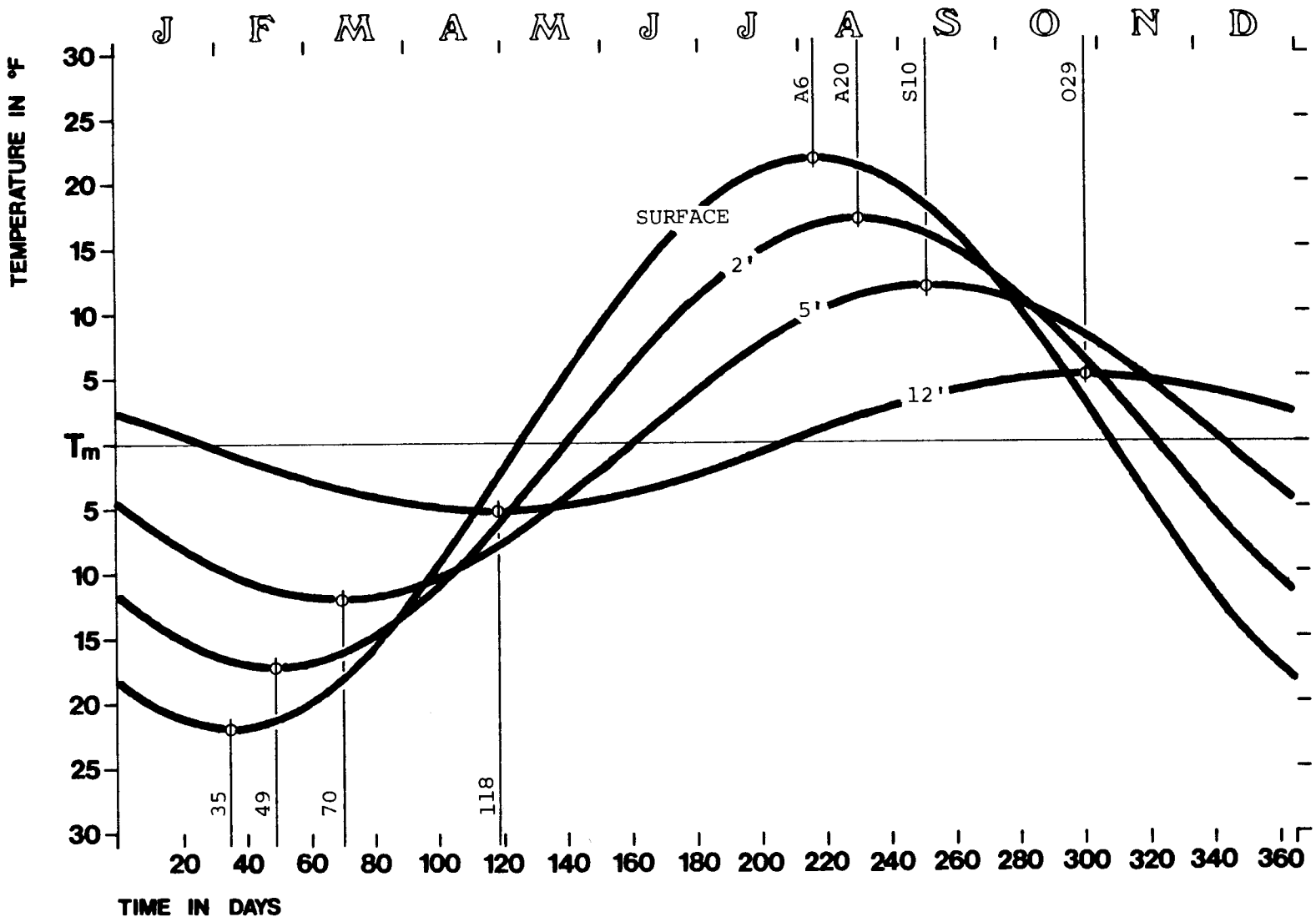

Figure 23. Phase lag between different depths is readily seen by comparing dates of occurence of corresponding maximum and minimum temperatures ($\alpha = 0.6$ sq ft/day, approximately 1 week/ft).

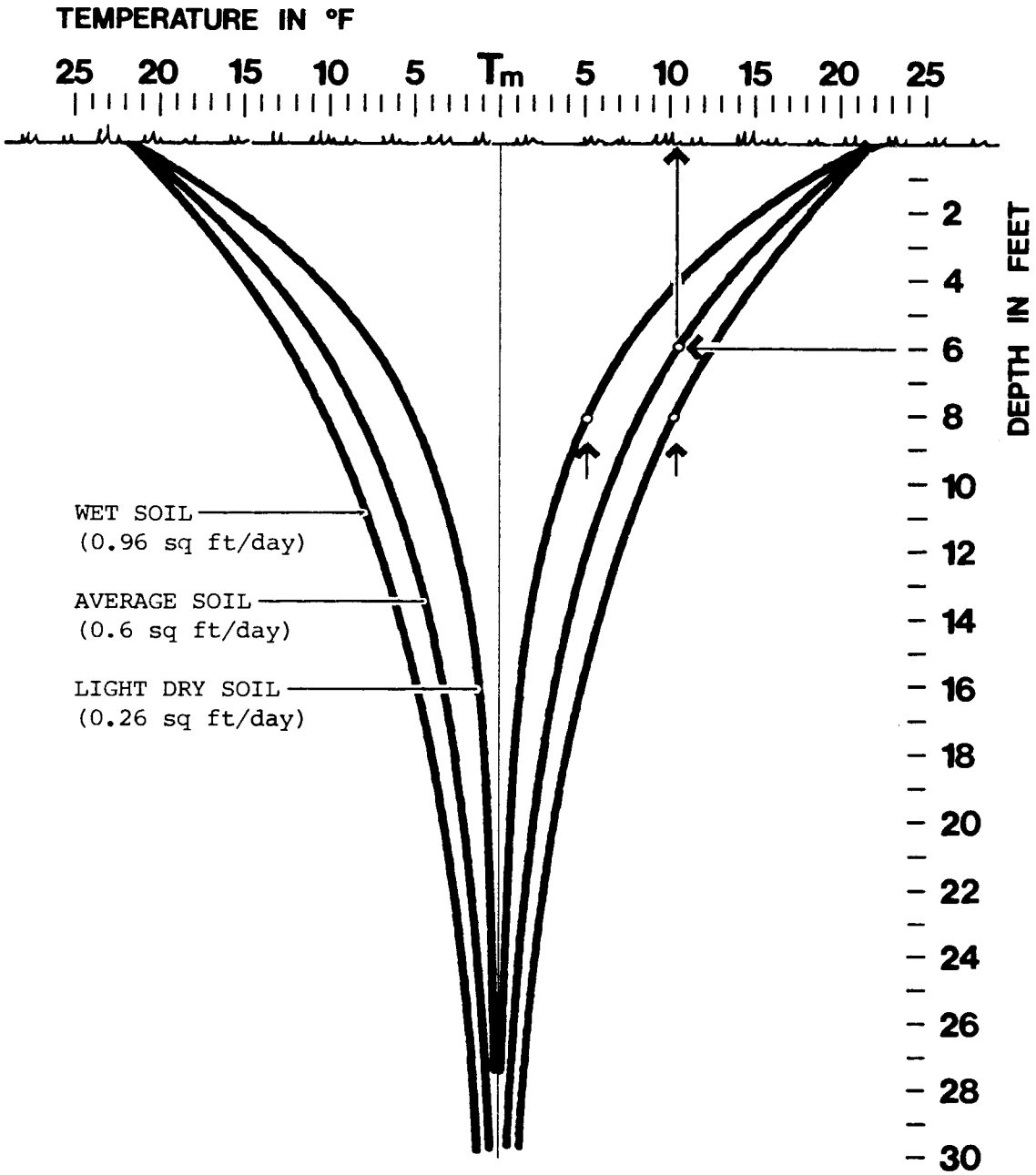

Figure 24. Thermal diffusivity has a profound effect on the shape of the damping curve. Note that the amplitude for a light, dry soil is one-half that of a heavy, damp soil at a depth of 8 feet.

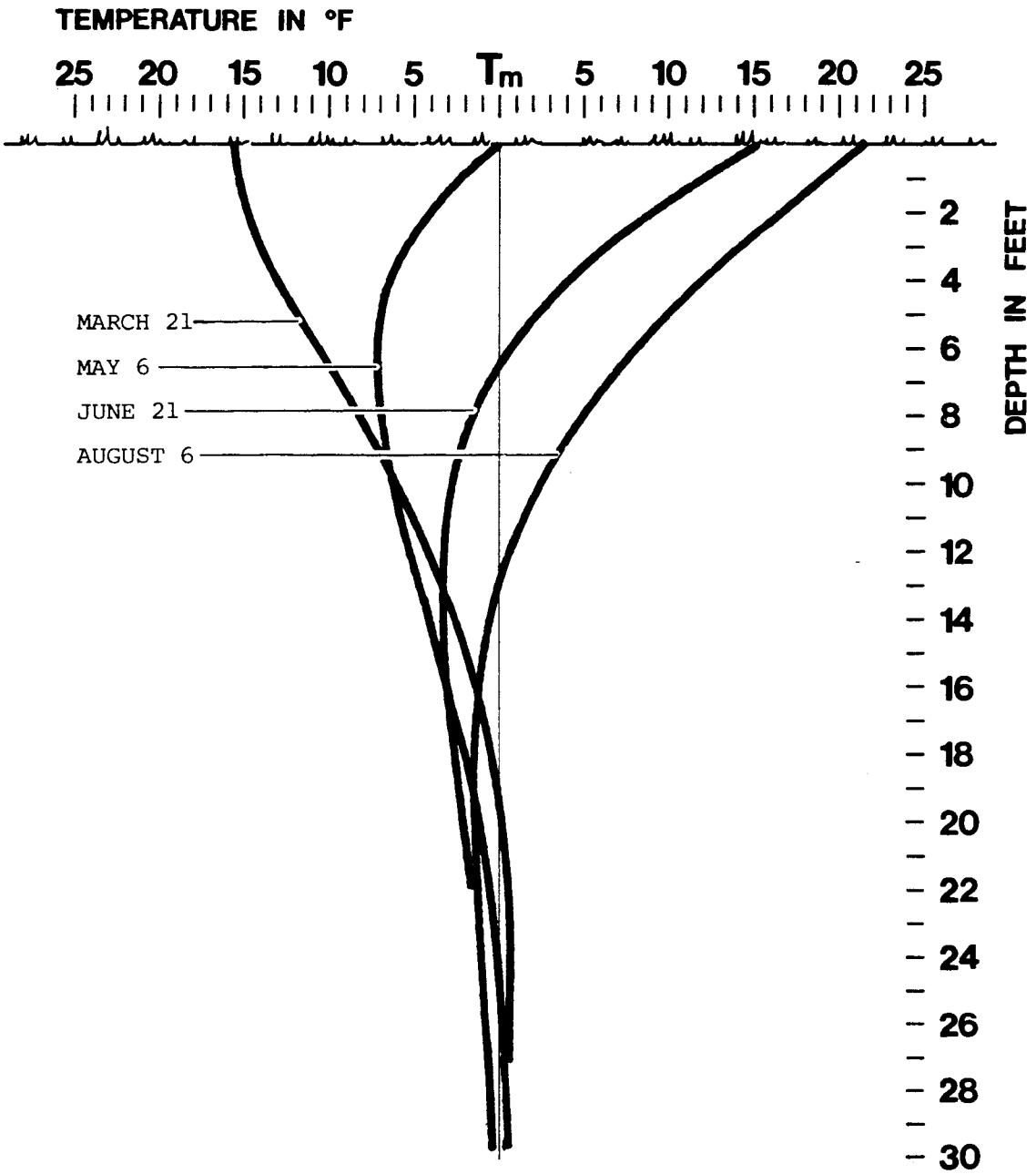

Figure 25a. Set of tautochrones at 1/8 cycle intervals, during the period of net heat storage through the surface ($A_s = 22F$; $\alpha = 0.6$ sq ft/day).

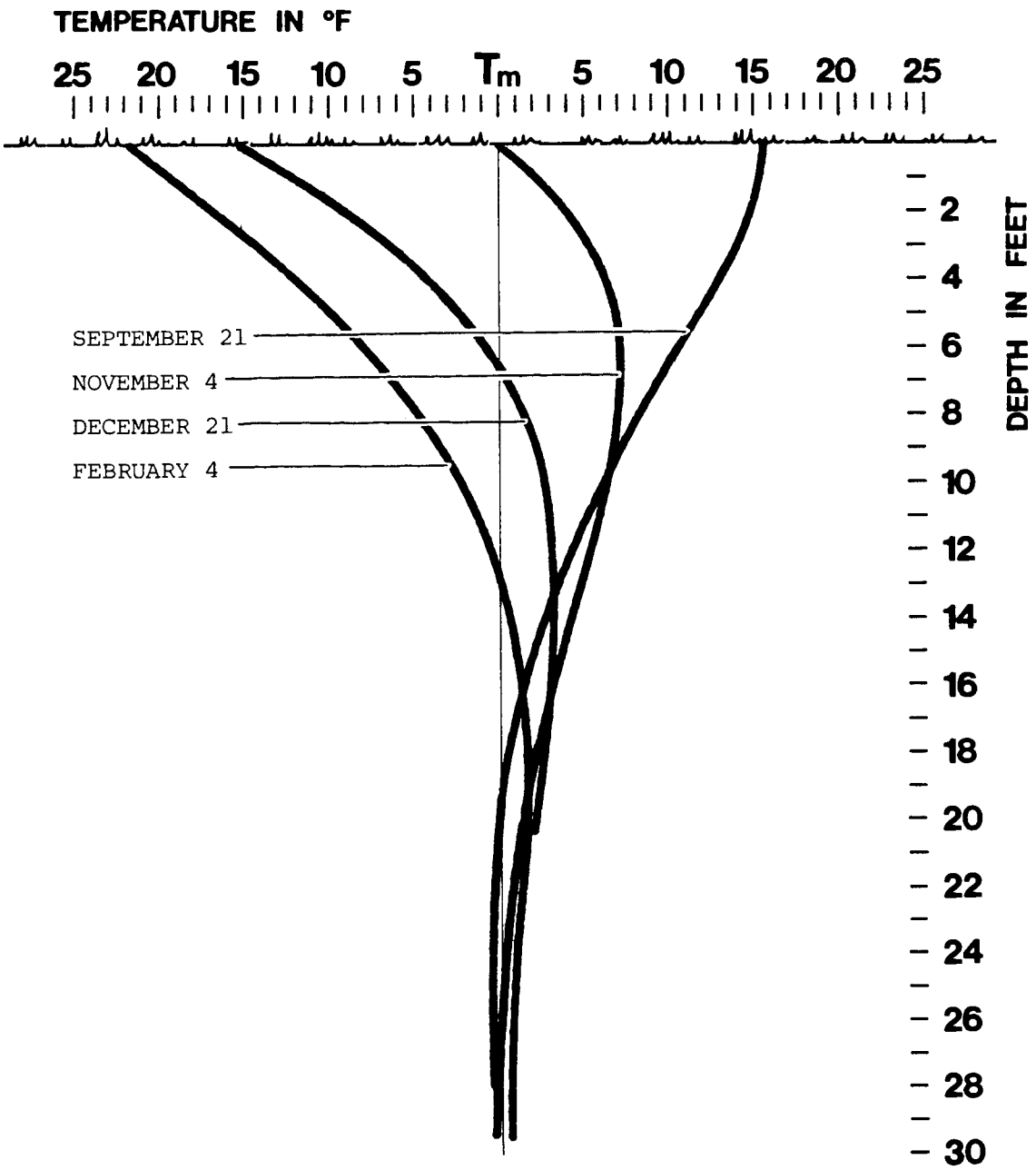

Figure 25b. Set of tautochrones at 1/8 cycle intervals, during the period of net heat loss through the surface ($A_s = 22F$; $\alpha = 0.6$ sq ft/day).

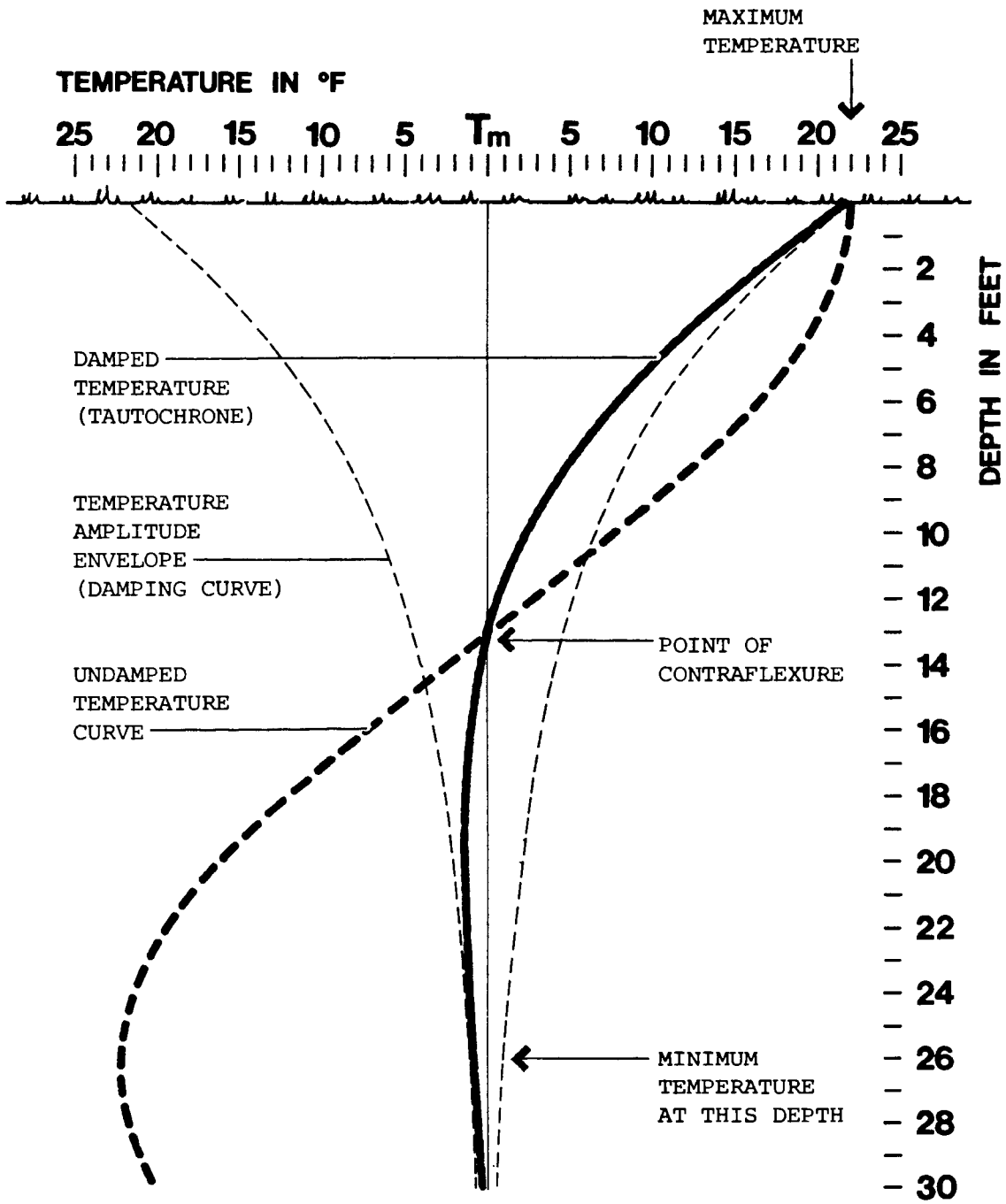

Figure 26. The tautochrone can be visualized as a projection of an undamped sinusoidal curve. Since amplitude diminishes with depth, the tautochrone is confine to wriggle within the constriction of the damping envelope. The wave moves downward with time.

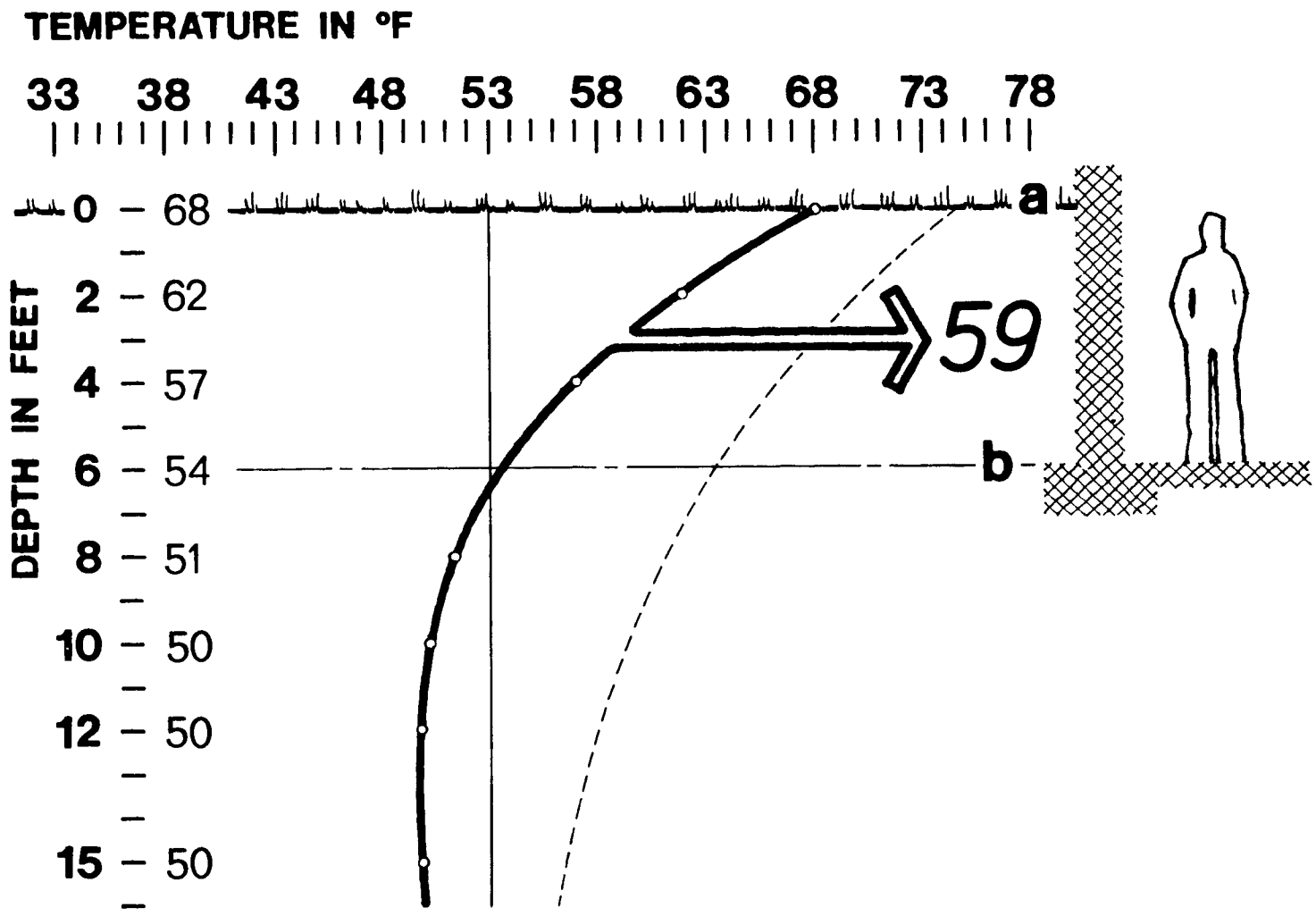

Figure 27a. Average temperature of 0-6' profile, New York, June 21 ($T_m = 53$, $A_s = 22$, $\alpha = 0.6$ sq ft/day, $t_o = 35$ days).

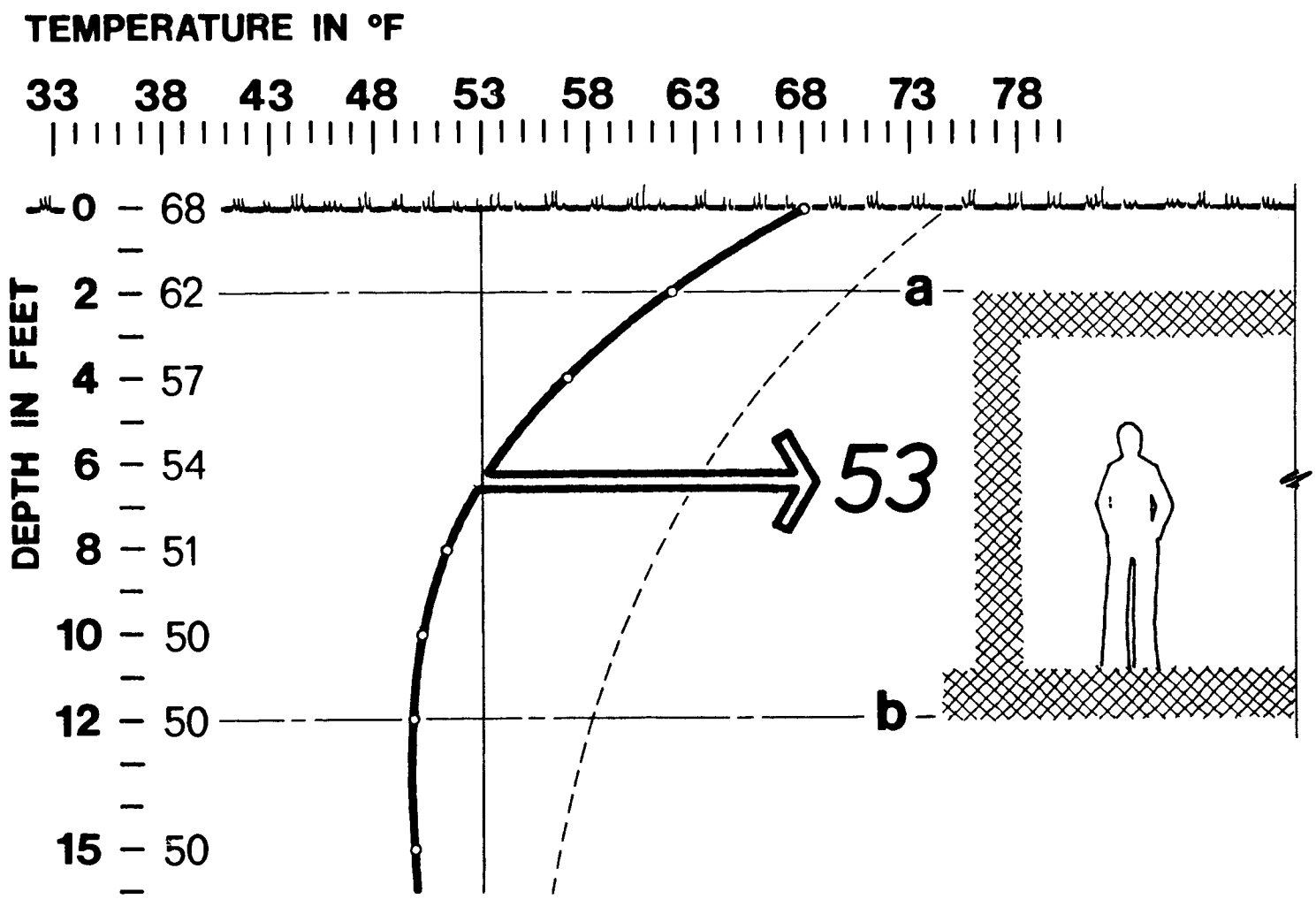

Figure 27b. Average temperature of 2-12' profile, New York, June 21 ($T_m = 53$, $A_s = 22$, $\alpha = 0.6$ sq ft/day, $t_o = 35$ days).

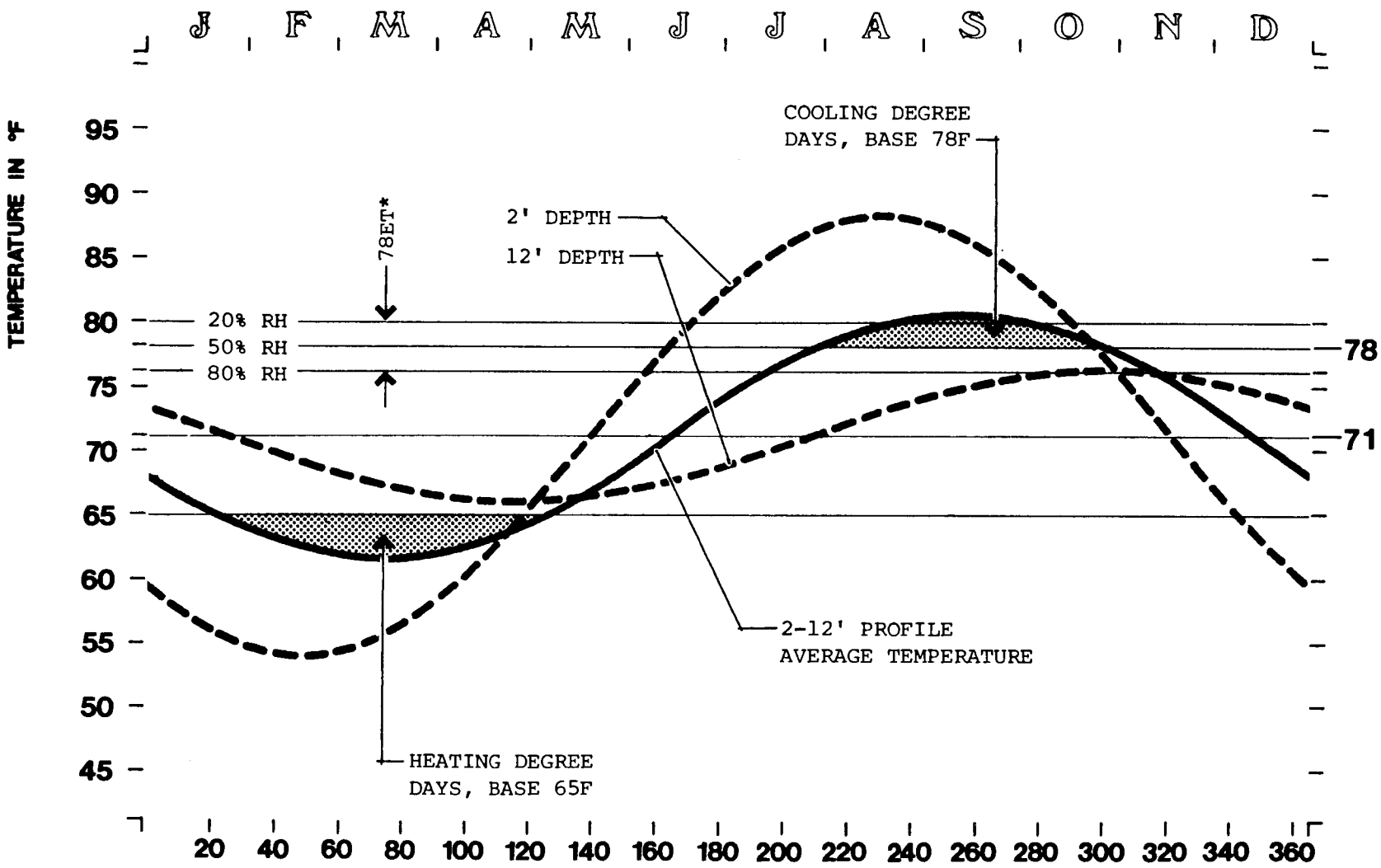

Figure 28. Graphic interpretation of heating and cooling degree days computed for the average temperature of the 2-12' earth profile.

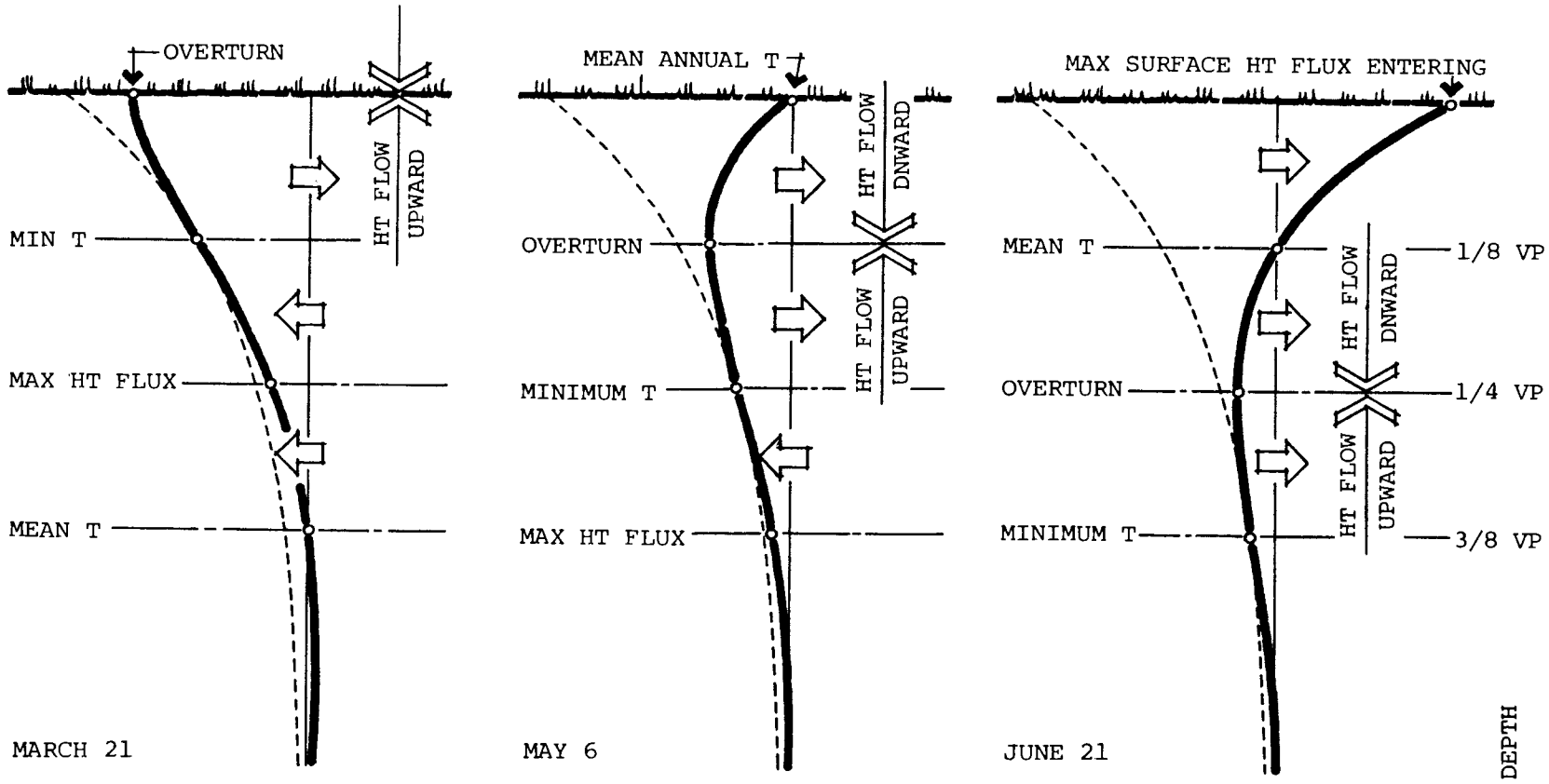

Figure 29. Tautochrones at 1/8 cycle intervals show progressive penetration of various stages of the annual cycle into the ground. Note levels of change in direction of heat flow (Overturn).

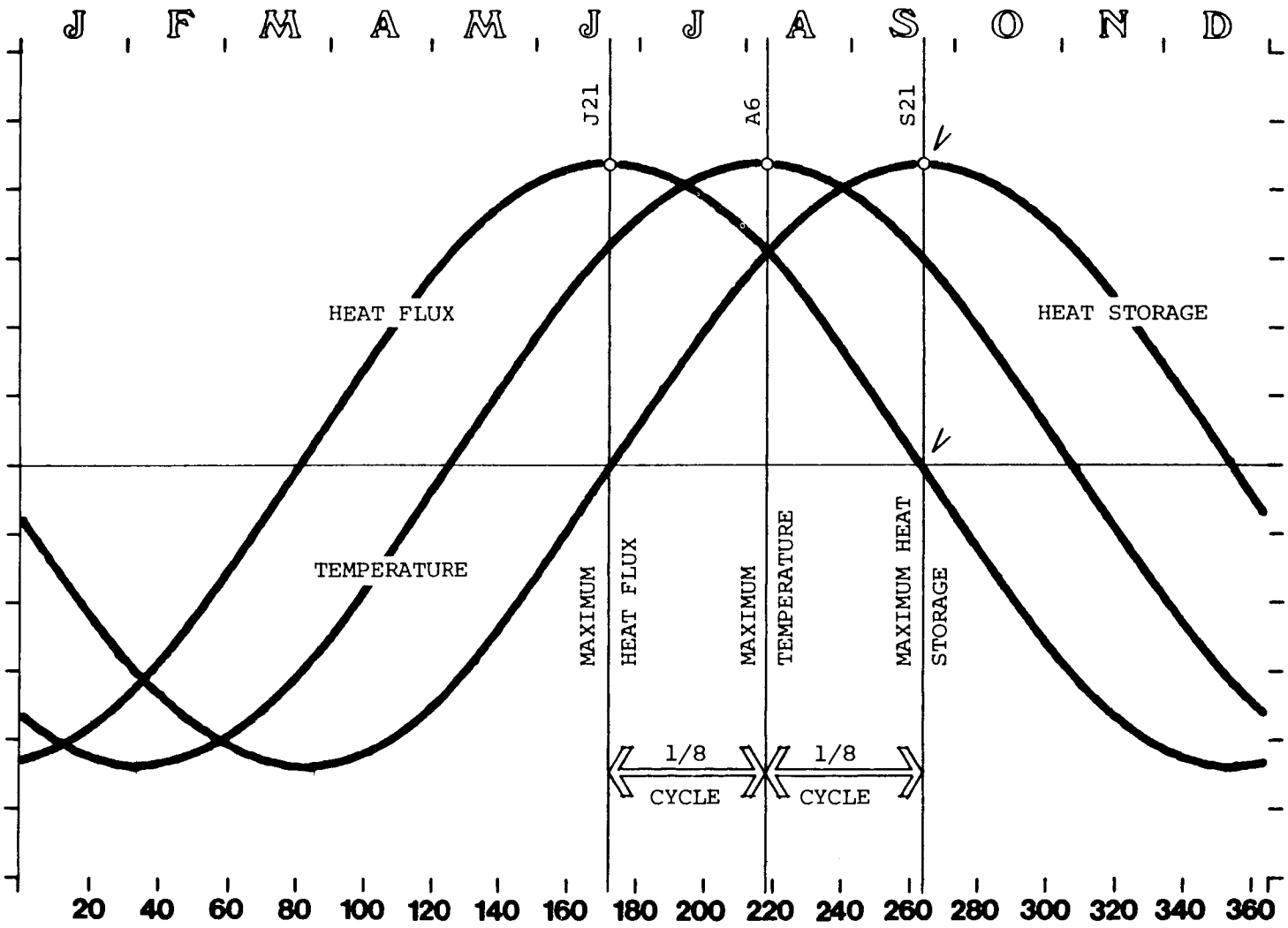

Figure 30. Heat storage is the area bounded by the heat flux curve. The ground is fully charged at the moment when heat flux crosses from a positive (net heat flow into the ground) to a negative (net heat loss) value.

RELATIONSHIP BETWEEN UNDISTURBED GROUND TEMPERATURE AND TEMPERATURE FIELD SURROUNDING EARTH SHELTERED BUILDINGS

Although undisturbed ground temperatures are of interest as an indicator of initial conditions in the ground, it would be more useful to learn if any simple relationships can be found between undisturbed temperatures and the disturbed temperatue field which is created by heat exchange between the building and its enveloping soil. A related problem has been solved analytically for predicting the disturbed temperature at any point in the ground beneath a heated slab-on-grade [58]; even this problem is extremely complex, so it is not anticipated that an analytical solution for predicting the temperature disturbance around a structure buried in the soil would be easily usable in practice.

It has been shown that the steady state method of estimating winter heat loss devised by Boileau and Latta [13] and subsequently adopted by ASHRAE [9] is valid for, at least, certain parts of the country for the early months of the year [66]. No simple method for computing summer heat flux has been suggested. With this in mind, measured temperatures of the walls and surrounding soils of two different underground structures have been plotted for comparison with predicted undisturbed ground temperatures for each region. A comparison with the theoretical disturbance predicted by steady state theory also follows.

Ohio Test House Basement

Figure 31 graphs the average temperature of a 6 foot deep uninsulated masonry basement wall over the course of a year, as reported by McBride et al [65]. Compared to this is the predicted 0-6 foot profile average undisturbed temperature for the conditions (T_m = 53F,

A_s = 22F; t_o = 14,35). It can be seen that while the basement wall temperature follows the general sinusoidal pattern of the undisturbed soil profile, the annual mean temperature of the wall-soil interface is 13.5F higher than the undisturbed mean. If the phase of the ground temperature wave is aligned to correspond with that of the observed wall face temperature (i.e., t_o = 14 days), a difference of abut 10F is found during the summer months of 1974; entering the summer of 1975, however, the observed temperatures appear to more closely approximate the predictions. These differences can be attributed to differences in weather from one year to the next, to which relatively shallow soil temperatures are sensitive. The T_m value of 53F used for the predictons of undisturbed temperatures was selected because it was reported by the researchers as the observed temperature of water from a local well.

Wall heat flux estimated by the researchers is also presented on Figure 31. The cooling rate of the uninsulated wall for June 1975 and August through October 1974 barely exceeds 1.5 Btu/ft^2(hr), although in July 1974 it was estimated to be as high as 2.67 Btu/ft^2(hr). Winter heat loss was nearly constant throughout the months of December 1974 to April 1975, averaging about 5.4 Btu/ft^2(hr).

Feisel House

Temperatures observed by Feisel [26] at the exterior face of the wall of an underground house near Rapid City, South Dakota, at a depth of 7 feet are plotted in Figure 32. Also plotted are ground temperatures for the 7 foot depth at a distance of 2 feet from the wall, and predicted undisturbed ground temperatures at the same depth, for the assumed conditions (T_m = 50, A_s = 26; t_o = 5, 35). Again, the sinusoidal pattern is evident, and if the phase of the predicted undisturbed temperature wave is resolved with that of the wall and of the position 2 feet from the wall (i.e., so t_o = 5 days), the difference between the predicted and measured wall face temperatures

ranges almost uniformly between 5 and 6F throughout the year. As would be expected, the difference between predicted undisturbed temperatures and temperatures observed at a distance 2 feet from the wall is less, at no time exceeding 4F. If a phase constant of t_o = 35, as assumed in the tables, is initially given, however, differences between predicted undisturbed and measured wall face temperatures are sometimes as great as 10 or 11F. The average wall temperature at the 7 foot depth for the one year period illustrated (June 28, 1978-1979) is 55F, while the average temperature at this depth 2 feet from the wall is 52.4F. The value of 50F for T_m used in the predictions is estimated from the NWWA's isothermal map, Figure 14. No microclimatic effects were considered so as to alter this mean annual value.

Figure 33 plots wall temperatures observed at a depth of 4 feet against undisturbed temperature predictions for the condition (T_m = 50, A_s = 26, t_o = 35) from the ground temperature tables contained at the end of this report, and for the adjusted condition (T_m = 52, A_s = 26, t_o = 7). This exercise reveals excellent agreement between measured and predicted values, when the proper phase relationship is known. If T_m is set equal to the average of all temperatures throughout the year at the 4 foot depth, this adjusted undisturbed temperature falls within 2F of observed values for approximately 6 months of the year.

Figure 34 plots the observed temperature at the outside base of the wall at a depth of 14 feet, along with the predicted temperature at a depth of 15 feet (from the tables). What is most remarkable here is the extreme difference in phase between the predictions and the observed temperatures. This can probably be attributed to the fact that the underground house possesses a crawl space which is utilized as an air distribution plenum (Figure 35). Since the crawl space perimeter is not insulateed, the soil at the base of the wall is much more closely coupled with the interior than with the ground surface; its phase, therefore, reflects simultaneous outdoor conditions

as transmitted by indoor air instead of the delayed phase of the surface wave as conducted through the ground.

Discussion

Great care must be taken before drawing conclusions from comparisons between predicted and disturbed temperatures. In theory, a perfectly insulated wall would cause no temperature disturbance, so that adjacent soil would be expected to follow predicted undisturbed temperatures. A poorly insulated wall, on the other hand, will allow heat exchange between the structure and the soil, with a resulting temperature disturbance in the ground. The general pattern of the preceding examples demonstrates this: while the temperature of the outside face of the uninsulated basement wall exhibits large departures from the undisturbed temperature, the temperatures of the outside face of the insulated wall of the underground house and undisturbed soil show much better agreement (for similar annual amplitudes).

The broad implication is that as the need for accurate soil temperature prediction increases (with little insulation), the magnitude of error increases when one uses undisturbed temperature methods. Conversely, the acceptability of using undisturbed soil temperature estimates improves as the need for accuracy (i.e., with increasing insulation levels) diminishes. The magnitude of error in estimating winter heat loss values is discussed briefly in another section of this report.

Since, by definition, undisturbed temperatures are independent of ground heating effects of buildings, there is no way in which they can be used to study optimizaton of insulation thickness requirements or the implications of different insulation placement configurations. They can be used to ascertain initial conditions in the ground as may be necessary in calculating the performance of devices such as earth-

air heat exchangers. Undisturbed temperatures can also be used to predict certain limiting conditions for ground cooling opportunities. For instance, summer heat loss rates cannot naturally exceed that predicted by using the difference between undisturbed soil and indoor temperatures as the driving potential. Since the surrounding soil, in fact, stores lost building heat, actual summer cooling rates will be less than computed using this potential. In this manner, undisturbed ground temperatures can be used to identify if any initial cooling potential exists in the ground. Following from this, undisturbed temperatures can be used as a guide to the desirability of various ground temperature modification techniques.

Steady State Prediction of Temperature Disturbance

A method was given in 1968 by Boileau and Latta [13] for estimating winter heat losses from basements. This simple procedure applies to relatively shallow construction in which it is assumed that during the course of winter months a steady state condition is developed.* Heat discharged from subgrade walls theoretically follows a circular arc to the surface, centered upon the intersection of the ground surface and the inside wall surface planes. The ground surface is considered the only sink, and its temperature is taken as the minimum annual ground surface temperature by the relation $(T_m - A_s)$. In areas devoid of deep seasonal snow cover, this can usually be approximated by the January or February monthly average air temperature. Deep ground temperatures are disregarded on the basis that the walls are more closely coupled to the surface than to the deep ground, and

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*Steady state procedures for calculating basement heat losses have been investigated by Elliot and Baker [23] with an electrical analog technique. A shape factor for a rectangle within a semi-infinite plate, corresponding to the "subgrade chamber" form of construction, has also been determined by electrical analog techniques [4] for two dimensional steady state analyses.

that most of the floor area of a residential basement is also more closely coupled to the surface than to deep ground. This would not be true if the basement were located below ground water characterized by an appreciable flow.

Heat flux is calculated as the quotient of the temperature differential between ground surface and indoor temperature and the resistance of the soil-wall assembly. For convenience, the soil is assumed to possess uniform conductivity, and the resistance of the wall is expressed as an equivalent thickness of soil. This method has subsequently been adopted by ASHRAE and appears in its Fundamentals Handbook [9]. Computer simulations performed at the University of Minnesota [66] and by Szydlowski [83] describe late winter temperature distributions similar to those assumed by steady state analysis; these lend support to steady state techniques for estimating maximum winter heat loss rates, at least for uninsulated or uniformly insulated walls.

Assumption of steady state conditions permits plotting of a disturbed temperature field within the immediate proximity of a subgrade wall. All that is required to accomplis this is to plot the circular heat flow lines from the desired depths and to subdivide these into equal increments. The temperature distribution in any vertical profile at a horizontal distance x from the wall can be found be a simple trignometric analysis, shown in Figure 36. The example given here assumes a 12 foot deep wall, and design conditions corresponding to Columbus, Ohio, as given by or inferred from McBride et al [65]. These are: ground surface temperature = 33F, indoor air temperature = 65F; T_m = 53, A_s = 22 was selected for the undisturbed ground temperature analysis as this is considered normal for central Ohio, even though design ground surface temperature is assumed as 33F (for the year 1975).

Figure 37 plots steady state predictions of temperature distribution as a function of depth for the soil-wall interface (here the wall

is treated as 1 foot of soil) and at horizontal distances of 1 foot and 6 feet from the wall. Also plotted are the predicted undisturbed temperature profiles for the 21st days of January, February and March. Temperatures calculated by the different means are presented in Table 8, which also includes actual observations of basement wall and surrounding temperatures reported by McBride.

It can be seen from Figure 37 that the temperature of the soil in immediate proximity to the wall is very different from undisturbed temperatures. This difference exceeds 10F at most depths, and is well in excess of 20F at some depths. The difference between undisturbed temperatures and the temperature of the soil at a horizontal distance of 1 foot from the wall exceeds 10F throughout much of the profile. This means that gross overestimates in heat loss would be predicted by using undisturbed temperatures as a driving force, as is currently the practice in some computer codes such as NBSLD. This conclusion has also been reached by Meixel et al [66] and by Davies [21], both working with finite difference model programs.

The most remarkable aspect of Figure 37 is the striking likeness between the predicted steady state temperature distribution at a horizontal distance of 6 feet from the wall and the January (and February) tautochrones. This is largely coincidental, since the steady state method in no way considers annual temperature variation. Natural temperature events in the ground may be viewed as a kind of precursor, however, which help to establish seasonal steady state conditions.

No simple relationships are apparent between the undisturbed and disturbed temperatures that would be useful in predicting wall heat loss. The shape of the January tautochrone is similar to that of the disturbed temperature profile 1 foot from the wall, and it is possible to select other January tautochrones from the tables that show no more than 4F error at any depth (Figure 38). This requires setting T_m equal to the average temperature of the disturbed profile, which is

unknown without going through the steady state analysis. Since the steady state analysis itself is simple and assumed to be fairly accurate, such an approximation method does not seem warranted.

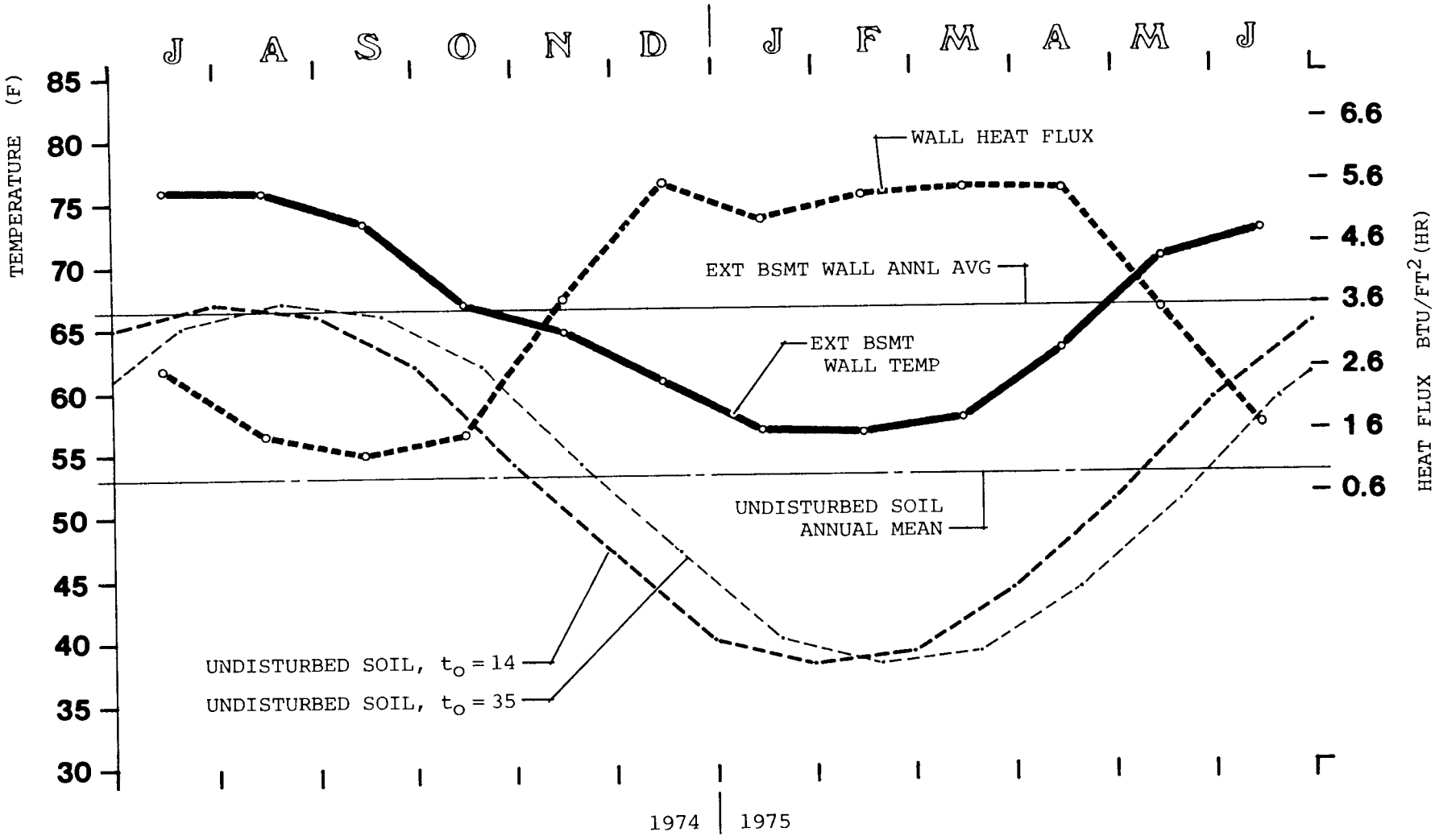


Figure 31. Comparsion of measured temperature of the outside of an uninsulated masonry basement wall in Columbus, Ohio, averaged over its 0-6' depth, to predicted undisturbed temperatures for the Columbus area. Computed heat flux is also graphed.

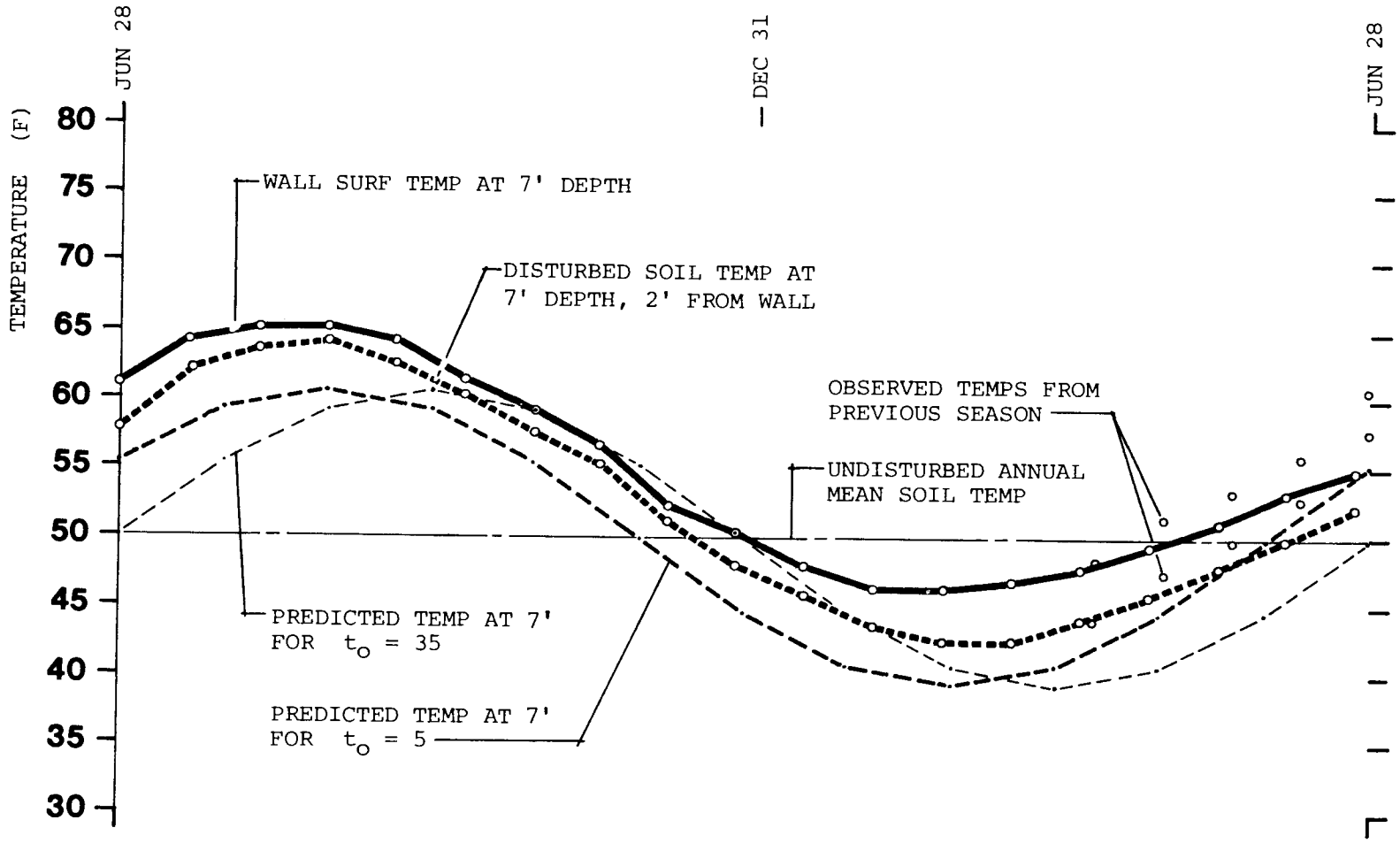


Figure 32. Comparison of observed wall surface and disturbed soil temperatures at the 7' depth to predicted undisturbed temperatures for $T_m = 50F$, $A_s = 26F$, $\alpha = .52$ sq ft/day, for the phase constants $t_o = 35$ and $t_o = 5$ days.

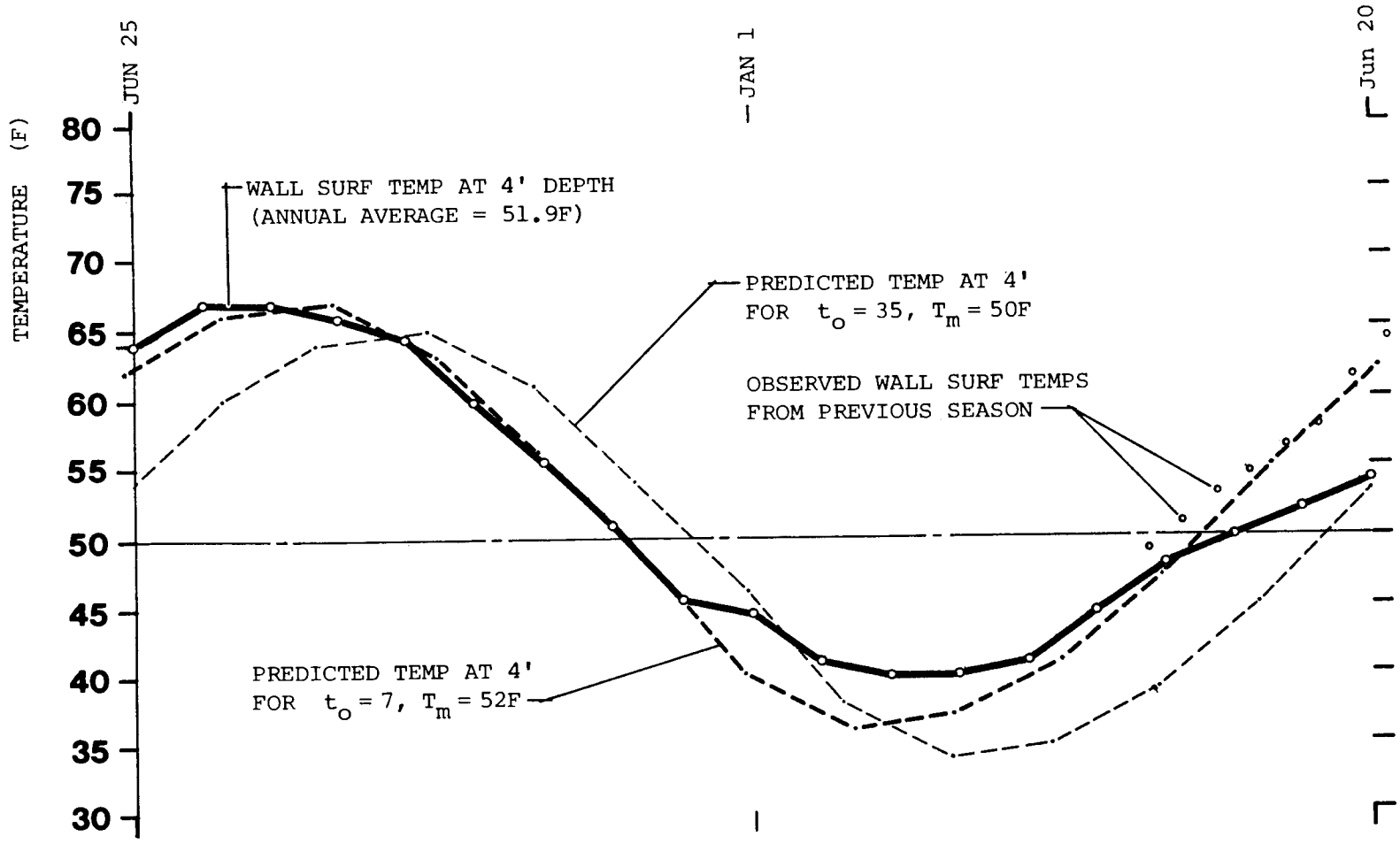


Figure 33. Comparison of observed wall surface temperatures at the 4' depth to predicted temperatures for $T_m = 50F$, $A_s = 26F$, $\alpha = .52$ sq ft/day, $t_o = 35$. A "corrected" curve is also plotted, for T_m set to the annual wall surface temperature average (52F), and for the best phase agreement.

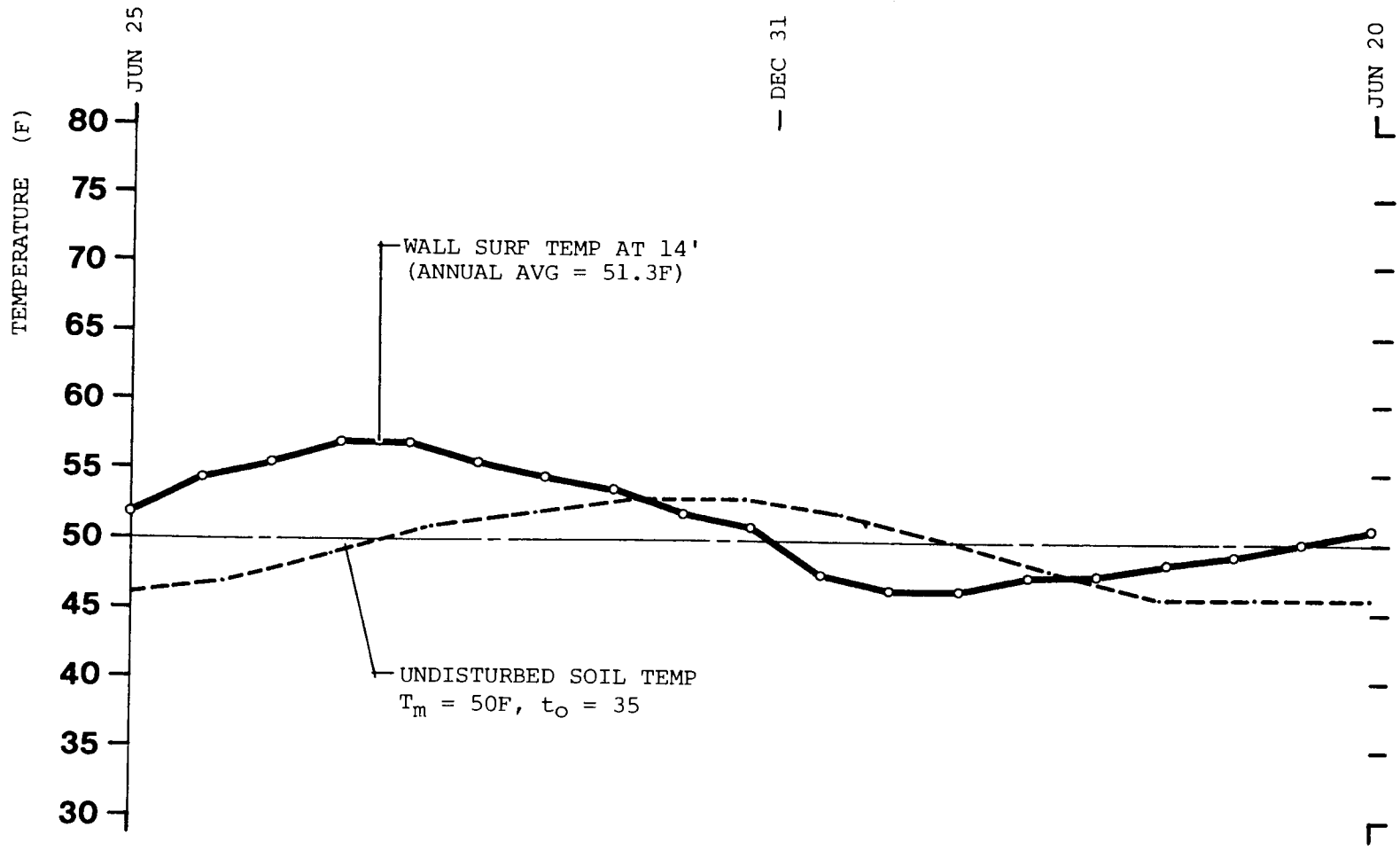


Figure 34. Comparsion of exterior wall surface temperature at a depth of 14' with predicted undisturbed soil temperature at 15', for the conditions T_m = 50F, A_s = 26F, α = .52 sq ft/day, and t_o = 35 days.

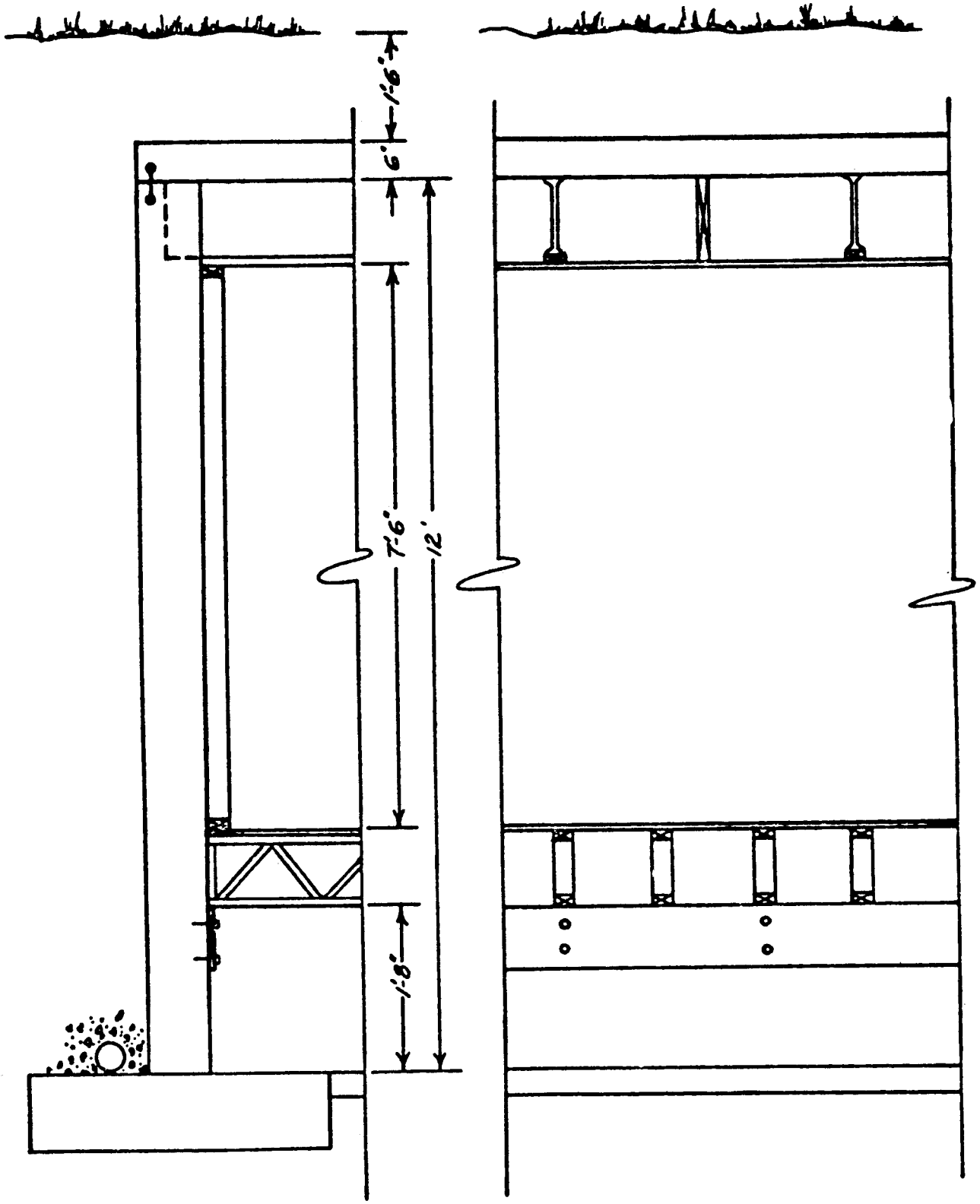
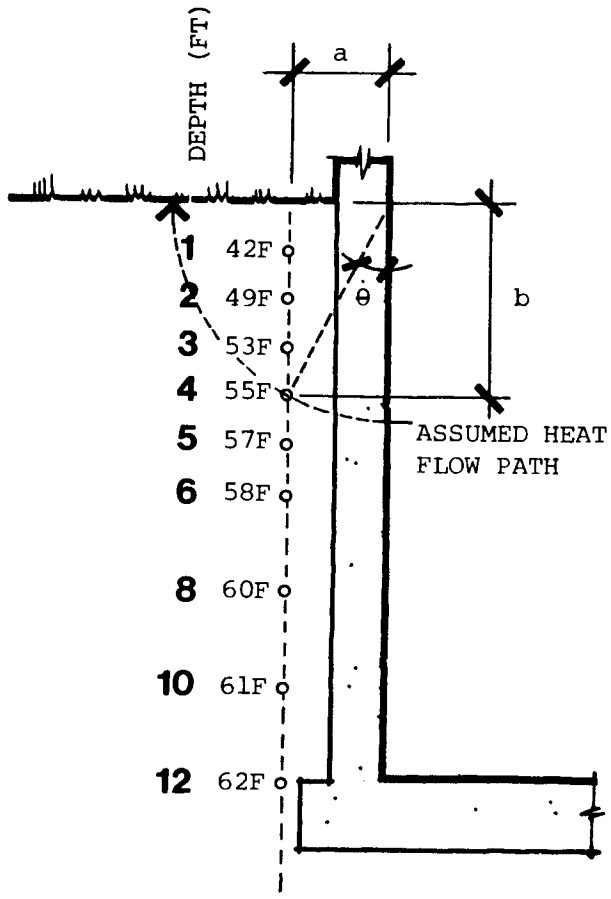


Figure 35. Wall section of Feisel House, showing crawl space plenum.



TEMPERATURE OF PROFILE AT HORIZONTAL DISTANCE a FROM INSIDE FACE OF WALL: (conductivity of wall assumed nearly equal to that of soil)

TEMPERATURE AT a, $T_a = T_i - (\theta/90)T_o$

where a = arctan (a/b)

EXAMPLE:

Given: $T_i = 65F$

$T_o = 32F$

Find temperature at a = 2', b = 4':

Solution: $\theta = \arctan(2'/4') = 27^o$

$T_{(a,b)} = 65 - (27/90)32$

$= 55F$

Figure 36. Estimation of profile temperatures by steady state theory of heat loss.

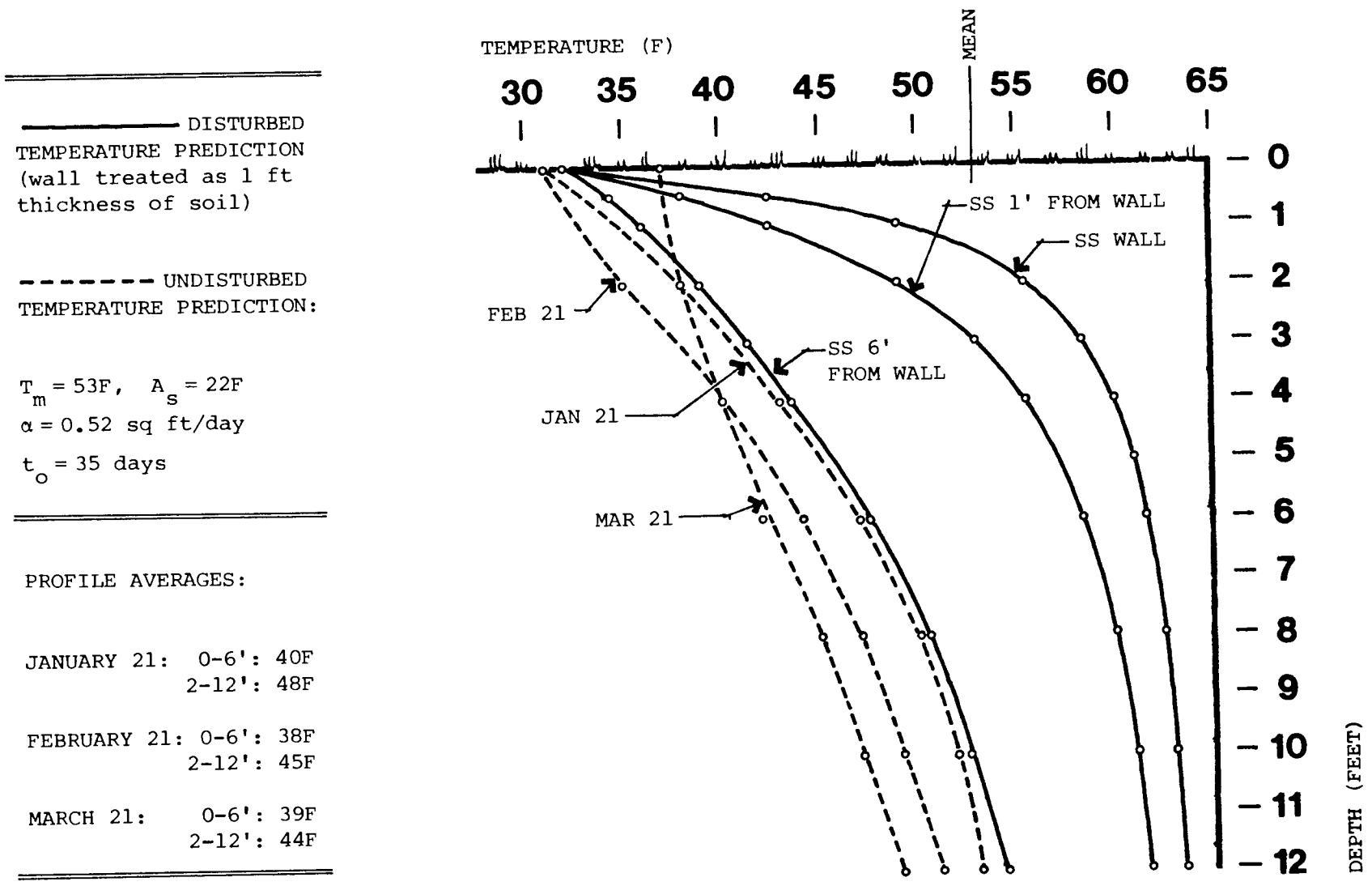


Figure 37. Comparison of undisturbed temperature predictions from the tables for the stated conditions with estimated disturbed temperatures at the wall surface and various horizontal distances from the wall, by steady state theory.

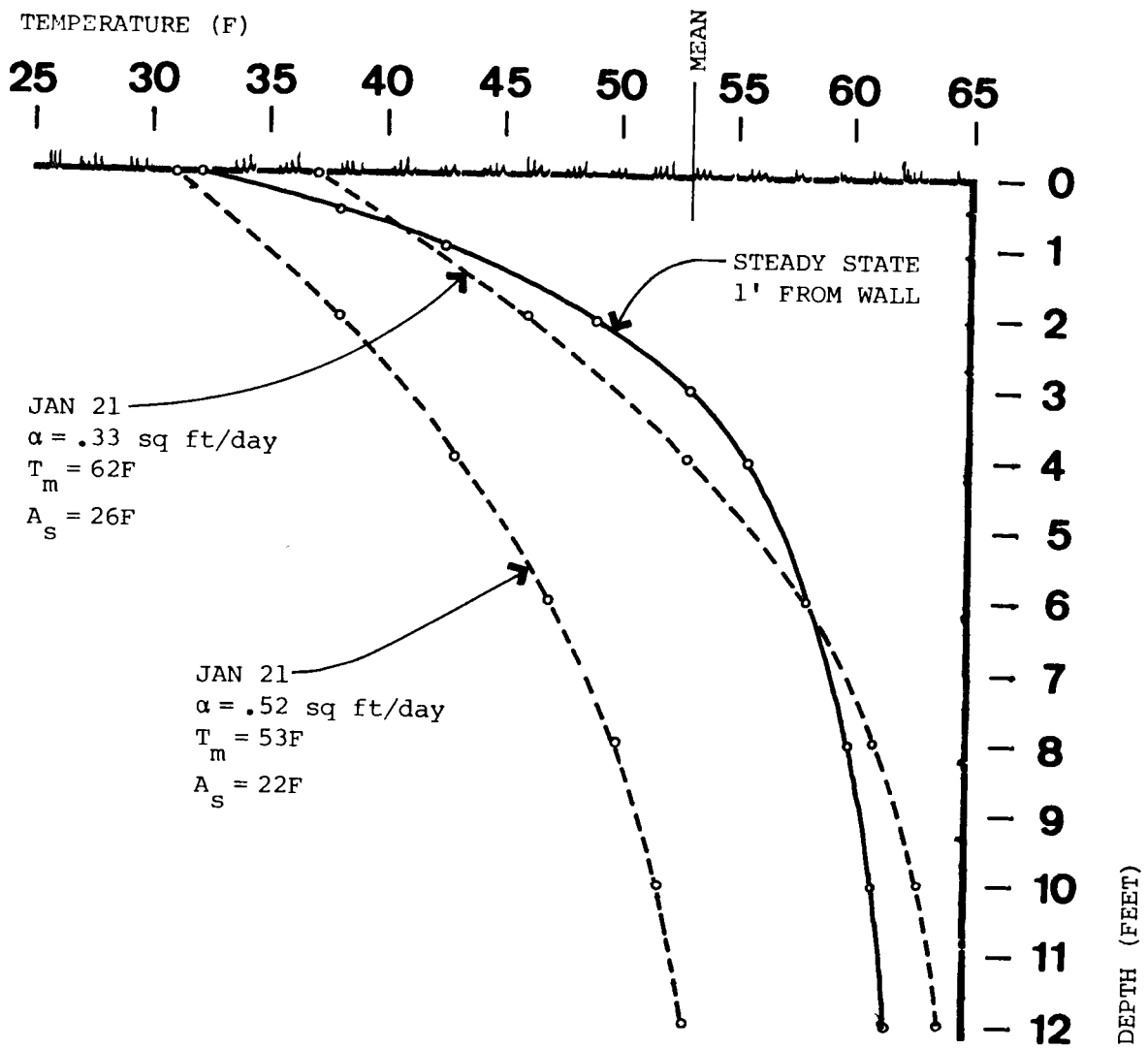


Figure 38. Comparison of undisturbed temperature predictions with estimated distribution of disturbed temperatures by steady state theory.

TABLE 8. Comparison of disturbed and undisturbed temperatures

Profile Description	January	February	March
0-6' steady state, wall T[a]		52.5	
0-6' ss, soil T 1' from wall		50.5	
0-6' ss, soil T 6' from wall		40.6	
0-6' observed wall T[b]	56.4	56.3	57.7
0-6' undisturbed soil T[c]	40	38	39
1-7' observed T 6' from wall	46.7	45.8	47.1
1-7' ss, soil T 6' from wall		43	
2-12' ss, predicted wall T		61.2	
2-12' ss, soil T 1' from wall		58	
2-12' ss, soil T 6' from wall		48	
2-12' undisturbed soil T	48	44	45

[a]wall conductance assumed equal to one foot of soil
[b]uninsulated masonry wall, k = 0.67 Btu/ft(hr)F
[c]assumed: T_m = 53F, A_s = 22, k = .52 ft^2/day, t_o = 35 days

COMFORT AND CLIMATE

The purpose of climate control is to maintain, or to minimize the energy cost of maintaining, thermal comfort conditions whithin building interiors. Maintenance of thermal comfort is a problem of heat balance between the body and its surroundings.

The body exchanges heat with its environment through four processes:

1) conduction (contact)
2) conduction-convection (air movement)
3) evaporation of skin mositure
4) radiation (solar and thermal)

The body itself generates heat, the amount of which varies according to level of activity (see Table 9). The metabolic rate of heat production plus environmental heat sources and sinks govern the heat budget of the body. Factors governing the rate of heat exchange and, consequently, the sense of comfort, comprise (corresponding respectively to the foregoing four processes),

a) thermal resistance of clothing and temperature of surfaces in contact with the body
b) thermal resistance of clothing, air temperture, and speed of air movement
c) (water) vapor pressure of the air
d) temperature of surrounding surfaces (and area of the body exposed)

Comfort Conditions and Standards

For building design and engineering purposes, human thermal comfort has been defined as [9], "that state of mind which expresses satisfaction with the thermal environment." Many researchers prefer the term "thermal neutrality" to "thermal comfort," to emphasize the qualification that the subject feels neither too hot nor too cold, nor feels any local discomfort due to asymetric radiation, drafts, cold floors, non-uniform clothing, etc.

Numerous tests have been conducted to determine what sets of conditions are judged most comfortable by the agreement of test volunteers. Investigators working at Kansas State University under sponsorship of ASHRAE found that the most comfortable condition for subjects wearing light clothing suitable for office wear (0.4-0.6 clo) corresponded to a dry bulb temperature of 79F at 50 percent relative humidity, for air velocity less than 35 feet per minute [9]. A comfort zone enveloping the range of satisfaction of 80 percent of the subjects can be drawn on the psychrometric chart (Figure 39). Other responses of the KSU test subjects have been analyzed and reduced to a series of equations describing "cold" to "hot" conditions. These are given in Table 10, (found on Figure 39), and are also plotted on Figure 39. For all tests, subjects were sedentary (activity level = 1 met).

In addition to its influence upon the rate of skin moisture evaporation, vapor pressure has been described in terms of its effect upon one's psycho-physiological state. Le Roy [59] has ascribed the designations, "healthy," "soothing," "depressing," and "debilitating" to vapor pressure ranges between 12 and 16, 16 and 21.2, 21.2 and 26.4, and in excess of 26.4 millibars, respectively. These are also plotted on Figure 39. Discomfort limits of 5 and 18 millimeters of mercury have been cited by Goldman [37], and 5 and 17 mm Hg by Givoni [32].

Comfort ranges and limits have been identified and published as standards for building engineering and for prescribing safe job conditions for workers. The Occupational Safety and Health Administration (OSHA), for example, has established recommended limits for different levels of work activity. These are stated for two different air speed ranges (Table 11), according to a simplified heat-stress index known as Wet Bulb Globe Temperature (WBGT). The WBGT is a function of wet bulb and globe temperatures, the latter of which is a combined measure of air and radiant temperatures (for indoor environments),

$$WBGT = 0.7\ WBT + 0.2\ GT + 0.1\ DBT$$

If the mean radiant temperature is assumed equal to the dry bulb temperature, then GT = DBT, and the OSHA limits can easily be plotted on the psychrometric chart (Figure 40). Although the OSHA limits are not perfect indicators of physiological stress [see 11], they give some additional human meaning to the psychrometric chart. Also depicted on Figure 40 is the boundary described by Bridger and Helfand [41] as the "Danger Line for Heat Stroke."

The most familiar set of comfort conditions is that described in ASHRAE comfort Standard 55-74. It is based on the responses of sedentary adults (activity level 1.0-1.2 met) wearing light office clothing (0.5-0.7 clo). The ASHRAE 55-74 comfort zone extends from 72F to 78F on the new Effective Temperature (ET*) scale, and is bounded by vapor pressures of 5 and 14 mm Hg (Figure 40). It assumes air movement rates of less than 45 fpm. Like the ASHRAE-KSU studies, the 55-74 comfort zone represents limits within which 80 percent of subjects, tested at the J. B. Pierce Foundation at Yale University, expressed satisfaction with their thermal environment under carefully controlled conditions. The 2 degree difference between the optimum of 76ET* in the Pierce Foundation study and 78ET* in the KSU experiments is accounted for by slight differences in test conditions; lighter clothing is characteristic of the KSU conditions (0.5 vs 0.6 clo), and the

Pierce Foundation tests involved slightly greater work activity rates (1.1 vs 1.0 met units). With these reconciled, results of the independent studies are virtually identical.

Effect of Clothing

Aside from increasing metabolic heat production or ingesting hot or cold foods or liquids, the only practical opportunity that the individual has to alter his or her comfort condition is to add or subtract clothing, or seek a different environment (which is not applicable to the present discussion). According to a rule of thumb cited by Goldman [38], air temperature departures from the optimum for 0.6 clo resistance can be offset by 1F for each 0.1 clo deviation from the standard for sedentary individuals (light office work, 100-200 kcal/hour), and by 2F for each 0.1 clo deviation at higher work levels. For moderate work activity levels, therefore, comfort can be achieved at 68-70F simply by increasing clothing. Fanger [24; also 9] has published a series of widely utilized charts which allow the comfort standards to be corrected for other conditions. According to Fanger's charts, comfort is attained at 68F by increasing clo value to 0.9 to 1.4, when air velocity is 20-30 fpm or less.

The acceptability of 68F as a comfort standard has been widely discussed. Gonzalez [39] has verified its acceptability in experiments in which he found that 80 percent of test subjects expressed thermal satisfaction with 68F temperature with clothing levels of 0.9 to 1.2 clo—somewhat less than predicted by the Fanger charts.* Practical limits on how low air temperatures can go with compensation by

---

*A clo value of 1.0 corresponds to heavy slacks, a light sweater, blouse and jacket for women, and heavy trousers, sweater, shirt and jacket for men.

increased clothing are set by the temperature of fingers and other relatively exposed parts of the body, such as the ankles. Gagge and Nevins [28] indicate that while a loss of dexterity may occur when air temperature falls below 65F, no degradation is expected at 68F. The conclusions of Gonzalez, Gagge and Nevins and others is that thermal comfort can be achieved at 68F without extraordinary or burdensome increases in the amount of clothing worn.

Effect of Air Movement

Air movement influences bodily heat balance and, hence, thermal comfort by 1) affecting the rate of conductive-convective heat transfer between the skin and the air, and by 2) affecting the rate of bodily cooling through evaporation of skin moisture. The former is governed by air dry bulb temperature; increasing air speed increases the rate of heat transfer, but the direction of heat flow depends upon whether the temperature of the air is greater or less than skin temperature (about 90-95F). Heat is removed from the body by conduction-convection when air temperature is less than 90F, but heat is added to the body by conduction-convection when air temperature approaches and exceeds skin temperature. The rate of evaporation is governed by both air speed and vapor pressure. Increasing air speed always increases evaporative cooling effect, although at high vapor pressures, the overall effect many be small.

Within certain conditions, the effect of increased air movement is to extend the upper limit of the comfort zone to higher temperatures. A recent paper by Arens et al. [6] illustrates these extended limits for a variety of different air speeds on the psychrometric chart (Figure 41). Because the rate of heat exchange caused by increasing air movement is coupled to vapor pressure as well as to dry bulb temperature, the lines of equal comfort are skewed, favoring higher temperatures at low vapor pressure, and lower temperature at

high vapor pressure. Note also that increase in air speed is able to offset a higher temperature increase at low vapor pressure than at high vapor pressure.

Effect of Mean Radiant Temperature (MRT)

Heat is exchanged between the body and the surrounding environment by thermal radiation. The temperature of surrounding surfaces is assumed to equal air temperature in most comfort standards, such as the relationships depicted in Figures 39-41. Under actual conditions, the temperature of room surfaces vary, and may significantly differ from air temperature. This is especially true of the warm interior face of Trombe Walls and radiant-heating floors and ceilings, and the cool faces of window glass surfaces and subgrade walls.

Although the rate of radiant heat exchange between the body and its surroundings is chiefly dependent upon surface temperature differences between these, several factors must be considered in analysis of the heat balance. Among these factors are air temperature, air speed, and clothing level. Fanger's charts [9] show that for sedentary adults at typical summer clo levels of 0.5 , and at relatively still air conditions (velocity less than 20 fpm, or 0.1 m/s), for an increase in air temperature from 78 to 88F, the mean radiant temperature (MRT) must drop from 78 to 68F in order to maintain a sensation of equal comfort. At low air speeds of 40 fpm (0.2 m/s), a 10F increase in air temperature from 80 to 90F must be offset by a decrease in MRT of 14F, from 80 to 64F. Under nearly still air conditions, therefore, a decrease of 1 to 1.4F in MRT is required to offset every 1F increase in air temperature. At the unique air temperature of 87F (according to Fanger's charts), an MRT of 69F is necessary to maintain comfort conditions, regardless of air speed, when it is less than 1.5 m/s.

Mean radiant temperature is defined as [9], "the uniform surface temperature of an imaginary black enclosure with which man exchanges the same heat by radiation as in the actual environment." In other words, MRT is the average of all room surfaces, weighted according to emissivity (which is nearly constant for most building materials). The radiant heating or cooling ability of any surface, therefore, must be evaluated in the context of its area in proportion to the area and temperature of other surfaces in the room. The angle of exposure of surface to body and the orientation of exposed parts of the body must also by considered.

It is noteworthy that, whereas with a still air temperature of 90F, an MRT of 67F is required to achieve comfort (at 0.5 clo), an equal sensation of comfort with 90F air temperature is achieved with a ventilation air speed of 20fpm (1 m/s) at 0.4 clo. The latter may be read directly from Figure 41a. while the former is deduced from Fanger's charts.

TABLE 10 **Equations for Predicting Thermal Sensation (Y)* of Men, Women, and Men and Women Combined** After Exposure Periods of 1, 2, and 3 hr to any Given Dry-Bulb Temperature (t) and Vapor Pressure (P)**

Exposure (hr)	Sex	Regression Equations t = degrees Celsius. P = vapor pressure, torr.***
1.0	Male	$Y = 0.220\,t + 0.031\,P - 5.673$
	Female	$Y = 0.272\,t + 0.033\,P - 7.245$
	Combined	$Y = 0.245\,t + 0.033\,P - 6.475$
2.0	Male	$Y = 0.221\,t + 0.036\,P - 6.024$
	Female	$Y = 0.283\,t + 0.028\,P - 7.694$
	Combined	$Y = 0.252\,t + 0.032\,P - 6.859$
3.0	Male	$Y = 0.212\,t + 0.039\,P - 5.949$
	Female	$Y = 0.275\,t + 0.034\,P - 8.622$
	Combined	$Y = 0.243\,t + 0.037\,P - 6.802$

*Y values will range from − 3 to + 3 where − 3 is cold; −2 is cool; −1 is slightly cool; 0 is comfortable; + 1 is slightly warm; + 2 is warm; and + 3 is hot.

**For young adult subjects with sedentary activity and wearing a clothing ensemble with a thermal resistance of approximately 0.5 clo, MRT ≅ DBT and air velocities are <0.2 m/s.

***To convert torr (mm Hg, 0°C) to pascals, multiply by 133.322.

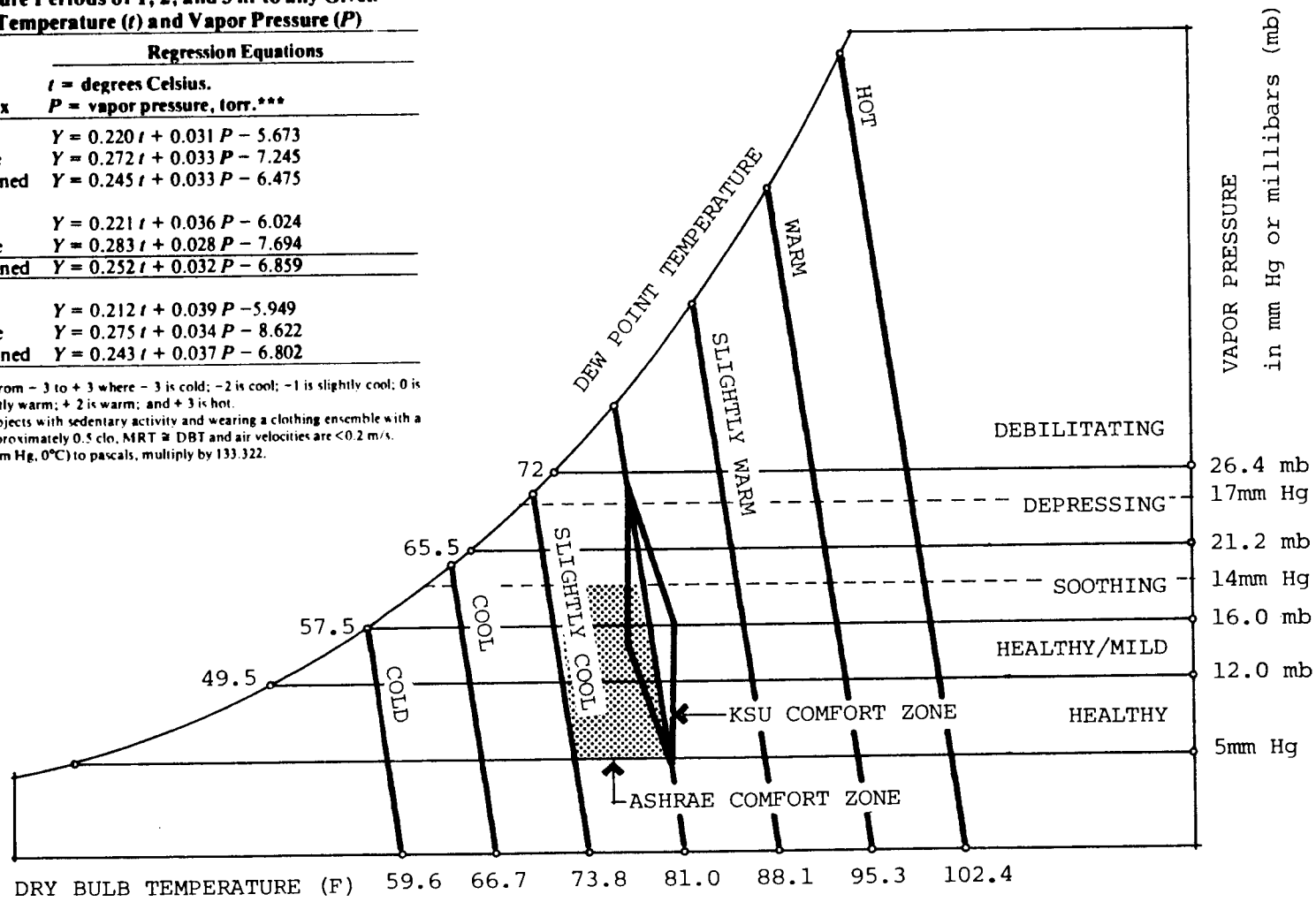


Figure 39. Comfort characterizations expressed graphically on the psychrometric chart.

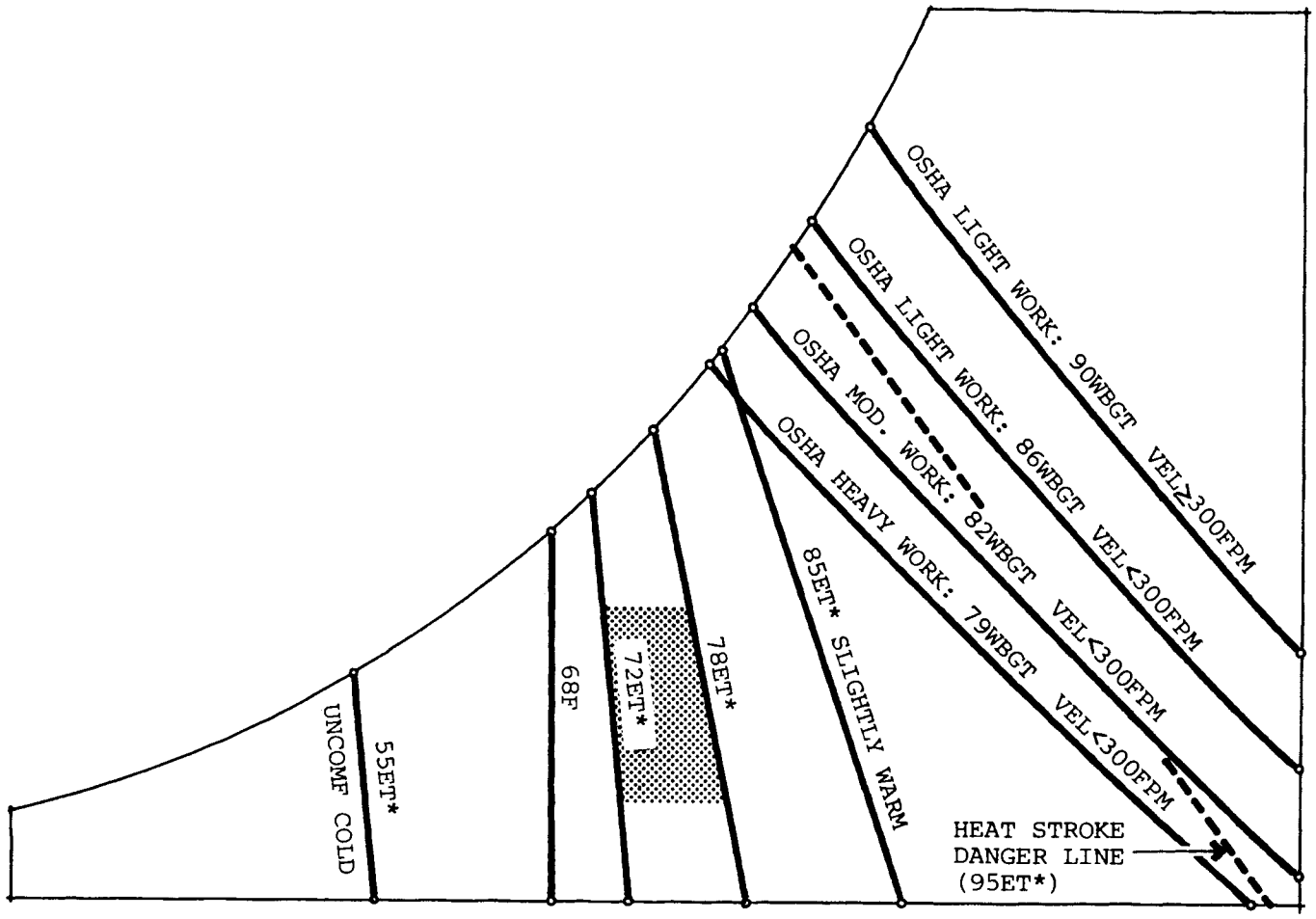


Figure 40. Comparison of ASHRAE normal comfort zone for office clothing to OSHA work limits; 86WBGT corresponds alsomost exactly to the designation "uncomfortably warm" (98ET*) for office dress and low air speeds.

Figure 41a. A new bioclimatic chart prepared by Arens et al; Givoni's ventilation effectiveness zone is superimposed (shaded area) for comparison.

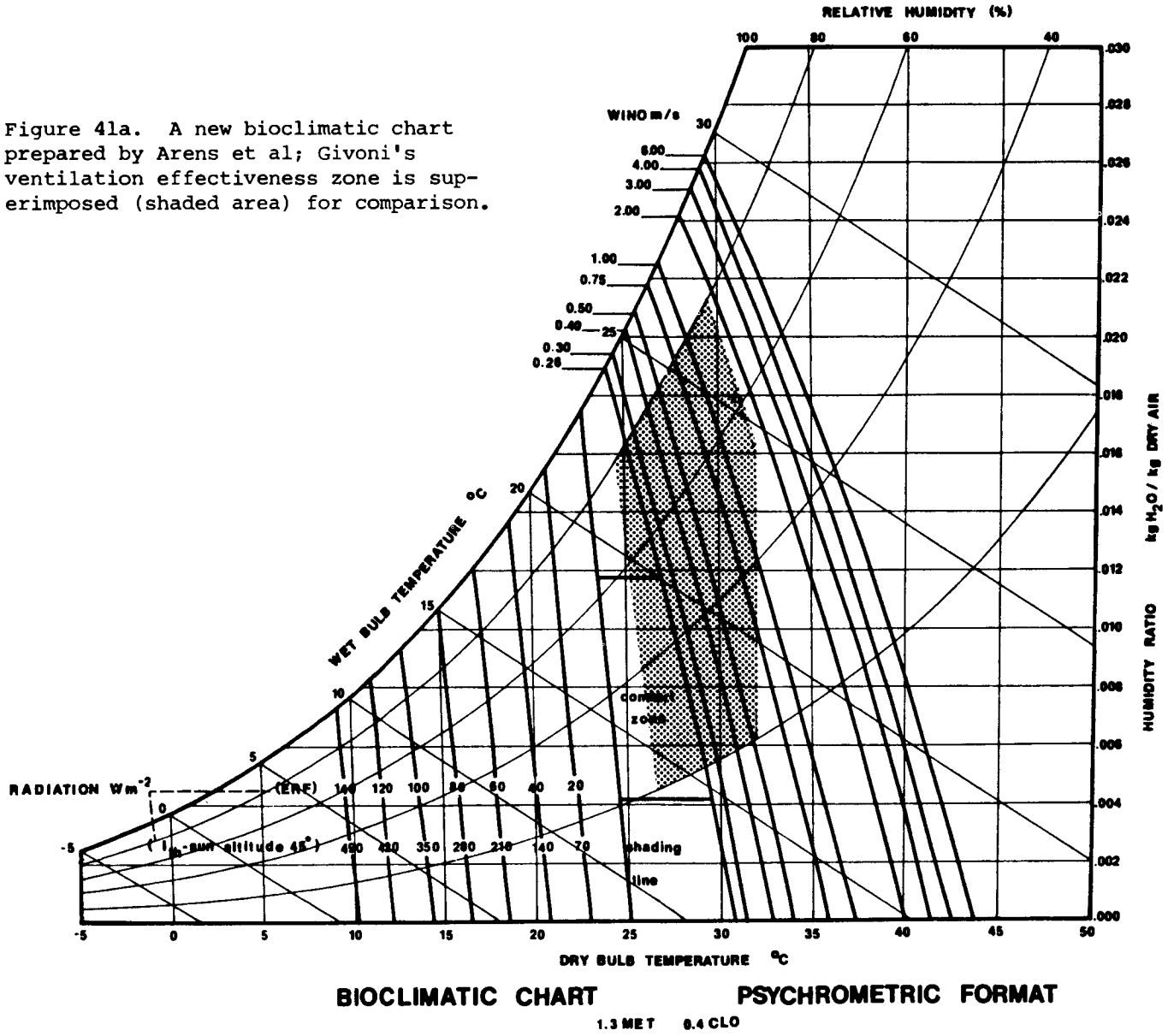
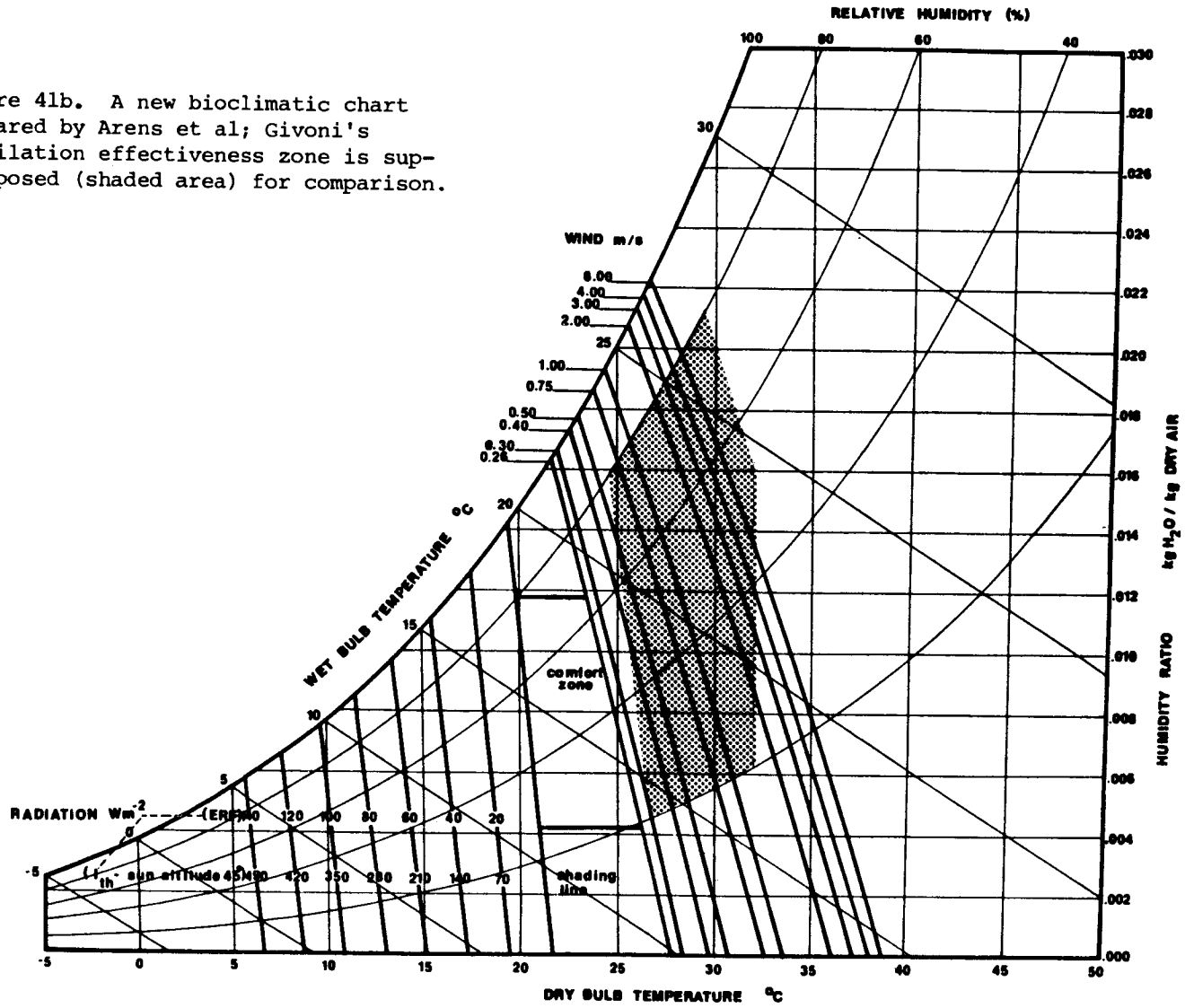


Figure 41b. A new bioclimatic chart prepared by Arens et al; Givoni's ventilation effectiveness zone is superimposed (shaded area) for comparison.



BIOCLIMATIC CHART **PSYCHROMETRIC FORMAT**

1.3 MET 0.6 CLO

TABLE 9. Metabolic heat production rates

A Metabolic Rate at Different Typical Activities[44-50]

Activity	Metabolic Rate in Met units*
RESTING	
Sleeping	0.7
Reclining	0.8
Seated, quiet	1.0
Standing, relaxed	1.2
WALKING	
On the level mph	
2	2.0
3	2.6
4	3.8
MISCELLANEOUS OCCUPATIONS	
Bakery (e.g., cleaning tins, packing boxes)	1.4 to 2.0
Brewery (e.g., filling bottles, loading beer boxes onto belt)	1.2 to 2.4
Carpentry	
Machine sawing, table	1.8 to 2.2
Sawing by hand	4.0 to 4.8
Planning by hand	5.6 to 6.4
Foundry Work	
Using a pneumatic hammer	3.0 to 3.4
Tending furnaces	5.0 to 7.0
Garage Work (e.g., replacing tires, raising cars by jack)	2.2 to 3.0
General Laboratory Work	1.4 to 1.8
Machine Work	
Light (e.g., electrical industry)	2.0 to 2.4
Heavy (e.g., steel work)	3.5 to 4.5
Shop Assistant	2.0
Teacher	1.6
Watch repairer, seated	1.1
Vehicle driving	
Car	1.5
Motorcycle	2.0
Heavy vehicle	3.2
Aircraft flying routine	1.4
Instrument landing	1.8
Combat flying	2.4
DOMESTIC WORK, WOMEN	
House cleaning	2.0 to 3.4
Cooking	1.6 to 2.0
Washing by hand and ironing	2.0 to 3.6
Shopping	1.4 to 1.8
OFFICE WORK	
Typing	1.2 to 1.4
Miscellaneous office work	1.1 to 1.3
Drafting	1.1 to 1.3
LEISURE ACTIVITIES	
Stream fishing	1.2 to 2.0
Calisthenics exercise	3.0 to 4.0
Dancing, social	2.4 to 4.4
Tennis, singles	3.6 to 4.6
Squash, singles	5.0 to 7.2
Basketball, half court, intramural	5.0 to 7.6
Wrestling-competitive or intensive	7.0 to 8.7
Golf, swinging and walking	1.4 to 2.6
Golf, swinging and golf cart	1.4 to 1.8

*Ranges are for activities which may vary considerably from one place of work or leisure to another or when performed by different people. 1 met = 58.2 W/m^2; 50 kcal/hr · m^2; 18.4 Btuh/ft^2. Some activities are difficult to evaluate because of differences in exercise intensity and body position.

B Determination of Metabolic Activity for Office Work†

Activity	Metabolic Rate, W/m^2
Seated Reading	55
Seated Writing	60
Seated Typing	65
Seated Filing	70
Seated Talking	65
Standing Talking	70
Standing Filing	80
Walking	100
Lifting/Packing	120

†$M = M_1 \times$ Percent Time + $M_2 \times$ Percent Time + etc.
where
M = total metabolic activity, watts per square metre. $M_{1,2}$ metabolic rates given above.
Examples: Seated typing, 50%; standing filing, 50%: M = 65 (0.5) + 80 (0.5) = 32.5 + 40.0 = 72.5 W/m^2.

C Classification of Physical Effort[a]

Classification	$\dot{V}^b$	$\dot{V}^c_{O_2}$	Met[d]	H.R.[e]
Very light	10	0.5	1.6	80
Light	10 to 20	0.5 to 1.0	1.6 to 3.3	80 to 100
Moderate	20 to 35	1.0 to 1.5	3.3 to 5.0	100 to 120
Heavy	35 to 50	1.5 to 2.0	5.0 to 6.7	120 to 140
Very heavy	50 to 65	2.0 to 2.5	6.7 to 8.3	140 to 160
Unduly heavy	65 to 85	2.5 to 3.0	8.3 to 10.0	160 to 180
Exhausting	85 +	3.0 +	10.0 +	180

[a] Values listed apply to steady state work.
[b] Ventilation volume, litres per minute.
[c] Oxygen consumption, litres per minute.
[d] Multiples of the resting energy expenditure, (58.2 W/m^2) or (50 kcal/(m^2 · hr).
[e] Heart rate, beats per minute, for normal subjects. (For SI calculations, convert min to s.)

NOTE: Body surface area may be approximated by the formula,

$$\text{Area} = 0.202(w^{0.425})(h^{0.725})$$

for area in m^2, w in kg, and h in meters. An average size man has about 20 sq ft of skin area; this represents a heat production rate of about 360 Btu/hr at 1 met.

TABLE 11 Threshold WBGT values[a]

Workload	WGBT in degrees F	
	Low air velocity 300 fpm	high air velocity 300 fpm
Light (level 2) (<200 kcal/hour)	86	90
Moderate (level 3) (201-300 kcal/hour)	82	87
Heavy (level 4) (>300 kcal/hour)	79	84

[a]WBGT = 0.7 WBT + 0.3 GT, for indoor use (assumes DBT = GT)

STRATEGIES OF COMFORT CONTROL

Inasmuch as personal means of comfort control are limited to adjustments in clothing, the remaining factors in the comfort equation fall into the category of architectural and other environmental controls. The building envelope may be considered a control device, through which the flow of thermal energy is regulated. Four basic control options can be identified: external heat energy can be 1) admitted or 2) excluded, and internal heat energy can be 3) contained or 4) rejected. When applied to the three mechanisms of heat transfer, and considering latent heat conversion, a set of 16 hypothetical climate control strategies can be identified. These are diagrammed in Figure 42.

Not all 16 hypothetical control strategies are in fact practicable: since solar energy is the only important "passive" source of heat, for instance, "admit solar gain" is the only useful strategy available for heating. Heat is liberated by condensation, and heat may be admitted through convection and conduction (by the ground) in some instances, but these are usually either not useful or not available when needed. The major heat conservation strategies are conduction and infiltration (convection) controls; these also serve in a secondary sense to minimize radiant and latent heat losses. Heat gains may be minimized by preventing solar admittance through windows and by minimizing solar heat absorption at the exterior surface of the building shell. The major cooling strategies are ventilation, thermal radiation (to the sky), evaporative cooling, and ground coupling (conduction to a soil sink).

The applicability of all climate control strategies varies with meteorological conditions and, in the case of earth cooling, with

ground temperatures. A wide variety of actual design devices and building elements may be used to execute the strategies identified in Figure 42. Fifty such practices are discussed in some detail in a publication prepared by Watson and Labs [92] for the National Association at Home Builders Research Foundation.

Suitability of Above-Ground Climate Control Options

Evaluation of the suitability of above-ground climate control options is made possible by analyzing hour-by-hour weather data according to a method proposed by Baruch Givoni [32]. Givoni has delineated limits within which known design practices are able to modulate exterior climate in such a way as to produce comfortable interior conditions. These limits can be represented graphically on a psychometric chart, the resulting diagram being described as the "Building Bioclimatic Chart." The limits used for the analyses contained herein are presented in Figure 43; the limits are adjusted only slightly from Givoni's original delineation for ease in computation.

The weather data analyzed elsewhere in this report is presented at the percentage of annual hours falling in each of the 17 zones demarcated in Figure 43. The applicability of the fundamental climate control strategies is stated directly, as a sum of the appropriate partitionings. A key to these is found in Table 12 and discussion of the limits follow.

Admit Solar Gain Minimize Conduction Minimize Infiltration	ZONES (I-V)

The need for heating and heat conservation strategies is indicated whenever temperatures fall below the lower limits of the comfort

zone. In most houses, heating is not actually required until temperatures fall significantly below 68F for extended periods of time, since interior activities generate heat, and since all structures collect and store some solar heat. Computer simulations reveal that a ranch house typical of modern home building practice is capable of heating itself when daily temperatures average as low as 53F. This temperature of equilibrium is the lowest average daily temperature at which the house is able to maintain 68F indoor temperature without mechanical heating; it is described as the balance point of the house.

The temperature at which a house balances depends on intensity of solar gain, amount of internal gain, and the "lossiness" of the house, or its rate of conduction and infiltration losses. If internal gains and overall heat loss rate are held constant, the balance point can be related to solar receipt alone. The ability of a given house design to heat itself in any given climate can be assessed roughly by comparing the amount of solar radiation received during winter months and the balance point for the insolation level and house design to the temperature analysis of that region. Such an analysis offers preliminary insights into the value of fundamental strategies such as promotion of solar gain versus maximization of heat conservation efforts ("superinsulation"). The heating portion of the psychrometic chart has been partitioned into 5F increments to facilitate examination of local climates with respect to balance point temperature-insolation combinations; a study of these which gives meaning to the 5F incremental partitions is discussed in the "Balance Point Studies" appendix.

Minimize Solar Gain: ZONES (VI-XVII)

The comfort zone as presented in this paper assumes that the mean radiant temperature equals dry bulb temperature. Shading is therefore indicated whenever air temperature exceeds the lower limit of the comfort zone. This is taken here as 68F, although for summer clothing, a

limit of 72F is more normally assumed. It is apparent that shading is always applicable at temperatures in excess of comfort zone limits.

An exception occurs for conditions described by zone VIB; humidification by evaporation will lower temperatures initially falling in this zone below comfort limits. The passive strategy appropriate to conditions of zone VIB is evaporative cooling followed by solar heating.

Promote Natural Ventilation: ZONES (IX-XI)

As discussed in the previous section, increasing air movement has the effect of elevating comfort limits. For architectural applications, the extent of this is limited by air speeds which are considered bothersome. Nishi [70] relates the general rule that an increase in air movement of 20fpm (0.1 m/s) is able to offset a 2F increase in air temperature (for clo = 0.6), at an initial air temperature of 75F. He adds,

> However, individual tolerance and discomfort to the physical stimulus by wind velocity may set certain acceptable limits over 1.5 to 2.0 m/s (300-400 fpm) air velocity. Also, the "flying of paper" from the desk top which occurs at an air velocity of 0.8-1.2 m/s (160-240 fpm) over may become another restriction on the use of higher air velocity in the office-type space.

The upper limit of Givoni's extended comfort zone due to ventilation (zone IX) coincides approximately with the equivalent comfort line defined in Figure 41 for an air speed of 2 m/s with a clo value of 0.4 and a metabolic rate of 1.6 met units. The boundary was originally determined for a maximum wind speed of 1.5 m/s through use of Givoni's own "Index of Thermal Stress." Fanger's charts [24] indicate that an air speed of 150 fpm (0.75 m/s) is able to attain comfort for conditions as high as 85F at 80 percent RH (assuming 0.3 clo and

1.1 met); this set of conditions falls almost exactly on the upper limit of zone IX.

The bounds of the ventilation effectiveness zone additionally assumes that mean radiant temperature nearly equals air temperature. Architecturally, this applies to [32], "structures of medium to high thermal resistance with white external surfaces." Additionally, "the assumption is made that, with efficient ventilation, the indoor air temperature and vapor pressure during the day are identical with those outside, and hence only outdoor values are taken into account."

Promote Evaporative Cooling: ZONES (XI, XIII, XIV)

The following explanation of the delineation of the zones within which evaporative cooling is effective has been offered by Milne and Givoni [67]:

> When water is evaporated, cooling takes place because the energy needed to change water from a liquid state to a gas comes from the reduction in temperature of the surrounding air. In a well-designed system, no energy is gained or lost in the process, which means it must follow one of the lines of constant energy (enthalpy) which run diagonally down to the right [Figure 43]. This explains why the evaporative cooling zones extend downward at an angle. Its outer boundary is defined only by the cooling capacity of the volume of air that can be comfortably moved through the interior of the building. This also assumes that sufficient amounts of water are available. For all practical purposes, 25F temperature reductions are about the limit of what can be achieved at reasonable indoor air velocities.

Evaporative cooling devices may be either active, having a fan-driven mechanism, or passive, as in the case of porous mats placed over window openings which are driven by natural ventilation. Evaporation from sod roofs is a different mechanism which is not described by Givoni's bioclimatic analysis procedure.

Promote Radiant Cooling: ZONES (X-XIII)

The only mechanism for promoting radiant cooling to be considered here is heavy mass construction, particularly for heavy mass roofs with a clear exposure to the sky. The following explanantion is offered [67]:

> If the hottest extremes of outdoor conditions fall within the high-mass zone [X-XIII] and the average daily temperatures fall wthin the comfort zone, then comfortable indoor conditions can be easily achieved in high thermal-mass buildings. This design strategy is most appropriate in areas with a marked day-night temperature differential, such as warm-dry climates, where the thermal mass serves to "flatten out" the extremes and delay the effect of peak conditions to the interior. Such buildings might use heavy soil or masonry materials in floors, walls, and ceilings. In newer designs, such as roof-pond systems, water is used for thermal mass. When the daily temperature range is as high as 34F, an adobe wall 1 ft thick should result in an indoor temperature variation of about half that amount, as a rough rule of thumb, or 17F with a time-lag of about 12 hours. This means that the coldest part of the night is felt indoors at mid-afternoon. In this case, the naturally cooled building walls or roof/ceiling provide a cooling effect by absorbing sensible heat from interior partitions, floors, and furniture without appreciably cooling the interior air. The human body can then effortlessly dissipate heat at its normal rate to these objects or directly to the cold wall (or roof). Typically, in buildings designed for radiant cooling, openings are deeply recessed to prevent direct solar penetration, outside surfaces are as reflective as possible, and shaded outdoor living spaces are utilized. These are traditional building design features in the Mediterranean and other temperate to warm-dry climates.
>
> In more arid climates, the cooling of high-mass buildings neither adds nor subtracts moisture from the air, so that the limits of this zone simply extend out horizontally to the right of the comfort zone along the lines of constant moisture. Below the lower boundary of this zone, it is too dry for comfort, and high-mass construction will have no effect on this problem. The use of high thermal mass cooling is most effective as a "thermal flywheel," to absorb overheating effects during the day and to "cool down" at night, when outside temperature, wind, and sky conditions increase the cooling rate by conduction, convection, and

radiation. On clear dry nights the radiant temperature of the sky must be low enough to draw heat from roofs or other building surfaces. The upper limit of this zone is established by the fact that in humid climates, high-mass buildings are quite unsatisfactory, firstly because moisture precipitates on cold walls and floors creating serious (and quite unnecessary) mildew problems, and secondly, whatever cooling effect might be achieved by nighttime cooling is offset by the slow rate of cooling of high-mass structures (in contrast to the high rate of cooling of low-mass structures).

Radiant Cooling by means of Nighttime Ventilation

Another method of promoting radiant cooling involves flushing the building interior with cool air at nighttime, so that the coolth is stored in the structure from both interior and exterior faces. The structure is ventilated at night, but closed by day. The interior MRT is thereby lowered, allowing the body to dissipate heat by radiation to the cooled building surfaces.

Although weather data is not analyzed here in terms of satisfying this strategy, the cooling ability of high mass construction with programmed nighttime ventilation has the same vapor pressure limits as the nonventilated strategy (i.e., 5 and 17mm Hg). The dry bulb temperature limit varies with vapor pressure, being bounded roughly by the reciprocal of the air density of 14.5 ft^3/lb. The strategy is further described by Milne and Givoni [67]:

> High Mass with Programmed Nighttime Ventilation for Cooling: When only nighttime temperatures fall within the comfort zone much more care is required in designing and using the building if only passive means are available. Daytime comfort conditions can be maintained by carefully programmed ventilation: cooling the building's interior mass with nighttime breezes, then closing it up during the heat of the day. In extreme cases, mechanical ventilation may be necessary to move enough nighttime air through the building. Such buildings, like those described in the previous section, will typically have thick walls with a

highly reflective outer surface, a well-insulated and sometimes earth-covered roof, and deeply recessed, but operable, openings. For practical purposes, the outer limits of the zone are defined only by the maximum day-night temperature range that might occur in a hot-arid climate, usually in the range of 30F to 40F. Indigenous buildings that typify this design strategy are the cylindrical, thatched-roof mud dwellings of the Cameroon.

Promote Earth Cooling

Under many circumstances, the earth can serve as a sink for indoor heat through direct coupling of the wall to surrounding soil. The magnitude of earth conductive cooling depends upon the temperature differential between indoor air[x] volume and surface area and the heat transfer coefficient at this interface, and other factors, including the thermophysical properties of the earth and wall section.

A body occupying an earth sheltered space may also lose heat to the wall by thermal radiation. The radiation balance between the body and its surroundings depends upon the mean radiant temperature (MRT) of all surrounding surfaces, however. This means that if a cool wall accounts for only 20 percent of all room surfaces, the overall cooling effect is not likely to be very great. Referring to an example from the previous section, an MRT of 68F is able to offset air temperatures of 88F, providing a comfort sensation of 78F. If 80 percent of room surfaces were 75F in temperature, then the cool wall would have to have a surface temperature of 40F to produce a mean radiant temperature of 68F. No location in the United States has undisturbed ground temperatures anywhere near 40F. On the other hand, as noted earlier, an air speed velocity of less than 200 fpm (1 m/s) is able to maintain a comfort sensation of 78F when air temperature is 88F.

The foregoing example makes an abstraction of the problem, but only to make clear the issues. Ideally, as many surfaces as possible should have reduced temperatures, so that no one surface must have

[x] errata: insert "and the earth exterior to the wall, the relationship between room"

extraordinarily low temperatures, and so that the body can radiate more uniformly in all directions. In earth sheltered construction, this would require large surface-to-volume ratios, to maximize the wall area in contact with the earth. While this can be recommended in some regions, in others it will conflict with appropriate winter heat conservation strategies. In contrast, nighttime ventilation (see previous section) cools all interior surfaces as desired, although this practice is effective only in relatively arid climates where nighttime temperatures are sufficiently low.

There exists no way at present of predicting the summer surface temperature of subgrade walls by analytical methods. It is expected that wall temperatures will be elevated above undisturbed ground temperatures. Since undisturbed ground temperatures are relatively simple to estimate, these serve as an expedient means of identifying lower limits to which wall temperatures might—but would be unlikely to—reach. This simplifies the problem by providing the investigator with a conservative starting point for assessing the initial cooling potential of the ground. The ground temperature tables contained elsewhere in this report facilitate easy examination of undisturbed ground temperature conditions throughout the United States.

It should also be noted that wall surface temperatures that are low enough to provide useful radiant cooling for the body may also result in condensation. This is common to the experience of many basement owners, particularly throughout the Northeast. Daily maximum, average, and minimum dew point temperatures have been computed in the bioclimatic analysis here for 29 U.S. cities; these can be compared to local predictions of undisturbed soil temperatures to identify the likelihood of condensation as a persistent problem. Aside from dehumidification of indoor air, the only solution to elimination of condensation potential is to elevate the wall temperature. This is easily done by uncoupling the wall from the soil with insulation—at the same time forfeiting much of the cooling value of the wall.

Finally, it should be acknowledged that, although summer earth temperatures are too high throughout much of the southern U.S. to provide a positive cooling effect, they are usually significantly lower than coincident air and solair temperatures. Earth tempering, therefore, offers a useful means of reducing heat gain from the exterior.

Mechanical Cooling
Dehumidification
Restrict Conduction
Restrict Infiltration

Mechanical cooling is required for hours falling into zones (XV-XVII) in Figure 43. Dehumidification is required for hours falling into zones (VIII, XV, and XVI). Infiltration controls are necessary during all hours when mechanical systems are operating. Conduction control (insulation) is necessary whenever mechanical cooling is utilized, although it is not necessary for hours occupying zone VIII, provided that exterior building surfaces are shaded to prevent solar heat again.

Humidification: ZONES (VIA, VIB)

Humidification is necessary for hours falling in zones VIA and VIB. Since vaporizing moisture into the air has a cooling effect, subsequent heating is required for conditions initially falling within zone VIA. The small cooling effect produced by humidification for conditions initially falling in zone VIB is inconsequential. Neither conduction nor infiltration controls are important for conditions defined by zones VIA and VIB.

	CONDUCTION	CONVECTION	RADIATION	EVAPORATION
PROMOTE GAIN			promote solar gain	
RESIST LOSS	minimize conduction	minimize infiltration		
RESIST GAIN	minimize conduction	minimize infiltration	minimize solar gain	
PROMOTE LOSS	earth cooling	promote ventilation	radiation to sky	evaporative cooling

Figure 42. Strategies of climate control.

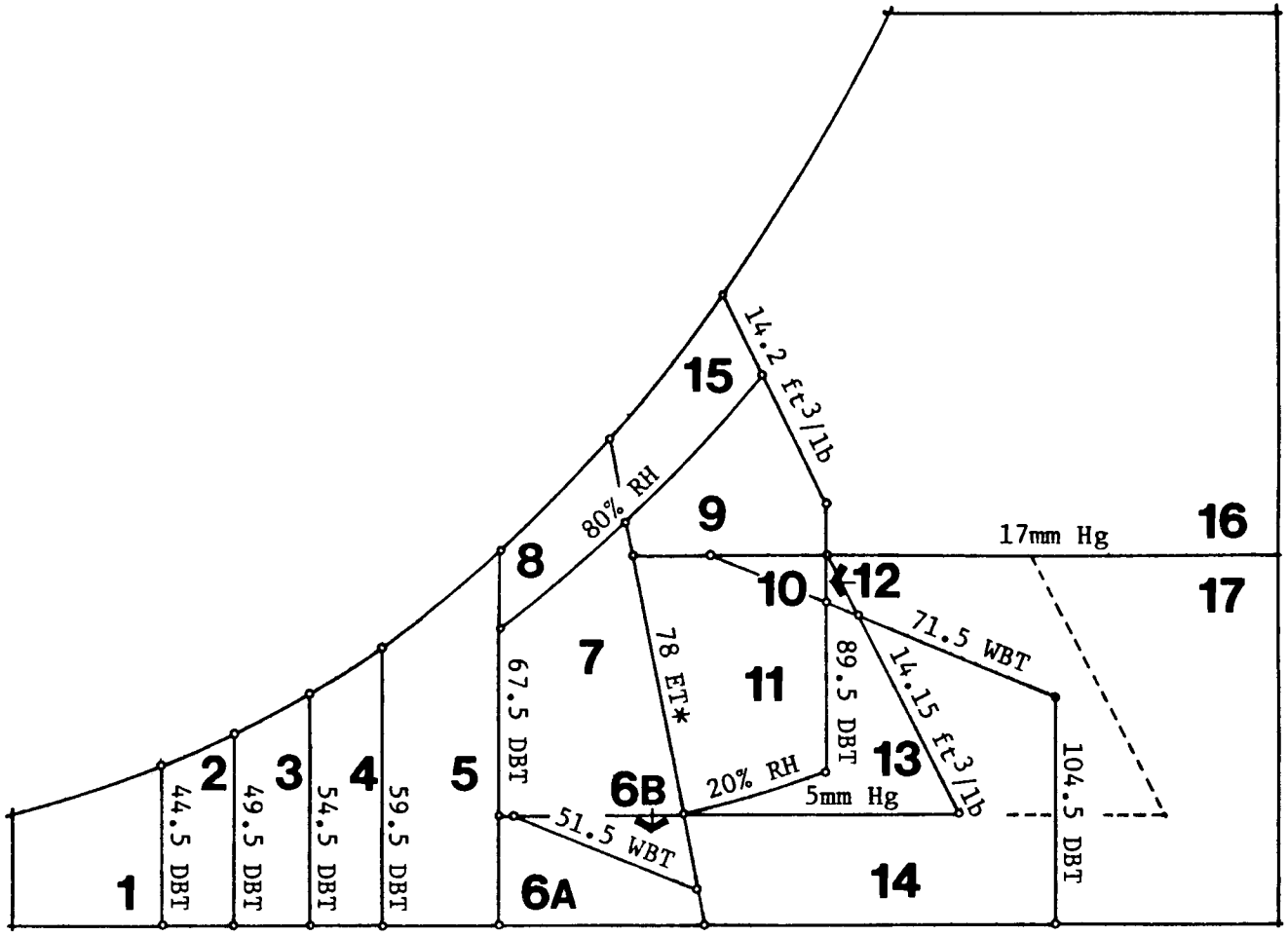


Figure 43. Building Bioclimatic Chart (after Givoni).

TABLE 12. Identification of climate control strategies on the Building Bioclimatic Chart (adapted after Givoni).

BIOCLIMATIC NEEDS ANALYSIS	
Total heating (< 68F)	1-5
Total cooling (> 78ET*)	9-17
Total comfort (68F - 78ET*, 5mm Hg - 80% RH)	7
Dehumidification (> 17 mm Hg or 80% RH)	8-9, 15-16
Humidification (< 5 mm Hg)	6A, 6B (14)
STRATEGIES OF CLIMATE CONTROL	
Restrict conduction	1-5; 9-11, 15-17
Restrict infiltration	1-5; 16-17
Promote solar gain	1-5
Restrict solar gain	6-17
Promote ventilation	9-11
Promote evaporative cooling	11, 13-14 (6B)
Promote radiant cooling	10-13
Mechanical cooling	17
Mechanical cooling & dehumidification	15-16

References

1 Donald W. Abrams, Charles C. Benton, and James M. Akridge. "Simulated and Measured Performance of Earth Cooling Tubes," 5th National Passive Solar Conference, J. Hayes and R. Snyder, editors, American Section, International Solar Energy Society, University of Delaware, Newark, 1980.

2 AIA Research Corporation. Regional Guidelines for Building Passive Energy Conserving Homes, U.S. Government Printing Office, Washington, D.C. 20402, 1978.

3 James M. Akridge and Charles C. Benton. "Bibliography: Earth Tempering and Ground Coupling," Southern Solar Energy Center, 61 Perimeter Park, Atlanta, GA, 30341, October 1980.

4 Robert V. Andrews. "Solving Conductive Heat Transfer Problems with Electrical-Analogue Shape Factors," Chemical Engineering Progress, Vol. 51, no. 2. pp. 67.F-71.F.

5 Edward Arens and William Carroll. Geographic Variation in the Heating and Cooling Requirements of a Typical Single-Family House, and Correlation of These Requirements to Degree Days, Building Science Series (BSS) 116, National Bureau of Standards, Washington, D.C. 1978.

6 Edward Arens, Richard Gonzalez, Larry Berglund, Preston McNall and Lutfi Zeren. "A New Bioclimatic Chart for Passive Solar Design," 5th National Passive Solar Conference, J. Hayes and R. Snyder, editors, American Section, International Solar Energy Society, University of Delaware, Newark, 1980.

7 Francisco H. Arumi. Thermal Inertia in Architectural Walls, Report to the Energy Research and Development Administration (ERDA) and the National Concrete Masonry Association (NCMA) National Concrete Masonry Association, Herndon, VA 1977.

8 ASHRAE. 1978 Applications Handbook, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York.

9 ASHRAE. 1977 Fundamentals Handbook, American Society of Heating, REfrigerating and Air-Conditioning Engineers, Inc, New York.

10 D. Aston. Soil Temperature Data 1958-1972, Atmospheric Environment Service CLI-2-73, Downsview, Canada, 1973.

11 N. Z. Azer and S. Hsu. "The Use of Modeling Thermal Responses in

the Analysis of Thermal Comfort of Indoor Environments," Thermal analysis-Human Comfort-Indoor Environments, B. W. Mangum and J. E. Hill, editors, Special Publication (SP)491, National Bureau of Standards (U.S. Government Printing Office SN 003-003-01849-0) 1977, pp. 18-34.

12 J. Douglas Balcomb, Editor. Passive Solar Design Handbook, Vol. 2: Passive Solar Design Analysis, Los Alamos Scientific Laboratory, Los Alamos, NM 1980, (Distribution by NTIS, Springfield, VA).

13 G. G. Boileau and J. K. Latta. Calculation of Basement Heat Losses, Technical Paper No. 292, NRC 10477, Division of Building Research, National Research Council Canada, Ottawa, 1968.

14 W. G. Brown. Graphical Determination of Temperature Under Heater or Cooled Areas on the Ground Surface, Technical Paper No. 163, NRC 7660, Division of Building Research, National Research Council Canada, Ottawa, 1963 (36 pp. + figures).

15 H. S. Carslaw and J. C. Jaeger. Conduction of Heat in Solids, Clarendon Press, Oxford, 1959.

16 Jen-hu Chang. "Global Distribution of the Annual Range in Soil Temperature," American Geophysical Union Transactions, Vol. 38, no. 5, October 1957, pp. 718-723.

17 Jen-hu Chang. Ground Temperature. Vol. I., Blue Hill Meteorological Observatory, Harvard Univ, Milton, Massachusetts, June 1958.

18 W. D. Collins. "Temperature of Water Available for Industrial Use in the United States," Water Supply Paper 520-F, U.S. Geological Survey, 1925.

19 G. A. Crabb, Jr. and J. L. Smith. "Soil-Temperature Comparisons under Varying Covers," Highway Research Board Bulletin 71, Washington, D.C., 1953, pp. 32-49.

20 Carl B. Crawford. "Soil Temperatures, A Review of Published Records," in Frost Action in Soils, Highway Research Board Special Report No. 2, NAS/NRC Publication No. 213, National Research Council, Washington, D.C., 1952.

21 Gary R. Davies. "Thermal Analysis of Earth Covered Buildings," 4th National Passive Solar Conference, G. Franta, editor, American Section, International Solar Energy Society, University of Delaware, Newark, 1979.

22 Ernst R. G. Eckert, Thomas P. Bligh, Emil Pfender. Energy Conservation by Subsurface Construction: Heat Transfer Studies in a Large Underground Building, Department of Mechanical Engineering, University of Minnesota, Minneapolis, Final Report, 1980.

23 J. M. Elliot and Merl Baker. "Heat Loss from a Heated Basement," ASHRAE Transactions, Vol. 66, Article 1724, 1960, pp. 400-413.

24 P. Ole Fanger. Thermal Comfort, Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, 1970.

25 Federal Construction Council, Standing Committee on Mechanical Engineering, Criteria for Underground Heat Distribution Systems, Technical Report No. 66, Building Research Advisory Board, National Research Council/National Academy of Sciences, Washington, D.C., 1975.

26 Lyle D. Feisel. "Economic and Design Considerations for an Underground House," in Passive Solar: Subdivisions, Windows, and Underground, expanded papers of the 4th National Passive Solar Conference Plenary Sessions, J. Cook, K. Labs, S. Selkowitz, and H. Wade, editors, 1981 (Mid-American Solar Energy Complex, MASEC Center, 8140 26th Ave. South, Minneapolis, MN 55420).

27 E. M. Fitton and C. F. Brooks. "Soil Temperatures in the United States," Monthly Weather Review, Vol. 59, No. 1, January 1931, pp. 6-16.

28 A. Pharo Gagge and Ralph G. Nevins. "Effect of Energy Conservation Guidelines on Comfort, Acceptability and Health," Thermal Analysis-Human Comfort-Indoor Environments, B. W. Mangum and J. E. Hill, editors, Special Publication (SP) 491, National Bureau of Standards (U.S. Government Printing Office SN 003-003-01849-0), 1977, pp. 93-116.

29 R. R. Gilpin. "The Ground Temperature Boundary Condition Provided by a Moss Covered Surface." ASME Paper No. 76-WA/HT-61, American Society of Mechanical Engineers, New York, 1976 (8 pp.).

30 R. R. Gilpin and B. K. Wong. "The Ground Temperature Regime and its Relationship to Soil Properties and Ground Surface Cover," ASME Paper No. 75-WA/HT-98, American Society of Mechanical Engineers, New York, 1975 (12 pp.).

31 R. R. Gilpin and B. K. Wong. "'Heat-Valve' Effects in the Ground Thermal Regime," Journal of Heat Transfer, (ASME), Vol. 98, No. 4, November 1976, pp. 537-542.

32 Baruch Givoni. Man, Climate and Architecture, Applied Science Publishers, Ltd., London (U.S. distributors, International Ideas, Inc., 1627 Spruce Street, Philadelphia, PA 19103) 2nd Edition, 1976.

33 Robert E. Goetz, Jr. Use of Degree Day Data to Compare Energy Consumption in Surface and Subsurface Construction, Masters Thesis, University of Maryland, Dept. of Meteorology, College Park, 1975.

34 L. W. Gold. "Influence of Surface Conditions on Ground Temperature," Canadian Journal of Earth Sciences, Vol. 4, April 1967, pp. 199-200.

35 L. W. Gold. "Influence of the Snow Cover on the Average Annual Ground Temperature at Ottawa, Canada," NRCC 7505, National Research Council Canada, Ottawa.

36 L. W. Gold and A. H. Lachenbruch. "Thermal Conditions in Permafrost--A Review of North American Literature," North American Contribution to the Second International Conference on Permafrost, Yakutsk, Siberia, National Academy of Sciences, Washington, D.C., 1973.

37 Ralph F. Goldman. "Establishment of the Boundaries to Comfort by Analyzing Discomfort," Thermal Analysis-Human Comfort-Indoor Environments, B. W. Mangum and J. E. Hill, editors, Special Publication (SP) 491, National Bureau of Standards, (U.S. Government Printing Office SN 003-003- 01849-0), 1977, pp. 52-64.

38 Ralph F. Goldman. "The Role of Clothing in Achieving Acceptability of Environmental Temperatures Between 65F and 85F," Energy Conservation Strategies in Buildings: Comfort, Acceptability, and Health, Jan A. J. Stolwijk, editor, John B. Pierce Foundation of Connecticut, Inc., Yale University, New Haven, 1978, pp. 38-52.

39 Richard R. Gonzalez. "Experimental Analysis of Thermal Acceptability," Thermal Analysis-Human Comfort-Indoor Environments, B. W. Mangum and J. E. Hill, editors, Special Publication (SP) 491, National Bureau of Standards, (U.S. Government Printing Office SN 003-003-01849-0), 1977, pp. 131-151.

40 Paul K. Grogger. "The Utilization of Microclimate to Conserve Energy in Single and Multi-Family Dwellings," Technology for Energy Conservation, proceedings of the 1979 Conference held at Tucson, Arizona, (available from Information Transfer, Inc., 1160 Rockville Pike, Rockville, MD 20852).

41 James D. Hardy. "Physiological and Health Effects of Ambient

Temperatures Between 65F and 85F," Energy Conservation Strategies in Buildings: Comfort, Acceptability, and Health, Jan A. J. Stolwijk, editor, John B. Pierce Foundation of Connecticut, Inc., Yale University, New Haven, 1978, pp. 14-37.

42 Victor R. Hasfurther and Robert D. Burman. "Soil Temperature Modeling Using Air Temperature as a Driving Mechanism," Transactions of the American Society of Agricultural Engineers, Vol. 17, No. , January/February 1974, pp. 78-81.

43 History of Soil Temperature Stations in the United States, Key to Meteorological Records Documentation No. 1.4, Department of Commerce Weather Bureau, Washington, D.C., 1961.

44 House Beautiful Climate Control Project. "Regional Climate Analyses and Design Data," published in the Bulletin of the American Institute of Architects, September 1949-January 1952, (facsimile reprints available from University Microfilms International, Ann Arbor, MI).

45 L. R. Ingersoll, O. J. Zobel, A. C. Ingersoll. Heat Conduction with Engineering, Geological and Other Applications, University of Wisconsin Press, Madison, Revised Edition, 1954.

46 Alfreds R. Jumikis. "Graphs for Disturbance-Temperature Distribution in Permafrost Under Heated Rectangular Structures," Third International Conference on Permafrost, Edmonton, Canada, 1978.

47 Alfreds R. Jumikis. Thermal Geotechnics, Rutgers University Press, New Brunswick, N.J., 1977.

48 A. K. Khatry, M. S. Sodha, and M. A. S. Malik. "Periodic Variation of Ground Temperature with Depth," Solar Energy (ISES), Vol. 20, No. 5, 1978, pp. 425-427.

49 Donald Kirkham. Advanced Soil Physics, Wiley-Interscience, John Wiley and Sons, Inc., New York, 1972.

50 Logan K. Kuiper. A Thermal Model for the Surface Temperature of Materials on the Earth's Surface, Technical Information Series No. 1, Iowa Geologic Survey, Iowa City, 1976 (18 pp.).

51 T. Kusuda. Earth Temperatures Beneath Five Different Surfaces, National Bureau of Standards Report 10373, Washington D.C., 1971.

52 T. Kusuda. "Heat Transfer Studies of Underground Chilled Water and Heat Distribution Systems," Underground Heat and Chilled Water Distribution Systems, T. Kusuda, editor, Building Science Series (BSS) 66, National Bureau of Standards, Washington, D.C., 1975.

53 T. Kusuda. Least Sqares Analysis of Annual Earth Temperature Cycles for Selected Stations in the Contiguous United States, National Bureau of Standards Report 9493, Washington, D.C., 1968.

54 T. Kusuda and P. R. Achenbach. "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States," ASHRAE Transactions, Article No. 1914, 1965.

55 T. Kusuda and P. R. Achenbach. Earth Temperature and Thermal Diffusivity at Selected Stations in the United States, National Bureau of Standards Report 8972, Washington, D.C.

56 Kenneth Labs. The Architectural Use of Underground Space: Issues and Applications, Masters Thesis, Washington University School of Architecture, St. Louis, 1975.

57 Kenneth Labs. "The Underground Advantage: Climate of Soils," in Passive Solar: Subdivisions, Windows, and Underground, expanded papers of the 4th National Passive Solar Conference Plenary Sessions, J. Cook, K. Labs, S. Selkowitz, and H. Wade, editors, 1981 (Mid-American Solar Energy Complex, MASEC Center, 8140 26th Ave. South, Minneapolis, MN 55420).

58 Arthur H. Lachenbruch. "Three Dimenstional Heat Conduction in Permafrost Beneath Heated Buildings," U.S . Geological Survey Bulletin 1052-B, 1957, pp. 51-69.

59 Helmut E. Landsberg. The Assessment of Human Bioclimate: A Limited Review of Physical Parameters, Technical Note No. 123, World Meterological Organization, Geneva, 1972.

60 Walter B. Langbein. "Computing Soil Temperatures," Transactions of the American Geophysical Union, Vol. 30, No. 4, August 1949, pp. 543-547.

61 Wolfgang Langewiesche. "There's a Gold Mine Under Your House," House Beautiful, Vol. 92, No. 8, August 1950, pp. 92-94, 133, 134, 135.

62 William H. K. Lee. "Review of Heat Flow Data," Terrestial Heat Flow, W. H. K. Lee, editor, Geophysical Monograph Series, No. 8, American Geophysical Union of the National Academy of Sciences, Publication No. 1288, Washington, D.C., 1965.

63 Heinz Lettau. "Improved Models of Thermal Diffusion in the Soil," Transactions of the American Geophysical Union, Vol. 35, No. 1, February 1954, pp. 121-132.

64 Vivian Loftness. Identifying Climatic Design Regions and Assessing Climatic Impact on Residential Building Design, Technical Paper No. 1, AIA Research Corporation, Washington, D.C., 1977.

65 Merle F. McBride, Robert S. Blancett, Charles F. Sepsy, and Charles D. Jones. "Measurement of Subgrade Temperatures for Prediction of Heat Loss in Basements," ASHRAE Transactions, Vol. 85, Part 1, Paper PH-79-7, No. 4, 1979, pp. 642-655.

66 George D. Meixel, Paul H. Shipp and Thomas P. Bligh. "The Impact of Insulation Placement on the Seasonal Heat Loss Through Basement and Earth Sheltered Walls," Underground Space (AUA), Vol. 5, No. 1, July/August 1980, pp. 41-47.

67 Murray Milne and Baruch Givoni. "Architectural Design Based on Climate," Energy Conservation Through Building Design, Donald Watson, editor, Architectural Record Books/McGraw-Hill Book Co., New York, 1979, pp. 96-113.

68 John L. Monteith, Principles of Environmental Physics, American Elsevier Publishing Co., New York, 1973.

69 Frank H. Nicholson and Hardy B. Granberg. "Permafrost and Snow-cover Relationships near Schefferville," North American Contribution to the Second International Conference on Permafrost, Yakutsk, Siberia, National Academy of Sciences, Washington, D.C., 1973.

70 Yasunobu Nishi. "The Role of Air Velocity in Promoting Comfort and Acceptability of Thermal Environments of 65F-85F," Energy Conservation Strategies in Buildings: Comfort, Acceptability, and Health, Jan A. J. Stolwijk, editor, John B. Pierce Foundation of Connecticut, Inc., Yale University, New Haven, 1978, pp. 71-94.

71 Victor Olgyay. Design with Climate; Bioclimatic Approach to Architectural Regionalism, Princeton Univ. Press, Princeton, N.J., 1963.

72 Passive Cooling Group, c/o Don Elmer, Building 67A, Lawrence Berkeley Laborator, Berkeley, CA 94720

73 D. C. Pearce and L. W. Gold. "Observations of Ground Temperature and Heat Flow at Ottawa, Canada," Journal of Geophysical Research, Vol. 64, No. 9, September 1959, pp. 1293-1298.

74 A. Peters. "Soil Thermal Properties: An Annotated Bibliography," 929, The Franklin Institute, Philadelphia, PA, October 1962.

75 C. H. B. Priestly. Turbulent Transfer in the Lower Atmosphere, University of Chicago Press, 1959.

76 S. J. Richards, R. M. Hagan, T. M. McCalla. "Soil Temperature and Plant Growth," Soil Physical Conditions and Plant Growth,

Vol. II of Agronomy: A Series of Monographs, B. T. Shaw, editor, Academic Press, New York, 1952, pp. 304-336.

77 R. F. Scott. Heat Exchange at the Ground Surface, Cold Regions Science and Engineering, II-A1, Part II: Physical Science, Section A: Geophysics. U.S. Army Materiel Command, Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1964 (49 pp.).

78 William D. Sellers. Physical Climatology, Chicago: Univ. of Chicago Press, Chicago, 1965.

79 Wayne L. Shick and Rudard A. Jones. The Illinois Lo-Cal House C2.3, Council Notes, Vol. 1, No. 4, Small Homes Council-Building Research Council, University of Illinois, Urbana-Champaign, 1976, 8 pp.

80 Paul Siple. "Climatic Criteria for Building Construction," Weather and the Building Industry, Research Conference Report, No. 1, National Research Council Building Research Advisory Board, Washington, D.C., 1950.

81 Paul Siple. "How Many Climates Do We Have in the U.S.?" House Beautiful, Vol. 91, No. 10, October 1949, pp. 136-137.

82 D. G. Stephenson. Insulation to Prevent Ground Freezing, Building Research Note No. 119, Division of Building Research, National Research Council, Canada, Ottowa, 1977.

83 Richard F. Szydlowski. Analysis of Transient Heat Loss in Earth Sheltered Structures, Masters Thesis, Iowa State University, Department of Mechanical Engineering, Ames, 1980.

84 Werner H. Terjung. "Annual Physioclimatic Stresses and Regimes in the United States," The Geographic Review, Vol. 57, 1967, pp. 225-240.

85 Werner H. Terjung. "Physiologic Climates of the Coterminous United States: A Bioclimatic Clissification Based on Man," Annals of the Association of American Geographers, Vol. 56, March 1966, pp. 141-179.

86 C. W. Thornthwaite. "An Approach to a Rational Classification of Climate," Geographic Review, Vol. 38, No. 1, 1948, pp. 55-94.

87 Underground Space Center, 11 Mines and Metallurgy, 221 Church Street, S.E., University of Minnesota, Minneapolis, MN 55455.

88 Stephen S. Visher. Climatic Atlas of the United States, Harvard University Press, Cambridge, 1954.

89 Stephen S. Visher. Climatic Laws, John Wiley & Sons, New York, 1924.

90 W. R. van Wijk and W.J. Derksen. "Sinusoidal Temperature Variation in a Layered Soil," Physics of Plant Environment, W. R. van Wijk, editor, North Holland Publishing Co., Amsterdam, 1966.

91 W. R. van Wijk and D. A. de Vries. "Periodic Temperature Variation in a Homogeneous Soil," Physics of Plant Environment, W. R. van Wijk, editor, North Holland Publishing Co., Amsterdam, 1966.

92 Donald Watson and Kenneth Labs. Climatic Design for Home Building, prepared for the National Association of Home Builders Research Foundation with support of the Department of Housing and Urban Development, 1980, (available from Donald Watson, FAIA, Box 401, Guilford, CT 06437).

93 G. P. Williams and L. W. Gold. Ground Temperatures, Canadian Building Digest, 180, Divison of Building Research, National Research Council Canada, Ottawa, July 1976, 4 pp.

94 B. K. Wong. The Ground Temperature Regime and its Relationship to Soil Properties, Surface Cover, and Environmental Boundary Conditions, Master of Science Thesis, University of Alberta (Dept. of Mechanical Eng.) Edmonton, 1975.

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