

MODELING TEMPERATURES OF ALASKAN PAVEMENTS - FY85

FINAL REPORT

William A. Braley
Engineering Research Center
Institute of Northern Engineering
University of Alaska-Fairbanks
Fairbanks, AK 99775

August 1986

Prepared for:

STATE OF ALASKA
DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES
RESEARCH SECTION
2301 Peger Road
Fairbanks, AK 99701-6394

in cooperation with

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Alaska Department of Transportation and Public Facilities. This report does not constitute a standard, specification or regulation.

1. Report No. FHWA AK-RD-86-11		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Modeling Temperatures of Alaskan Pavements - FY85				5. Report Date October 1985	
				6. Performing Organization Code	
7. Author(s) William A. Braley				8. Performing Organization Report No.	
9. Performing Organization Name and Address University of Alaska Institute of Water Resources/Engineering Experiment Station Fairbanks, AK 99775				10. Work Unit No. (TRIS)	
				11. Contract or Grant No. F24732	
12. Sponsoring Agency Name and Address State of Alaska Department of Transportation and Public Facilities Pouch Z Juneau, AK 99811				13. Type of Report and Period Covered FINAL REPORT	
				14. Sponsoring Agency Code	
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration					
16. Abstract A one-dimensional finite difference model for calculating the diurnal variation in highway pavement temperatures was developed. The model, which was written in Basic for use on an IBM-PC or compatible micro-computer and in Fortran for use on main-frame computers, calculates hourly values of pavement temperature based upon input values of wind speed, ambient air temperature, and incoming solar radiation. It is applicable to situations where base course materials are separated into layers having differing thermal properties and to cases where the base is undergoing freeze and thaw. Output from the model was compared to hourly values of pavement temperature measured at a highway research site in Fairbanks, Alaska.					
17. Key Words pavement temperature surface temperature finite differences thermal analysis energy balance			18. Distribution Statement No Restrictions		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages	22. Price N/A

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT.....	1
INTRODUCTION.....	2
MODELING PAVEMENT TEMPERATURES.....	3
DATA COLLECTION.....	7
MODEL OPERATION.....	8
MODEL VERIFICATION.....	9
CONCLUSIONS.....	11
REFERENCES.....	12
APPENDIX.....	14

ABSTRACT

A one-dimensional finite difference model for calculating the diurnal variation in highway pavement temperatures was developed. The model, which was written in BASIC for use on an IBM-PC or compatible microcomputer and in FORTRAN for use on mainframe computers, calculates hourly values of pavement temperature based upon input values of wind speed, ambient air temperature, and incoming solar radiation. The model is applicable to situations where base course materials are separated into layers having differing thermal properties, and to cases where the base is undergoing freeze and thaw. Output from the model was compared to hourly values of pavement temperature measured at a highway research site in Fairbanks, Alaska.

INTRODUCTION

Diurnal fluctuations in temperature of asphaltic-concrete pavements cause diurnal changes in the stiffness of the pavement. Since the amount of fatigue life subtracted from a pavement structure for a given vehicular loading is dependent upon the pavement's stiffness, the reduction in a pavement's fatigue life for a given vehicle will also vary diurnally. The question then arises as to whether the fatigue life of a pavement structure may be increased by scheduling vehicular loading according to the diurnal fluctuations of pavement stiffness.

In studying this problem, it is first necessary to determine the variation in diurnal pavement temperatures for various geographic locations and times of the year. The objective of this study was to create a mathematical model capable of accurately estimating pavement temperatures based upon easily collected or calculated meteorological parameters. These parameters included wind speed, incoming shortwave radiation, and ambient air temperature above the pavement surface.

My modeling techniques was a one-dimensional finite difference method which calculated the variation in enthalpy within a roadway structure through time. This technique allowed the flexibility of modeling layered materials having varying thermal properties, and the inclusion of the effect of phase change on the thermal regime. The model was developed on an IBM mainframe 370/VM system in FORTRAN. The model was also converted to BASIC on an IBM-PC computer.

This model was developed for the Research Section of the Alaska Department of Transportation and Public Facilities (DOT&PF). The model was designed and tested for a subarctic climate. Models capable of determining pavement surface and subsurface temperatures have been developed for the arctic and subarctic climates (Goodrich, 1974; Hildebrand and Haas, 1983). However, these models were not designed for estimating short-term, diurnal, temperature variations. Several models and methodologies have been developed for estimating diurnal variations of pavement temperature (Barber, 1975; Straub et al., 1968; Rumney and Jimenez, 1972). These were developed and tested in temperate climates and their applicability to subarctic conditions is not known.

My model might also be applied to the study of any problem related to short-term variation in surface and subsurface temperatures. An example of such a problem would be the examination of depth of thaw in a road embankment during the spring thaw cycle. In such a case, it would be possible to predict how deep the roadway will thaw several weeks into the future. This would help determine when the roadway would be highly susceptible to damage from vehicular loading due to thaw weakening of the base material, and would help determine when load restrictions must be applied.

MODELING PAVEMENT TEMPERATURES

The modeling technique that I used to predict pavement temperatures based upon environmental parameters may be viewed in two parts: the modeling of heat transfer processes in the embankment and in the asphaltic concrete pavement; and the modeling of the surface energy balance. The conductive and phase-change energy transfers in the material portion of this problem were modeled using a one-dimensional finite difference scheme formulated in terms of enthalpy (the sum of sensible and latent heats). A diagrammatic representation of the nodes and elements used in this model is given in Figure 1.

The heat conduction equation expressed in terms of enthalpy is

$$\frac{\delta}{\delta x} \left(K \frac{\delta T}{\delta x} \right) = \frac{\delta H}{\delta t} \quad (1)$$

where

H = enthalpy

K = thermal conductivity

t = time

T = temperature

x = distance from ground surface

For simplicity in modeling, the enthalpy of the system is assigned a value of zero as the temperature approaches the freezing temperature

from the negative side. The temperature is then related to the enthalpy of the system by the following formulas.

$$T = \begin{cases} T_f + H/C_f & H \leq 0 \\ T_f & 0 < H < L \\ T_f + (H-L)/C_t & H \geq L \end{cases} \quad (2)$$

where

$$\begin{aligned} T_f &= \text{temperature at freezing } (^{\circ}\text{F}) \\ C_f &= \text{frozen volumetric heat capacity (Btu/hr-ft}^3\text{-}^{\circ}\text{F)} \\ C_t &= \text{thawed volumetric heat capacity (Btu/hr-ft}^3\text{-}^{\circ}\text{F)} \\ L &= \text{latent heat (Btu/ft}^3\text{)}. \end{aligned}$$

The explicit finite difference representation of equation (1) for a nonhomogeneous soil system which may undergo phase change and may have varying element size is

$$H_i^{j+1} = H_i^j + \frac{\Delta t}{\Delta x_i} \left[\frac{T_{i+1}^j - T_i^j}{R_i + R_{i+1}} + \frac{T_{i-1}^j - T_i^j}{R_i + R_{i-1}} \right] \quad (3)$$

where R_i , the thermal resistance of an element, is defined as

$$R_i = \frac{\Delta x_i / 2}{K_i} \quad (4)$$

The surface node of the model must be handled in a special manner since conduction occurs in only one direction from this node. The heat transfer process to the atmosphere, Q_{surf} , is determined by the surface energy balance. For node 1, the finite difference formulation is

$$H_1^{j+1} = H_1^j + \frac{\Delta t \cdot 2}{\Delta x_1} \left[\frac{T_2^j - T_1^j}{R_1 + R_2} \right] + Q_{\text{surf}} \quad (5)$$

In both equations (3) and (5), it is necessary to select a time step (Δt) and an element size (Δx) such that

$$\Delta t \leq \frac{(\Delta x_i)^2 C_i}{2K_i}; \quad i = 2, 3, 4 \dots n \quad (6)$$

for all interior nodes, and

$$\Delta t \leq \frac{(\Delta x_1)^2 C_i}{2K_1 \left(\frac{h_c \Delta x_1}{K_1} + 1 \right)} \quad (7)$$

for the surface nodes with convection, where h_c is the convection coefficient, equation (13). This is to insure a stable solution. Based upon the element sizes given in Figure 1, a time step of 0.0333 hr (2 min) was selected for use in testing the model.

The energy transfer at the surface, Q_{surf} in Equation (5), may be expressed as

$$Q_{\text{surf}} = Q_{\text{sw}} - Q_{\text{lw}} - Q_{\text{conv}} \quad (8)$$

where

- Q_{sw} = solar or shortwave radiation
- Q_{lw} = infrared or longwave radiation
- Q_{conv} = convective heat transfer.

This formulation ignores energy transfers due to evaporation, rainfall, snowfall and snowmelt. The asphaltic concrete surface was considered to be impermeable to moisture transfers, so evaporative cooling of the soil was ignored. Energy transfers due to precipitation and snowmelt were ignored because clear days were of primary interest in this study. Clear days have the highest Q_{sw} input and Q_{lw} losses leading to the maximum swing in diurnal pavement temperatures. These conditions lead to the largest diurnal fluctuations in pavement stiffness, which is the primary focus of this model.

The hourly value of the shortwave radiation incident at the surface is one of the required inputs to this model. The incident radiation for any time step is linearly interpolated from the hourly values. The

shortwave radiation at the surface is adjusted to account for a portion of energy being reflected back to the atmosphere. This formula is

$$Q_{sw} = Q_h * (1 - \alpha) \quad (9)$$

where Q_h is the incident shortwave energy at the surface and α is the albedo of the surface.

The clear sky longwave radiation, Q_{lw} , was estimated using

$$Q_{lw} = (E_a * T_{air}^4 - E_s * T_{sur}^4) * \sigma \quad (10)$$

where T is expressed as degrees Rankine, and σ represents the Stephen-Boltzman constant, 0.1714×10^{-8} Btu/hr-ft²-°R⁴. E_a and E_s represent the atmospheric and surface emissivities. E_s is an input to the model, while E_a is calculated based upon atmospheric temperature using a model derived by Idso and Jackson (1969). This is

$$E_a = 1 - 0.216 \times \exp[-7.77 \times 10^{-4} \times \{5/9 \times (T_{air} - 32)\}^2] \quad (11)$$

where T_{air} is air temperature expressed in °F. The reasoning behind this formula is that the atmospheric longwave radiation is primarily a function of the water vapor concentration in the lower atmosphere. Since the vapor concentration of the atmosphere is correlated with temperature, Idso and Jackson were able to derive this function correlated with temperatures measured several feet above the surface. This function also accounts for the freezing of atmospheric water vapor as the temperature falls below freezing. The E_a values generated by this equation as a function of air temperature are shown in Figure 2.

The convective heat transfer from the surface, Q_{conv} , is determined by

$$Q_{conv} = h_c (T_{sur} - T_{air}) \text{ (Btu/hr-ft}^2\text{-°F)} \quad (12)$$

The convective heat transfer coefficient, h_c , is based upon the roughness of the surface and the speed of the wind above the surface. In this model h_c was estimated using

$$h_c = 1 U \times .3 \text{ (Btu/hr-ft}^2\text{-!F)} \quad (13)$$

where U is wind speed in mph.

DATA COLLECTION

For purposes of testing the model, data consisting of hourly pavement temperatures, air temperature, wind speed, and incident solar radiation were collected from March 1984 to April 1985. The test site (Figure 3) from which these data were retrieved is located on Peger Road (Fairbanks, Alaska) adjacent to the Interior District offices of DOT&PF. This research site was originally constructed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) to study the subsurface thermal effect of various pavement surface colorations (Berg, 1985).

The portion of Peger Road containing the test sections was reconstructed in the summer of 1981. Previous to the application of the 2-inch-thick asphaltic concrete pavement, 1-inch-diameter PVC pipes were placed horizontally across the road near the top of the base course. These pipes extend 2 ft beyond the pavement on each side. Following application of the pavement, 6-inch-diameter cores were removed above the PVC pipe in each test section. Thermocouple wires were fed through the pipe, and two thermocouples were epoxied in a hole drilled through the core such that the thermocouple sensors were 1/8 in from the top of core. The core was then replaced in the roadway and cemented in place using warm liquid asphalt. Of the eight test sections constructed by CRREL, only section numbers 7 and 8 were used in this study. These sections received no surface treatments during the previous study, so they had the same coloration and texture as the existing road.

Meteorological instruments consisting of a cup anemometer, a total hemispherical shortwave pyranometer, and a thermocouple to monitor ambient air temperature were located adjacent to a parking lot in the DOT&PF facility approximately 300 ft from the test section. Extension wire from this instrumentation and the test section thermocouples were

brought into one of the DOT&PF's office buildings and connected to a Hewlett Packard-85 data acquisition unit.

Data collected and stored by the data acquisition unit consisted of hourly temperatures of pavement and air, and average hourly wind speed and solar radiation. Wind speed and radiation data were averaged from readings taken every two minutes.

During the year of data collection, interrupts occurred twice due to power failures and malfunctioning of the uninterruptable power supply to which the data collection equipment was connected. Also, a malfunction in the cup anemometer in August of 1984 rendered all subsequent wind data useless. To replace the missing wind speed information, data from the National Weather Service's Fairbanks International Airport meteorological site were used. These data consisted of three-hour averages. Hourly averages were interpolated from the data. The Fairbanks International Airport is located several miles from the Peger Road facility.

MODEL OPERATION

The finite difference model previously described was tested using the environmental data from the Peger Road site. Output from the model, consisting of hourly values of pavement temperature at a depth of 1/8 in were compared to the measured pavement temperatures gathered at Peger Road.

The constant input requirements of the model consisted of the pavement surface albedo and emissivity, and the pavement structure's thermal properties including frozen and thawed thermal conductivity, frozen and thawed volumetric heat capacities, and the latent heat. In testing the model, a surface albedo of 0.15 and a surface emissivity of 0.9 were used. Thermal properties of the materials are given in Table 1. The final input requirements is the time step interval at which the model will recalculate the temperature regime in the structure. A value of 1/30 of an hour was selected based upon the thermal properties of the material and equation (6).

Time varying input to the model consists of average hourly air temperature ($^{\circ}\text{F}$), solar radiation (W/m^2), and average hourly wind speed (mph).

For comparison to the pavement temperatures collected at the Peger Road site, the depth for hourly pavement temperature output was selected as 1/8 in. The model determined this temperature by linearly interpolating between the temperatures calculated for node 1 (at the pavement surface) and node 2 (located 7/8 in from the top of the pavement).

In running a finite difference model such as this, initial temperatures must be assigned to nodes of the system. To do this, the model uses the first air temperature read from the data set and assigns this to the surface node of the column of elements. The last node in the column (node 100) is fixed at a temperature approximating groundwater temperature (34°F in the Fairbanks area). The initial temperatures of the intermediate nodes of the column are then linearly interpolated based upon these two temperatures. Using this technique, the model required five days of simulation time to reach equilibrium.

MODEL VERIFICATION

The period of simulation was determined by the length of the uninterrupted data collected at the Peger Road site. The three sets of continuous data varied from 51 to 237 days. Following the simulations using these data, the output for days having no cloud cover was extracted for comparison to the measured pavement temperature data. Determination of cloud cover was based upon the National Weather Service records taken at the Fairbanks International Airport. Of the 405 days simulated, 26 had no cloud cover.

Figure 4 gives the hourly mean values of measured air and pavement temperatures, wind speed and solar radiation, and the calculated pavement temperature from the model for days of the simulation having no cloud cover. Figures 5 and 6 give similar values for the days having the maximum and minimum diurnal variations in pavement temperatures.

Figures 7, 8 and 9 show the range and mean values of the environmental parameters used in the simulation.

In determining the ability of the model to predict pavement temperatures, the following calculation of error was used.

$$\text{error} = T_{\text{calc}} - T_{\text{meas}} \quad (14)$$

where T_{calc} is the pavement temperature calculated using the model and T_{meas} is the measured pavement temperature. Figure 10 shows the range and mean error by hour of the day, while Figure 11 shows the range and mean error by day of the year.

Figure 10 shows that the model is underpredicting pavement temperatures during periods having low or zero incoming solar radiation. This underprediction may be due to the model's overestimation of the nocturnal longwave energy losses from the pavement.

The overestimation by the model during daytime hours shown in Figure 10 is probably due to underprediction of energy losses due to convective cooling to the surface. Figure 9 shows that the mean wind speed for days having no cloud cover varied slightly throughout a diurnal period, with an average value of approximately 4 mph. The heat transferred by convection at such low wind speeds is minimal compared to the other energy transfer mechanisms, incoming solar radiation, conduction, and longwave radiant losses. Berg (1985) drew similar conclusions concerning the effect of naturally occurring winds on the heat transfer mechanism of a paved surface. Not considered by the model was the effect of traffic on the convective transfer process.

High concentrations of traffic will increase the turbulence in the air above the pavement, resulting in an increase of the convective heat losses when the air temperature is below that of the surface -- which, from observing the mean values in Figure 4, is true here. This is supported by the fact that the mean hourly pavement temperature follows the changes in air temperature, while the pavement temperatures calculated by the model are shifted from the air temperature and appear to be affected more by the solar radiation. Figure 12 shows the mean hourly error of the model compared to percentage of daily traffic volumes by hour. Traffic volumes were measured for one week from 3 June

1985 to 8 June 1985. Daily traffic volumes were approximately 5,000 vehicles per day. Figure 13 shows the mean error compared to mean values of hourly solar radiation.

CONCLUSIONS

The model should be useful in simulating diurnal pavement temperature fluctuations for analyzing changes in pavement strengths based upon temperature variations. In such analysis, the errors from the model's prediction of pavement temperature would become less significant as estimates are made of pavement modulus values and the resulting pavement strengths are calculated.

The model should better predict daytime pavement temperatures on a highway less traveled than the Peger Road test site. In such a situation, the turbulent effects of passing traffic would become minimal compared to the incoming solar radiation and turbulence due to wind. To improve the model's performance for city roads, it would be necessary to derive a traffic coefficient to be applied to the convective transfer portion of the model. This would require the measurement of the surface convective coefficient for a section of heavily traveled road and the correlation of these data with vehicular numbers, speeds and lengths of traffic passing over the section.

The calculation of the longwave radiation energy transfer in this model were made from surface and air temperature data. This was done to simplify the use of the model. Where improved estimates of pavement temperatures are required, using a more elaborate scheme of calculating longwave radiation may be warranted.

By altering the output derived from the model so that temperatures versus depths were given, it would be possible to monitor the progression of the freezing or thawing isotherm during the fall or spring. This would be useful for predicting when the road base will be thawed to such a depth as to warrant institution of vehicular load restriction. In such a case, two weeks of hypothetical data based upon historical data from previous years, and the actual weather conditions

previous to the period of time to be simulated would be constructed for use in the model.

Several such data sets could be designed to model a range of possible weather conditions. One data set could contain data showing an increase of air temperature above normal mean values for several weeks, while another could be used to model mean or below-mean temperatures. Using such a method, personnel charged with instituting load restrictions could estimate when restrictions will need to be applied.

Due to the nonavailability of short-term (hourly) data characterizing the surface energy balance and the subsurface thermal regime of a pavement structure in an arctic or subarctic environment, it was only possible to test the model's subsurface temperature prediction at a depth of 1/8 inch. The portion of my model that predicts subsurface temperatures is similar in design to that developed by Straub et al. (1968). That model was tested and proven using surface and subsurface temperature data collected in a temperate climate.

To conclusively test the reliability of using my model to estimate subsurface temperatures at a depth other than 1/8 inch, it will be necessary to collect further data. These data would include hourly temperature data at several points within a pavement and through a road's base and subbase materials, as well as incoming shortwave radiation, wind speed and air temperature.

REFERENCES

- Barber, E.S. 1957. Calculation of maximum pavement temperatures from weather report. HRB Bulletin 168. 8 pp.
- Berg, R.L. 1985. Effect of color and texture on the surface temperature of asphalt concrete pavements. Alaska Department of Transportation and Public Facilities, Fairbanks. Research Report 86-04. 69 pp.

Goodrich, L.E. 1974. A one-dimensional numerical model for geothermal problems. Division of Building Research, National Research Council of Canada, Ottawa, Ontario. Technical Paper 421. 22 pp.

Hildebrand, E.E., and R. Haas. 1983. Ground temperature and thaw settlement model for highway design in permafrost areas. Paper presented to the 23rd Annual Meeting of the Roads and Transportation Association of Canada, Edmonton, Alberta. 22 pp.

Idso, S.B., and R.D. Jackson. 1969. Thermal radiation from the atmosphere. Journal of Geophysical Research. 74(23):5397-5403.

Rumney, T.N., and R.A. Jimenez. 1971. Pavement temperatures in the southwest. Highway Research Record. 361:1-13.

Straub, A.L., H.L. Schenck, Jr., and F.E. Przybycien. 1968. Bituminous pavement temperature related to climate. Highway Research Record. 256:53-77.

APPENDIX

This appendix contains a brief description of how to use the model Pavetemp and provides a listing of the program codes for the model written in FORTRAN and BASIC.

Two input data files are required for both the FORTRAN and BASIC versions of the model. The first file contains the constants used in the model. These are input in free field format on the one record of the data file as follows.

SA SE AK1 AKF2 AKU2 C1 CF2 CU2 XLAT2 TIME OUID

where

SA = albedo of surface
SE = emissivity of surface
AK1 = thermal conductivity of pavement (Btu/ft-hr-°F)
AKF2 = frozen conductivity of base course (Btu/ft-hr-°F)
AKU2 = thawed conductivity of base course (Btu/ft-hr-°F)
C1 = volumetric specific heat of pavement (Btu/ft³-°F)
CF2 = frozen vol. specific heat of base course (Btu/ft³-°F)
CU2 = thawed vol. specific heat of base course (Btu/ft³-°F)
XLAT2 = latent heat of base course material (Btu/ft³)
TIME = number of time steps per hour of simulation time
OUID = depth at which calculated temperatures are output (ft).

The second data file contains the hourly environmental data in free field format, one hour of data per record.

DECD TA WS QS

where

DECD = any real number for output reference by the user
TA = ambient air temperature (°F)
WS = wind speed (mph)
QS = shortwave radiation (W/m²).

Output from the model consists of the variable DECD and the pavement temperature at user-specified depth OUID for each hour of simulation time.

The FORTRAN version of the program reads the data file containing the constants from input unit 05. The time varying input is read from unit 07. Output is written to unit 06. On the Alaska Department of Administration's IBM VM/370 computer system, an EXEC file exists for operating the program in this manner. If the program is to be used on another computer system, the user must insure that the program has access to the input and output units as specified above.

The BASIC program prompts the user to input the name of the files containing the constant and time varying data. An output file having the same file name as the time varying input data file with an extension of ".OUT" is created by the program. An example of this would be if the time varying input data file had a file specification of HOUR.DAT, the output file would be HOUR.OUT.

When using the BASIC version on a microcomputer, it will be necessary to compile the program to speed up computation. It is preferable to compile the program to make use of an 8087 math coprocessor. Use of the math coprocessor will increase computational speed drastically over the uncompiled BASIC version. This would allow using the program on a microcomputer for modeling short periods of time, such as several weeks.

Table 1. Material Properties

Material	Pavement	Base
Frozen thermal conductivity (Btu/ft·hr·F°)	---	2.0
Thawed thermal conductivity (Btu/ft·hr·F°)	.86	1.9
Frozen heat capacity (Btu/ft ³ ·F°)	---	28.0
Thawed heat capacity (Btu/ft ³ ·F°)	28.0	32.2
Latent heat (Btu/ft ³)	0.0	1210
Dry density (lb/ft ³)	145	140
Moisture content (percentage)	0.0	6.0

NODES USED IN THE FINITE DIFFERENCE MODEL

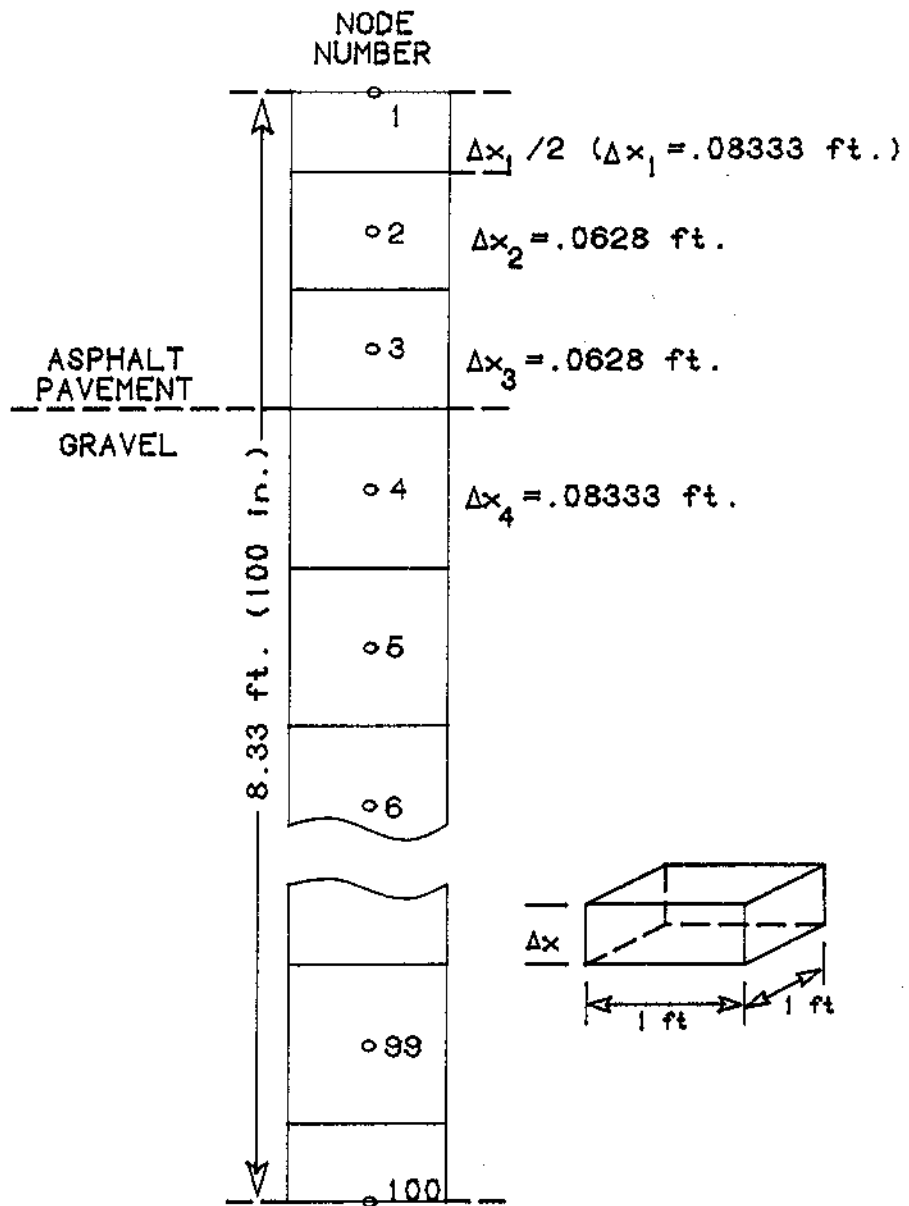


FIGURE 1

ATMOSPHERIC EMISSIVITY (E_a) VS. AIR TEMPERATURE

AFTER EDSO AND JACKSON (1969)

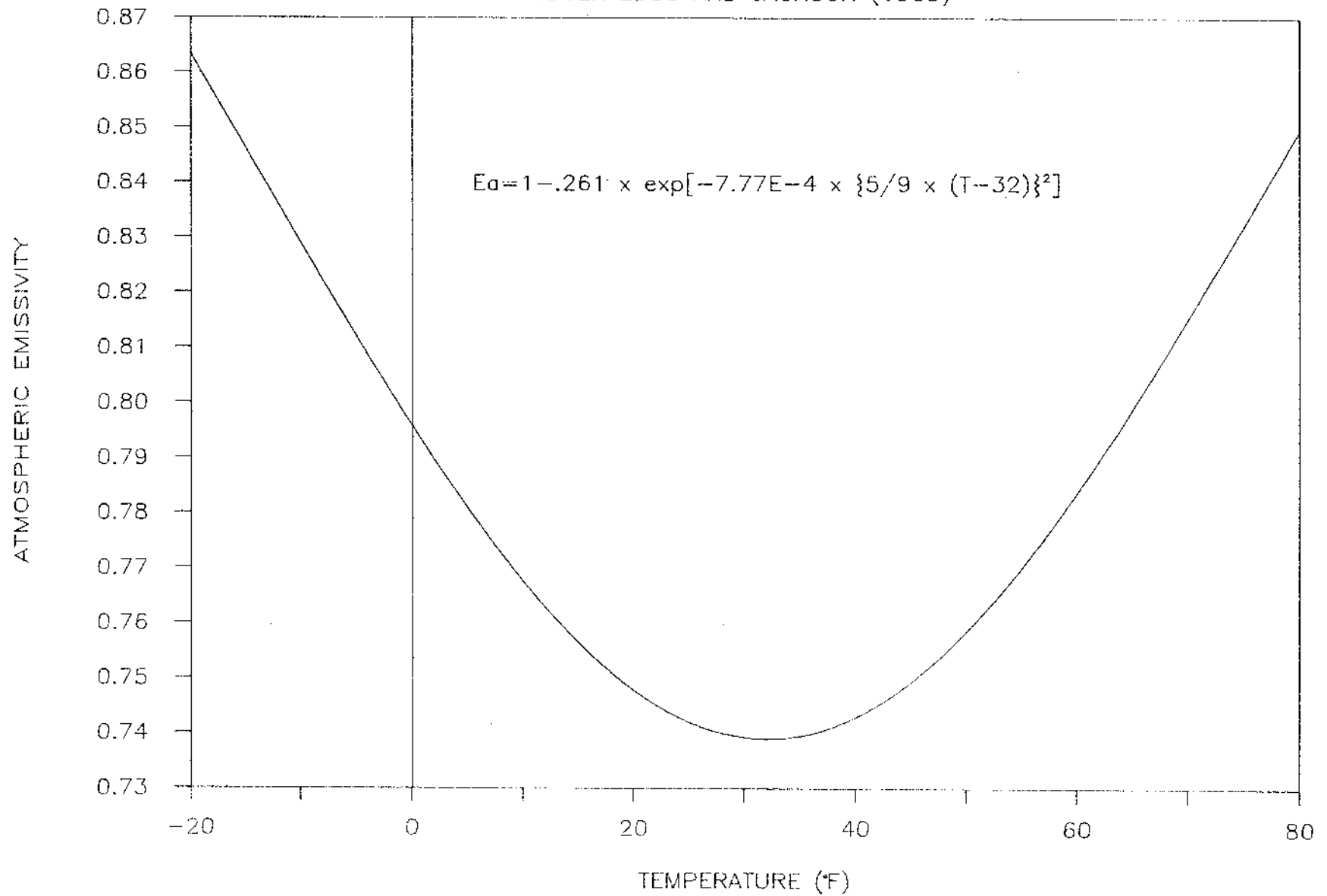


FIGURE 2

PEGER ROAD TEST SITE (AFTER BERG, 1983)

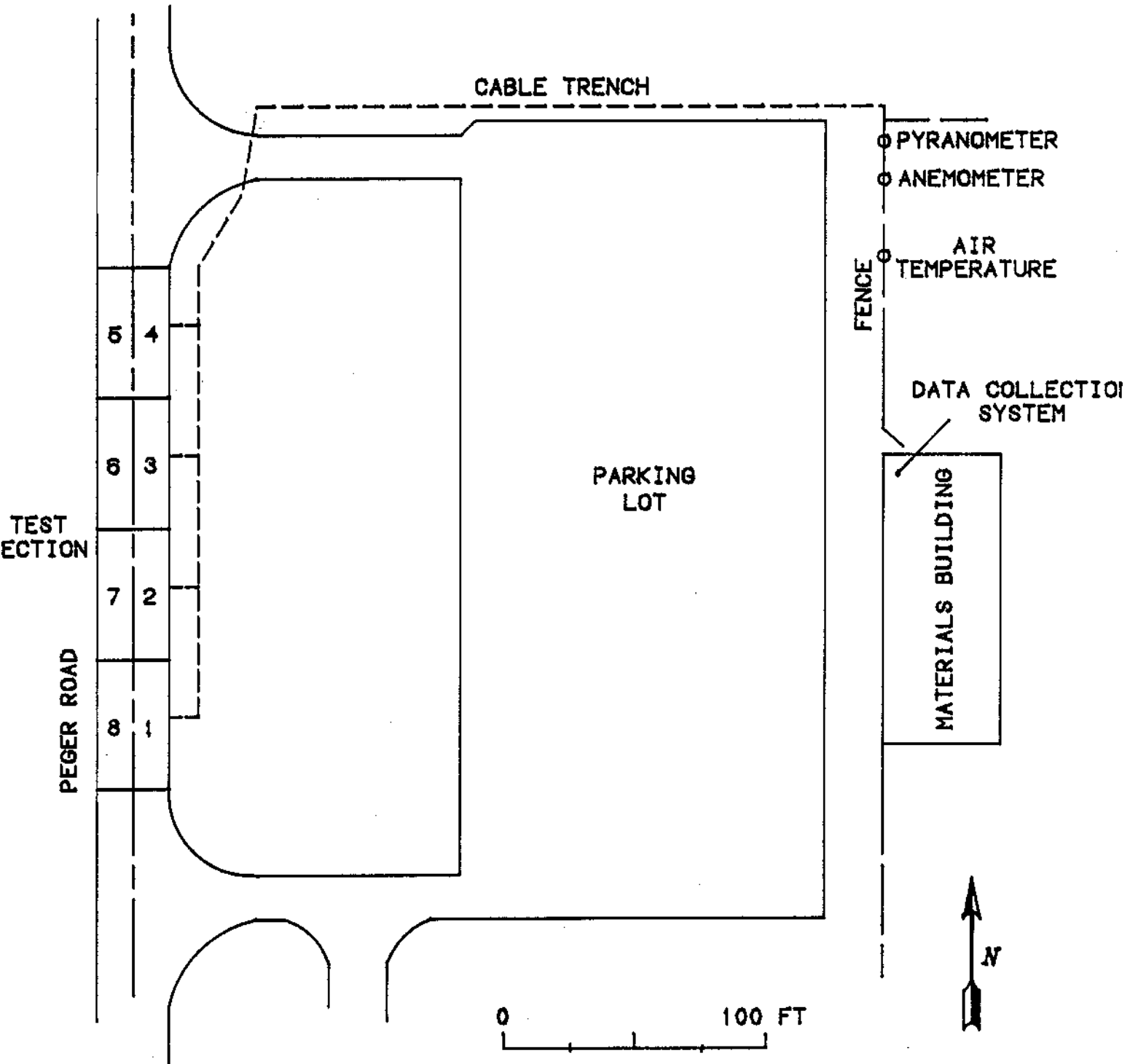
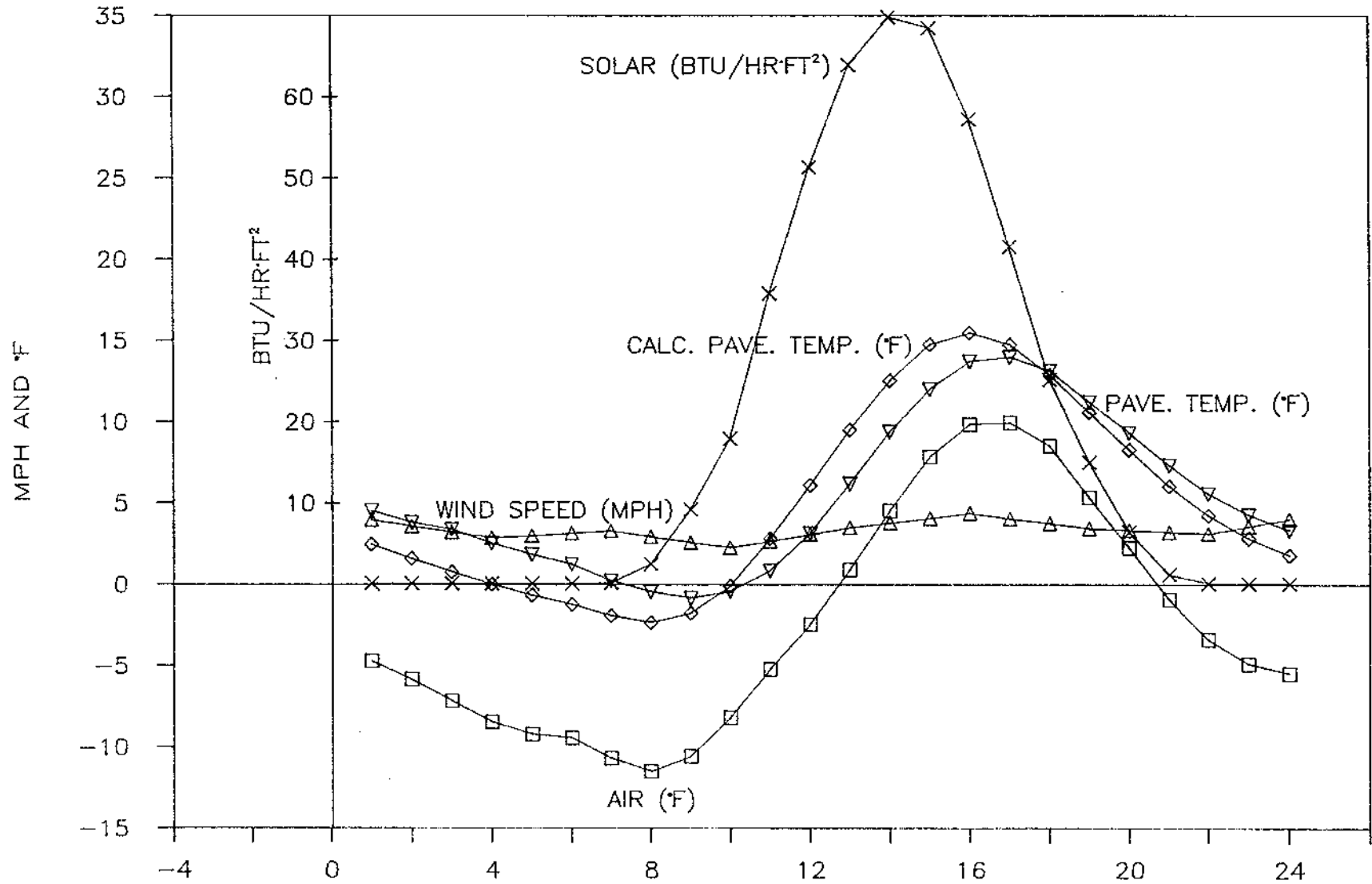


FIGURE 3

HOURLY MEAN VALUES

DAYS WITH ZERO CLOUD COVER

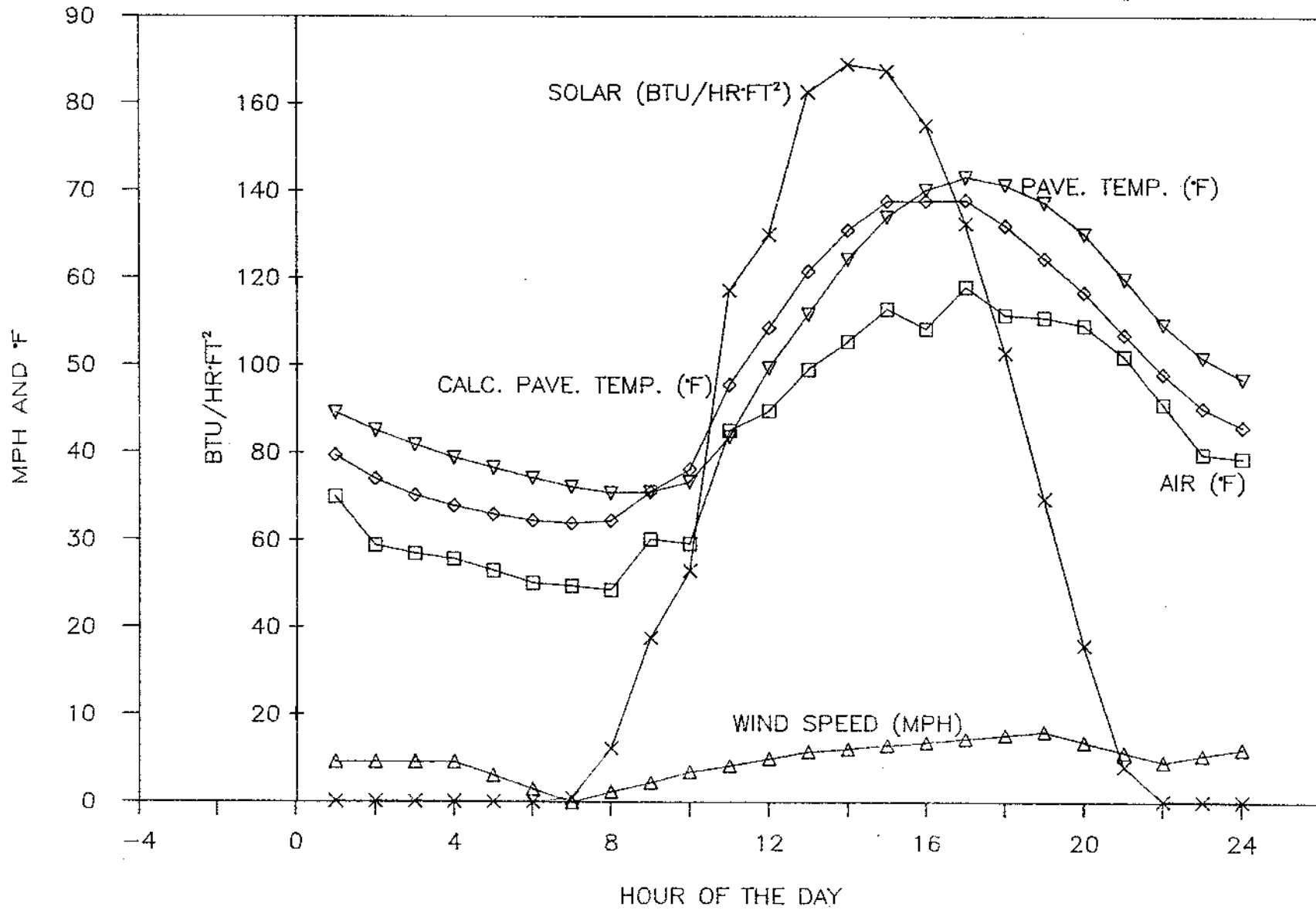


HOUR OF THE DAY

FIGURE 4

SEPTEMBER 2, 1984

DAY WITH MAXIMUM DIURNAL VARIATION IN PAVEMENT TEMPERATURES



HOUR OF THE DAY
FIGURE 5

DECEMBER 14, 1984

DAY WITH MINIMUM DIURNAL VARIATION IN PAVEMENT TEMPERATURES

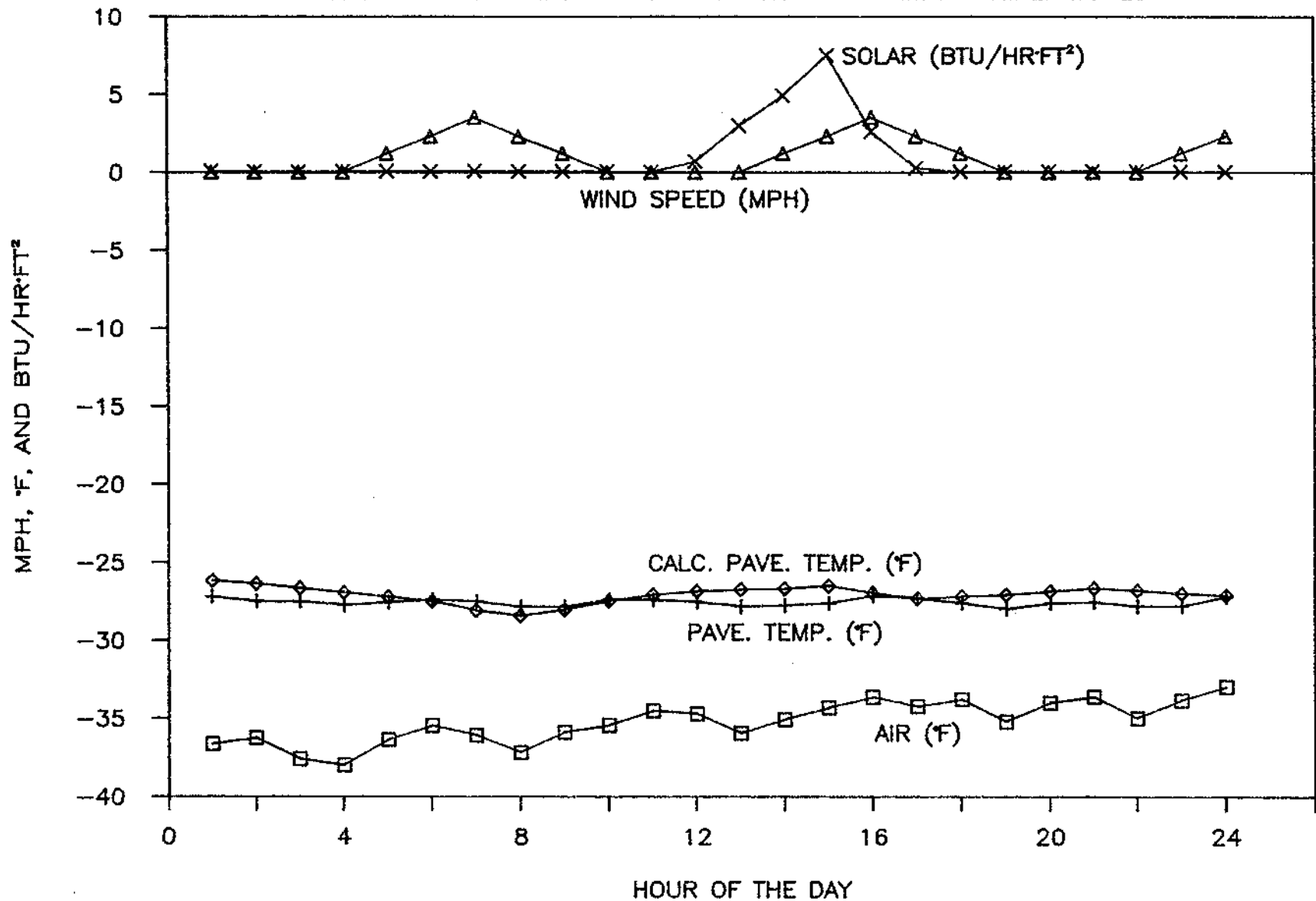
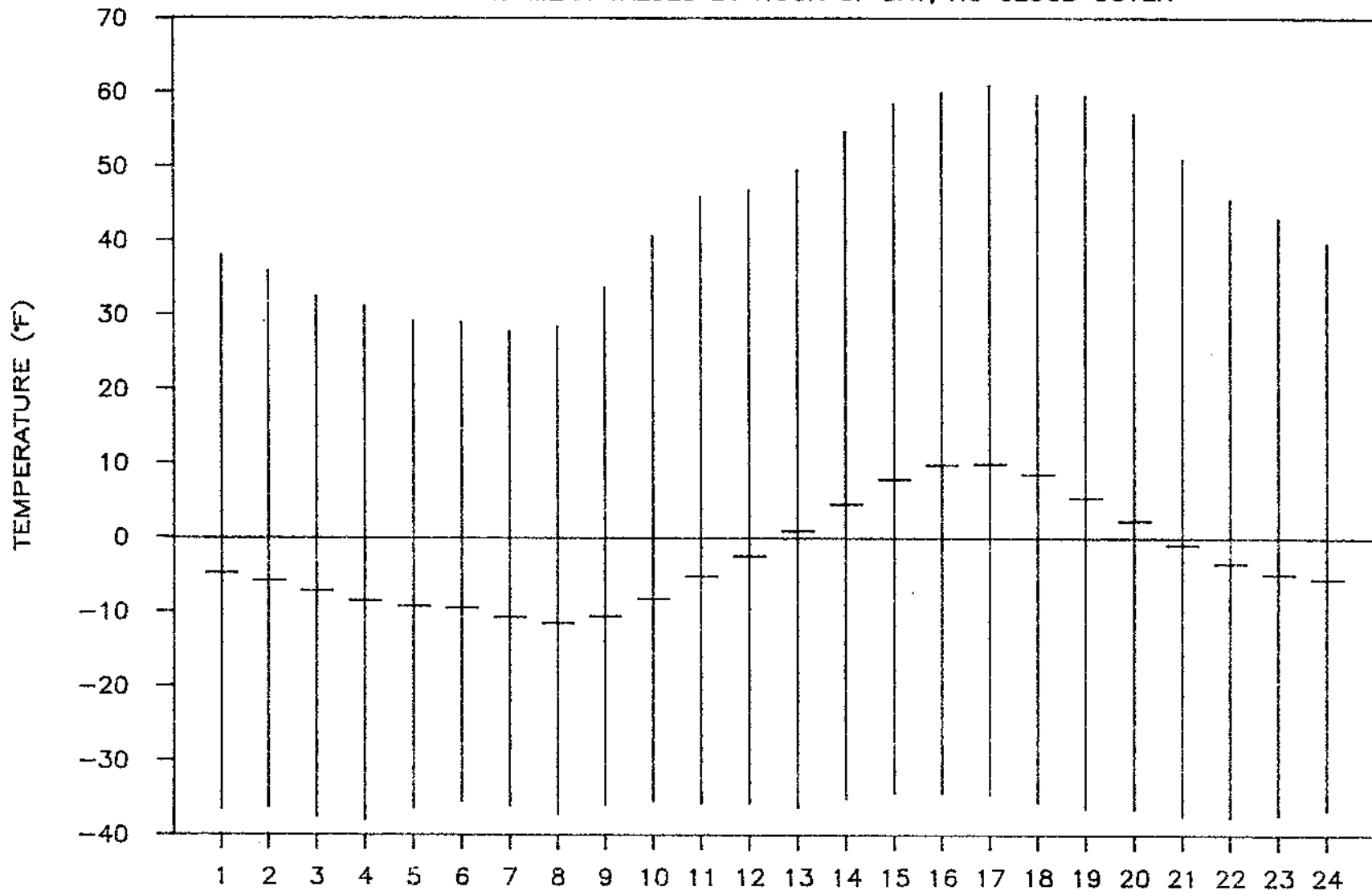


FIGURE 6

AIR TEMPERATURE

RANGE AND MEAN VALUES BY HOUR OF DAY, NO CLOUD COVER

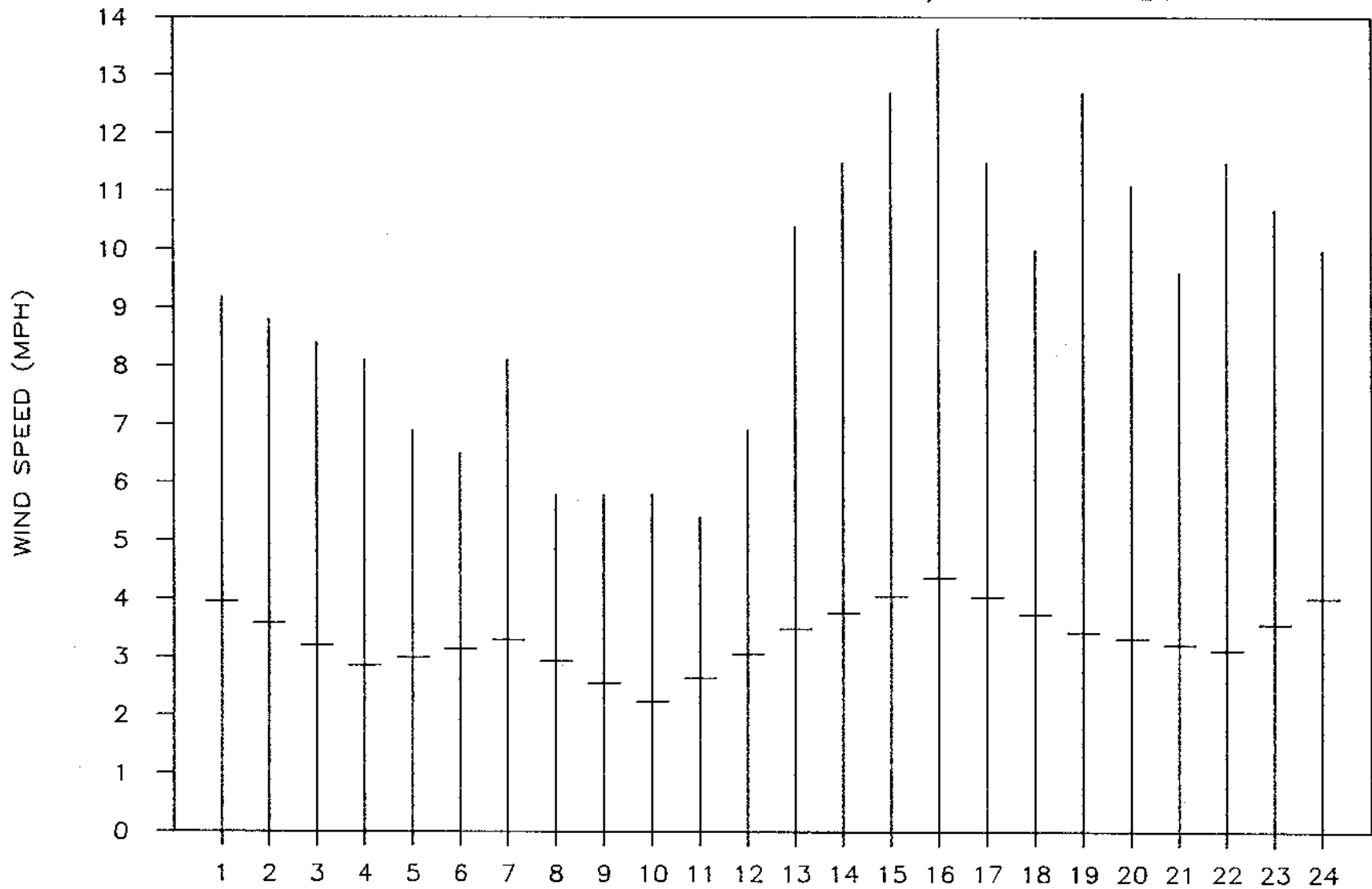


HOUR OF THE DAY

FIGURE 7

WIND SPEED

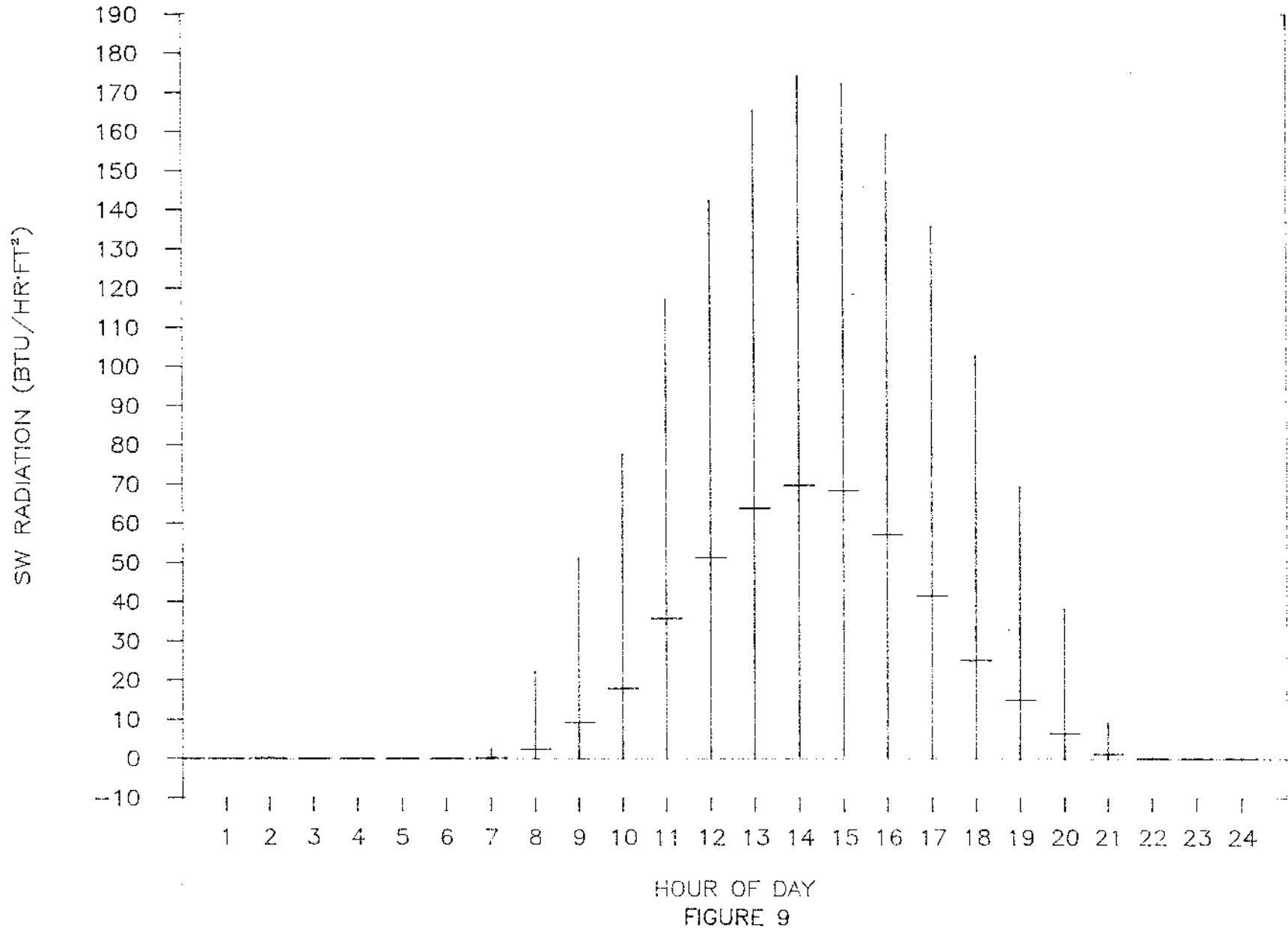
RANGE AND MEAN VALUES BY HOUR OF DAY, NO CLOUD COVER



HOUR OF DAY
FIGURE 8

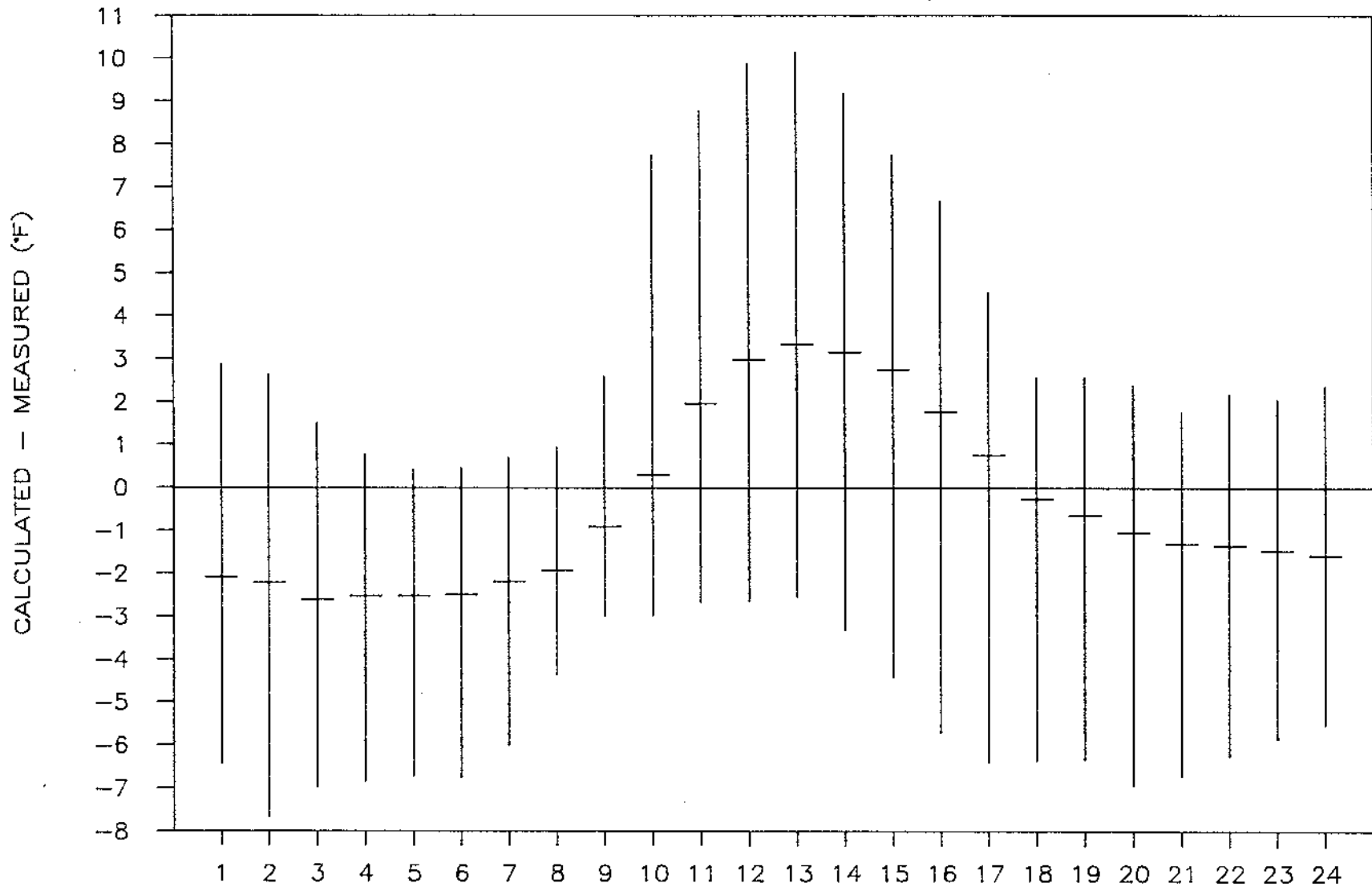
SHORT WAVE RADIATION

RANGE AND MEAN VALUES BY HOUR OF DAY, NO CLOUD COVER



CALCULATED - MEASURED PAVEMENT TEMPERATURES

RANGE AND MEAN VALUES BY HOUR OF DAY, NO CLOUD COVER

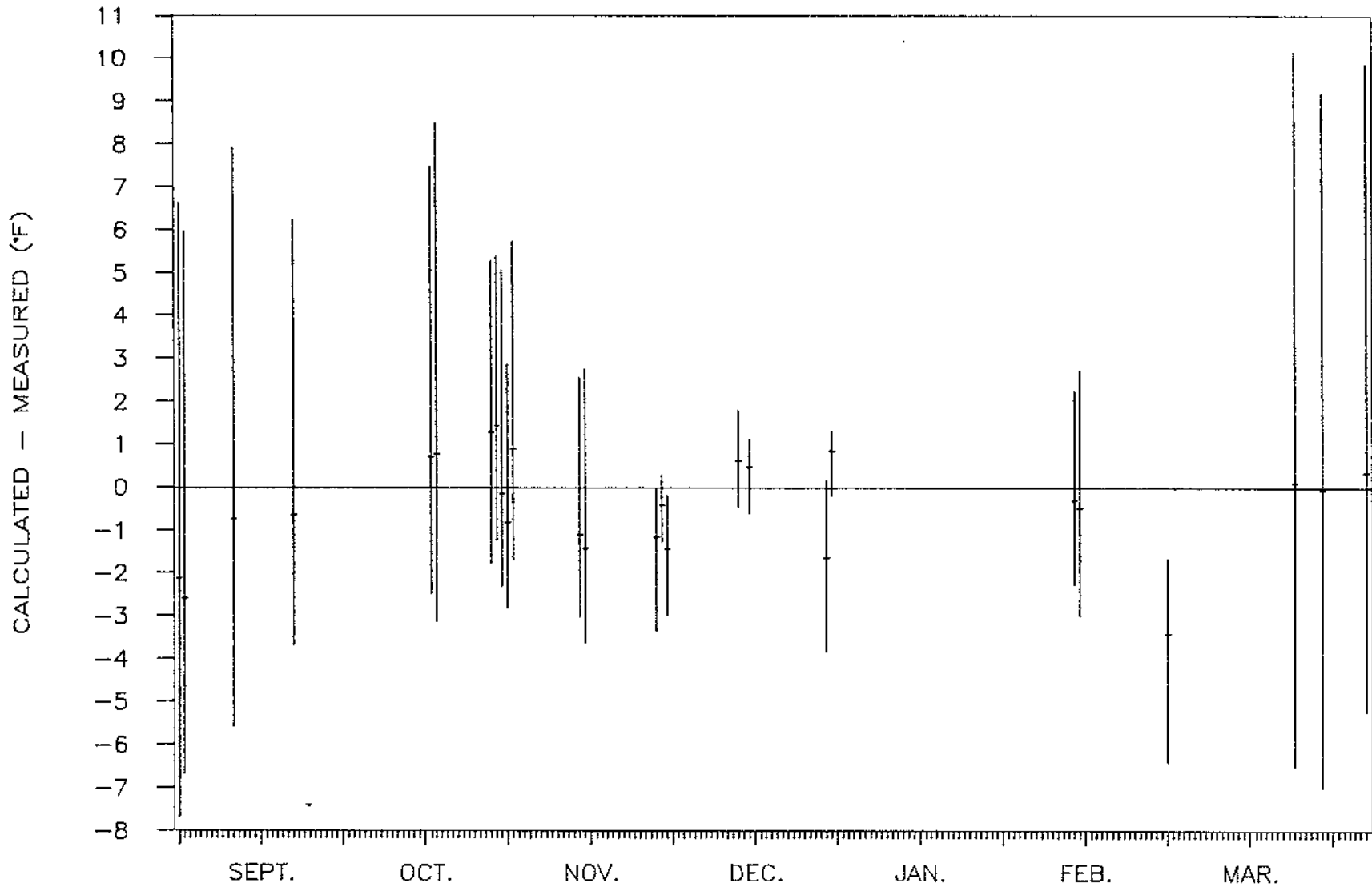


HOUR OF DAY

FIGURE 10

CALCULATED - MEASURED PAVEMENT TEMPERATURES

RANGE AND MEAN VALUE FOR ZERO CLOUD COVER DAYS



1984

FIGURE 11

1985

HOURLY MEAN ERROR AND PERCENTAGE OF DAILY TRAFFIC

FOR ZERO CLOUD COVER DAYS

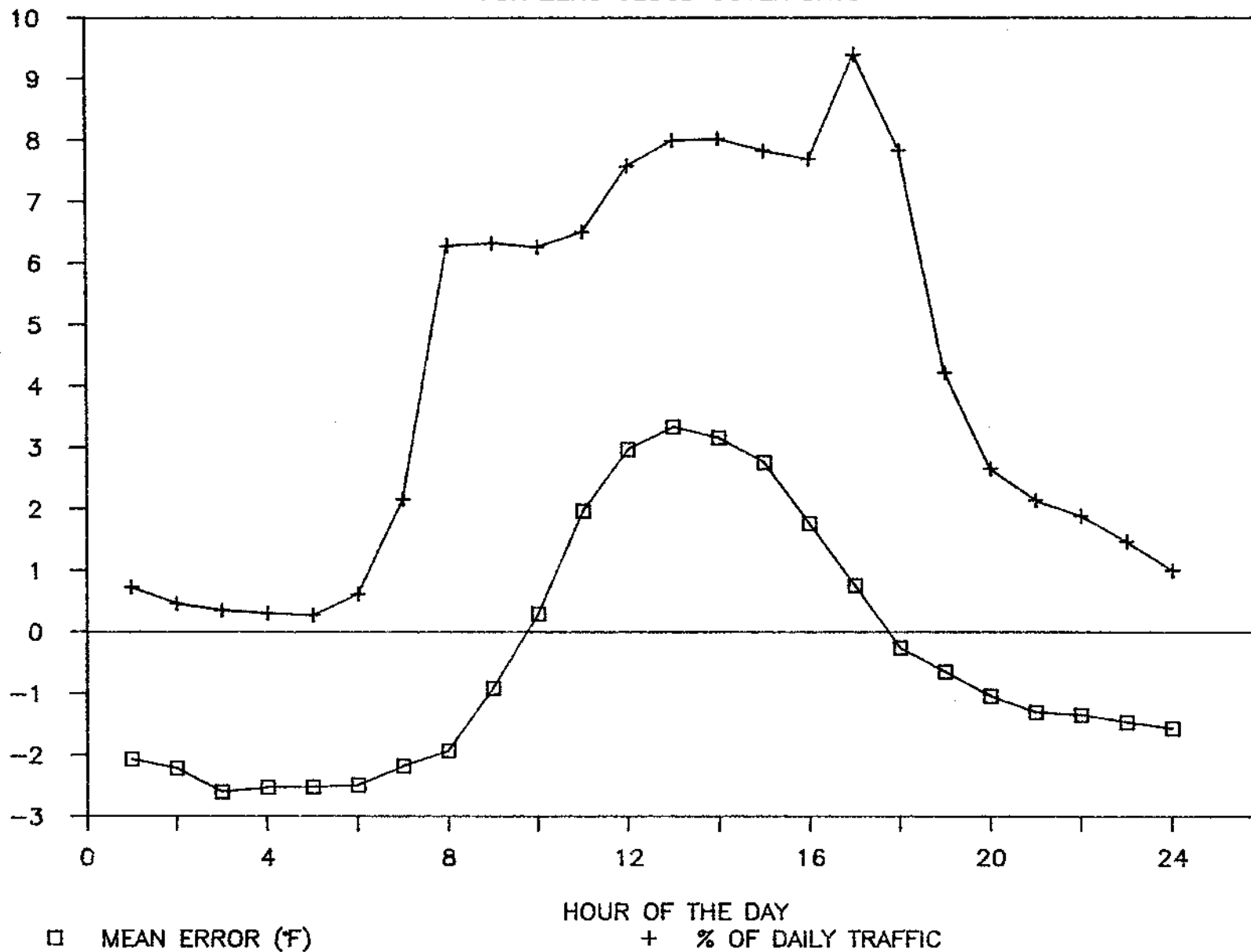


FIGURE 12

HOURLY MEAN ERROR AND PERCENTAGE OF DAILY SOLAR ENERGY

FOR ZERO CLOUD COVER DAYS

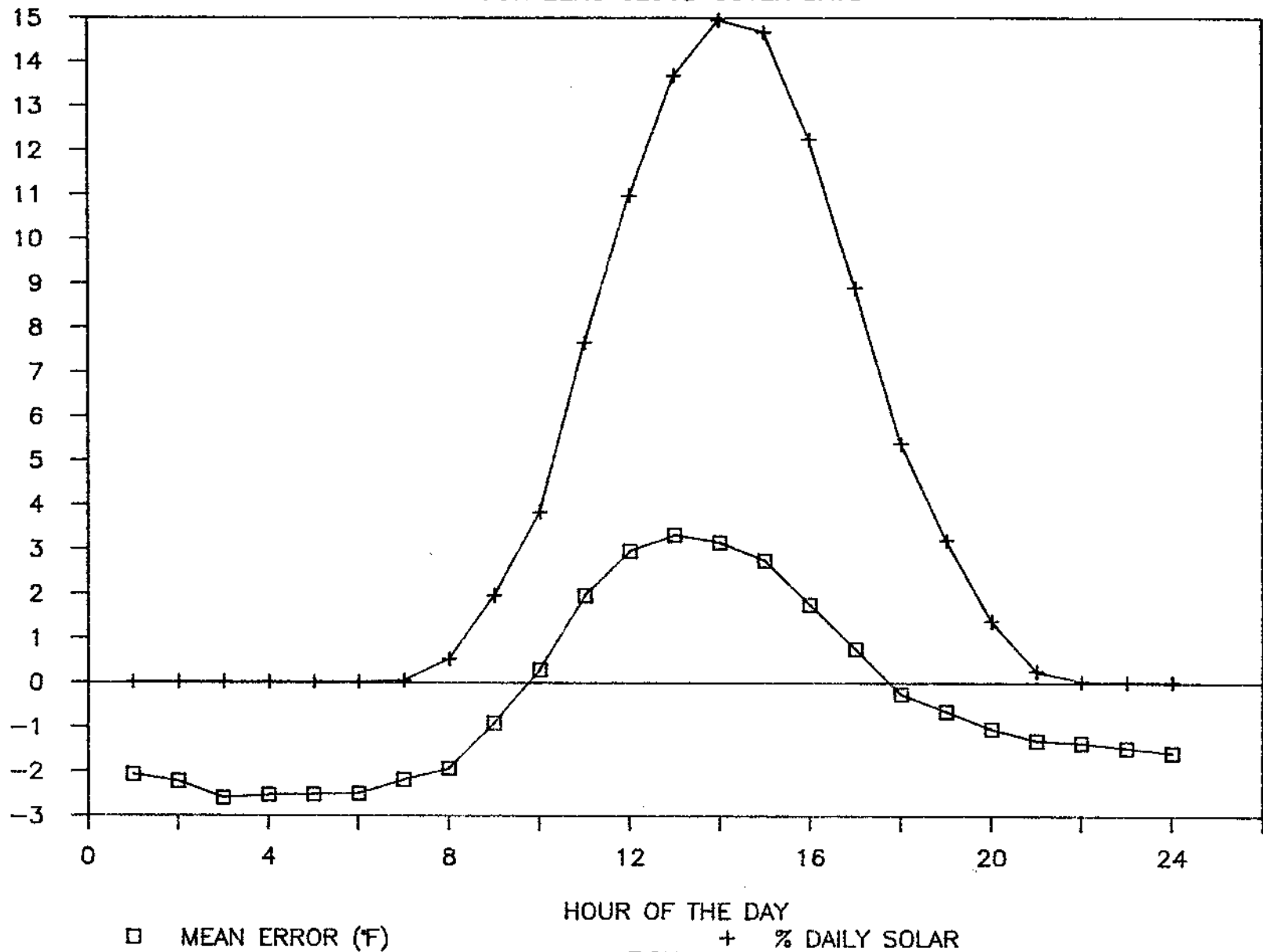


FIGURE 13

```

C*****
C
C   PAVETEMP
C
C   A FINITE DIFFERENCE MODEL FOR CALCULATING DIURNAL CHANGES
C   IN ASPHALTIC CONCRETE PAVEMENTS BASED UPON ENVIRONMENTAL PARAMETERS
C
C*****
C
C   WRITTEN FOR STATE OF ALASKA DEPARTMENT OF TRANSPORTATION AND
C   PUBLIC FACILITIES DIVISION OF PLANNING RESEARCH SECTION
C
C   W. ALAN BRALEY  9/9/85   MODIFIED 5/21/86
C
C*****
C INPUT VARIABLES
C UNIT 07
C SA - ALBEDO OF SURFACE
C SE - SURFACE EMMISIVITY
C AK1 - PAVEMENT CONDUCTIVITY (BTU/FT2-HR-F)
C AKF2 - FROZEN CONDUCTIVITY OF BASE MATERIAL (BTU/FT2-HR-F)
C AKU2 - THAWED CONDUCTIVITY OF BASE MATERIAL (BTU/FT2-HR-F)
C C1 - VOLUMETRIC HEAT CAPACITY OF PAVEMENT (BTU/FT3-F)
C CF2 - FROZEN VOLUMETRIC HEAT CAPACITY OF PAVEMENT (BTU/FT3-F)
C CU2 - THAWED VOLUMETRIC HEAT CAPACITY OF PAVEMENT (BTU/FT3-F)
C XLAT2 - LATENT HEAT OF BASE MATERIAL (BTU/FT3)
C TIME - # OF TIME STEPS PER HOUR
C OUTD - DEPTH FOR WHICH TEMPS. ARE TO BE OUTPUT (FT)
C
C UNIT 05
C
C NDH=1, # OF HOURS SIMULATED
C DECD(NDH) - NUMBER INDICATING HOUR OF SIMULATION (USED FOR OUTPUT)
C TA(NDH) - AVERAGE TEMPERATURE FOR HOUR (DEGREE F)
C WS(NDH) - AVERAGE WINDSPEED FOR HOUR (MPH)
C QS(NDH) - INCIDENT SHORTWAVE ENERGY FOR HOUR (W/M2)
C
C INTERNAL VARIABLES
C
C I=1,100, J=1,2
C DX(I) - THICKNES OF NODE I (FT)
C R(I) - RESISTANCE OF NODE I
C H(I,J) - ENTHALPY OF NODE I FOR TIME STEP J (J=1 PREVIOUS STEP,
C          J=2 CURRENT STEP)
C T(I,J) - TEMPERATURE OF NODE I FOR TIME STEP J
C
C STA - USED IN INTERPOLATION OF AIR TEMPERATURE BETWEEN HOURS
C SQS - " " " " SHORT WAVE RADIATION " "
C SWS - " " " " WIND SPEED " "
C
C TDEEP - DEEP GROUND TEMPERATURE
C SIG - STEPHEN-BOLTZ CONSTANT
C HW - CONVECTIVE COEFFICIENT, BASED UPON WIND SPEED
C
C*****

```

DIMENSION T(100, 2), AKF(100), AKU(100), CF(100), CU(100), XLAT(100),
+QS(6000), DECD(6000), TA(6000), WS(6000), H(100, 2), XK(100),
+R(100), DX(100)

C

TDEEP=34

SIG=1.714E-09

C READ ALBEDO, SURF EMISS, PAVE K, SOIL K FROZ, SOIL K UNFROZ, CAP PAVE
C SOIL CAP FROZ, SOIL CAP UNFORZ, LATENT HEAT SOIL, #TIME STEPS/HOUR
C AND DEPTH AT FOR WHICH OUTPUT IS TO BE GIVEN

READ(07, *) SA, SE, AK1, AKF2, AKU2, C1, CF2, CU2, XLAT2, TIME

WRITE(06, 78) SA, SE, AK1, AKF2, AKU2, C1, CF2, CU2, XLAT2, TIME

DT=1/TIME

ITIME = TIME

DO 150 I=1, 3

AKU(I)=AK1

AKF(I)=AK1

CU(I)=C1

CF(I)=C1

XLAT(I)=0

150 CONTINUE

DO 180 I=4, 100

AKU(I)=AKU2

AKF(I)=AKF2

CU(I)=CU2

CF(I)=CF2

XLAT(I)=XLAT2

180 CONTINUE

NDH=1

666 READ(05, *, END=777) DECD(NDH), TA(NDH), WS(NDH), QS(NDH)

NDH=NDH+1

GO TO 666

777 NDH=NDH-1

TDEP = 0

DMULT = 0

DO 111 I = 1, 100

DX(I) = .083333

IF((I.EQ.2).OR.(I.EQ.3)) DX(I) = .75*DX(I)

T(I, 1) = ((TDEEP-TA(1))/99)*(I-1)+TA(1)

IF((I.EQ.1).OR.(DMULT.GT.0)) GO TO 111

DADD = DX(I-1)/2 + DX(I)/2

TDEP = TDEP + DADD

IF(TDEP.LE.OUTD) GOTO 111

IOUT1 = I-1

IOUT2 = I

DMULT = -(TDEP - DADD - OUTD)/(DADD)

111 CONTINUE

DO 250 I = 1, 3

H(I, 1) = (T(I, 1) - 32) * CU(I)

250 CONTINUE

DO 251 I=4, 100

IF(T(I, 1).LE.32) H(I, 1) = (T(I, 1) - 32) * CF(I)

IF(T(I, 1).GT.32) H(I, 1) = (T(I, 1) - 32) * CU(I) + XLAT(I)

251 CONTINUE

```

DO 471 J=1, NDH-1
STA=(TA(J+1)-TA(J))/ITIME
SQS=(QS(J+1)-QS(J))/ITIME
SWS=(WS(J+1)-WS(J))/ITIME
DO 470 I=1, ITIME
QSS=QS(J)+SQS*(I-1)
TSS=TA(J)+STA*(I-1)
WSS=WS(J)+SWS*(I-1)
C CALCULATE CONVECTIVE COEFFICIENT
HW=1+.3*WSS
C CALCULATE ATMOSPHERIC EMISSIVITY
EMA=1-.261*EXP(-7.77E-4*(5/9*(TSS-32))**2)
C CONVERT SOLAR RADIATION TO BTU/FT^2-HR
QSS=QSS/3.155
C CALCULATE ENTHALPY AND TEMPERATURE FOR SURFACE NODE
R(1)=DX(1)/(2*AKU(1))
R(2)=DX(2)/(2*AKU(2))
H(1,2)=H(1,1)+2*DT/DX(1)*(HW*(TSS-T(1,1))+SIG*(EMA*(TSS+460)**4-
&SE*(T(1,1)+460)**4)+QSS*(1-SA)+((T(2,1)-T(1,1))/(R(1)+R(2))))
T(1,2)=32+(H(1,2)/CU(1))
C PASS FIXED BOTTOM TEMPERATURE TO NEXT TIME STEP
T(100,2)=T(100,1)
H(100,2)=H(100,1)
C
C CALCULATE ENTHALPY AND TEMP FOR NODES 2-99
C IF ENTHALPY>0 AND <LATENT HEAT THEN SET TEMP TO 32
C
DO 500 N=2,99
IF(T(N+1,1).LE.32) XK(N+1)=AKF(N+1)
IF(T(N+1,1).GT.32) XK(N+1)=AKU(N+1)
R(N+1)=(.5*DX(N+1))/XK(N+1)
H(N,2)=H(N,1)+(DT/DX(N))*((T(N+1,1)-T(N,1))/(R(N+1)+R(N))+
&(T(N-1,1)-T(N,1))/(R(N-1)+R(N)))
C FIND TEMPERATURE BASED UPON ENTHALPY
IF((H(N,2).GE.0).AND.(H(N,2).LE.XLAT(N))) T(N,2)=32
IF(H(N,2).GT.XLAT(N)) T(N,2)=32+(H(N,2)-XLAT(N))/CU(N)
IF(H(N,2).LT.0) T(N,2)=32+(H(N,2)/CF(N))
500 CONTINUE
C PASS TEMPERATURES AND ENTHALPIES FOR NEXT TIME STEP
DO 443 K = 1,100
T(K,1)=T(K,2)
443 H(K,1)=H(K,2)
470 CONTINUE
C INTERPOLATE TEMPERATURE AT DEPTH OUTD
TOUT=T(IOUT1,1)-(DMULT*(T(IOUT1,1)-T(IOUT2,1)))
C OUTPUT FOR CURRENT HOUR
WRITE(6,66)DECD(J+1),TOUT
471 CONTINUE
66 FORMAT (2F7.2)
78 FORMAT (10F7.2,F10.5)
STOP
END

```



```

510     XLAT(I)=0
520 NEXT I
530 FOR I = 4 TO 100
540     AKU(I)=AKU2
550     AKF(I)=AKF2
560     CU(I)=CU2
570     CF(I)=CF2
580     XLAT(I)=XLAT2
590 NEXT I
600     INPUT #2, DECD(1), TA(1), WS(1), QS(1)
610     TDEP = 0
620     DMULT = 0
630     FOR I = 1 TO 100
640         DX(I)=.083333
650         IF I = 2 OR I = 3 THEN DX(I)=.75*DX(I)
660         T(I,1)=((TDEEP-TA(1))/99)*(I-1)+TA(1)
670         IF (I = 1) OR (DMULT <> 0) THEN 740
680             DADD = DX(I-1)/2 + DX(I)/2
690             TDEP = TDEP + DADD
700             IF TDEP <= OUTD THEN 740
710             IOUT1 = I-1
720             IOUT2 = I
730             DMULT = -(TDEP-DADD-OUTD)/(DADD)
740     NEXT I
750     FOR I = 1 TO 3
760         H(I,1)=(T(I,1)-32)*CU(I)
770     NEXT I
780     FOR I = 4 TO 100
790         IF T(I,1) <= 32 THEN H(I,1)=(T(I,1)-32)*CF(I)
800         IF T(I,1) > 32 THEN H(I,1)=(T(I,1)-32)*CU(I)+XLAT(I)
810     NEXT I
820     WHILE NOT EOF(2)
830         INPUT #2, DECD(2), TA(2), WS(2), QS(2)
840         PRINT "DECIMAL DAY "; DECD(2)
850         STA=(TA(2)-TA(1))/30!
860         SQS=(QS(2)-QS(1))/30!
870         SWS=(WS(2)-WS(1))/30!
880         FOR I = 1 TO 30
890             QSS=QS(1)+SQS*(I-1)
900             TSS=TA(1)+STA*(I-1)
910             WSS=WS(1)+SWS*(I-1)
920             HW=1+.3*WSS
930             EMA=1-.261*EXP(-.000777*(5/9*(TSS-32))^2)
940             QSS=QSS/3.155
950 '
960 ' CALCULATE ENTHALPY FOR SURFACE NODE
970 '
980     R(1)=DX(1)/(2*AKU(1))
990     R(2)=DX(2)/(2*AKU(2))
1000     H(1,2)=H(1,1)+2*DT/DX(1)*(HW*(TSS-T(1,1))+SIG*(EMA*(TSS+460)^4
        -SE*(T(1,1)+460)^4)+QSS*(1-SA)+((T(2,1)-T(1,1))/(R(1)+R(2)))
1010     T(1,2)=32+(H(1,2)/CU(1))
1020     T(100,2)=T(100,1)
1030     H(100,2)=H(100,1)

```

```

1040 '
1050 ' CALCULATE ENTHALPY AND TEMP FOR NODES 2-99
1060 ' IF ENTHALPY>0 AND <LATENT HEAT THEN SET TEMP TO 32
1070 ' TEMP FOR THIS NODE IS INTERPOLATED BELOW
1080 '
1090 FOR N = 2 TO 99
1100     IF T(N+1, 1) <= 32 THEN XK(N+1)=AKF(N+1)
1110     IF T(N+1, 1) > 32 THEN XK(N+1)=AKU(N+1)
1120     R(N+1)=(.5*DX(N+1))/XK(N+1)
1130     H(N, 2)=H(N, 1)+(DT/DX(N))*((T(N+1, 1)-T(N, 1))/(R(N+1)+R(N))+(T(N-1, 1)
        T(N, 1))/(R(N-1)+R(N)))
1140 ' FIND TEMPERATURE BASED UPON ENTHALPY
1150     IF H(N, 2) >= 0 AND H(N, 2) <= XLAT(N) THEN T(N, 2)=32
1160     IF H(N, 2) > XLAT(N) THEN T(N, 2)=32+(H(N, 2)-XLAT(N))/CU(N)
1170     IF H(N, 2) < 0 THEN T(N, 2)=32+(H(N, 2)/CF(N))
1180 NEXT N
1190 '
1200 FOR K = 1 TO 100
1210     T(K, 1)=T(K, 2)
1220     H(K, 1)=H(K, 2)
1230     TA(1)=TA(2)
1240     WS(1)=WS(2)
1250     QS(1)=QS(2)
1260     DECD(1)=DECD(2)
1270 NEXT K
1280 NEXT I
1290 TOUT = T(IOUT1, 1)-(DMULT*(T(IOUT1, 1)-T(IOUT2, 1)))
1300 PRINT #3, USING "###.## ###.## "; DECD(2), TOUT
1310 WEND
1320 END

```