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NYTEMP User's Manual: A Pavement Temperature Model

HONG-JER CHEN

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STATE OF NEW YORK

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NYTEMP USER'S MANUAL:
A PAVEMENT TEMPERATURE MODEL

Hong-Jer Chen, Civil Engineer I

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16. Abstract

This report is a user's manual for the computer program NYTEMP, which was developed to model temperature distribution within pavement layers. The program includes two models: surface and air. The surface model is used to predict pavement temperatures when hourly pavement surface temperatures are known, and the air model when hourly air temperatures and solar radiation are known. Chapter I discusses NYTEMP input requirements, background, possible applications, and computer equipment requirements. Chapters II and III show how to use the program, from installation, inputting data, and running, to printing and plotting results. In Appendix A, two materials properties required by the program -- thermal conductivity and diffusivity -- are briefly defined and discussed, and some of their common values for pavement materials are provided. Appendix B deals with solar radiation, describing its nature, terminologies, types, units, and relationships between extraterrestrial and global radiation, as well as some available sources for solar radiation information and general weather data pertinent to using NYTEMP.

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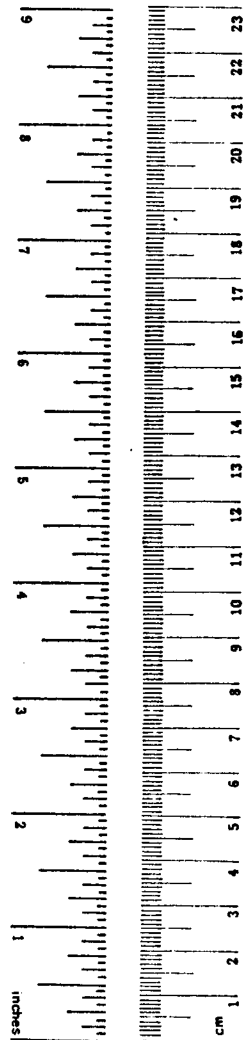
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

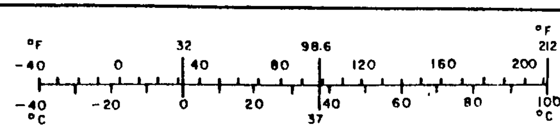
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

I. INTRODUCTION

A. The Program

NYTEMP is a computer program calculating temperature distribution within a pavement system for a certain time period. The mathematical model used is a finite difference solution of a one-dimensional heat-conduction equation. This model for predicting temperatures beneath pavements was presented by various researchers in the 1970s. Its merits, as outlined by Dempsey (1) and Wilson (2), were considered in developing the NYTEMP model. Written in Turbo Pascal language (v.4.0), it is user-friendly with an accuracy of ± 10 percent as compared to field-measured temperatures.

The program was developed as part of Research Project 188-01 ("Overlays on Faulted Concrete Pavements"). A temperature study was included to meet the client's interest in pavement blowups. Pavement temperature data were collected from 1987 to 1990 at two locations on I 87 and Rte 29, both in Saratoga County. Measured temperature data were used to verify the NYTEMP program during its development.

B. Its Applications

Temperature is a key factor in pavement engineering. Rigidity of asphalt concrete depends greatly on temperature, and temperature changes also cause rigid pavements to contract, expand, and curl. Following are some applications of the NYTEMP program:

1. Obtaining pavement layer temperatures during non-destructive testing, for accurate adjustment of backcalculated concrete modulus from in-situ temperature to the standard temperature.

2. Providing field asphalt-concrete pavement temperatures for estimating resilient modulus using empirical relationships.

3. Calculating pavement temperatures (given "design" air temperatures) for assessing fatigue cracking and rutting potential in flexible pavement design.

4. Providing temperature gradients to calculate curling stresses of concrete slabs in rigid pavement design.

5. Estimating frost depth during winter.

6. Serving as a research tool in such areas as the relation between thermal

properties and temperature of materials, seasonal characteristics, energy studies, etc.

C. Input Requirements and Model Selection

NYTEMP consists of two models: a surface model and an air model. The first is used when pavement surface temperatures can be measured. If not, the air model should be used, requiring knowledge of air temperature, which can be obtained by measuring it or from a weather station. Other common input requirements for both models include thermal diffusivity of the materials involved, their thermal conductivity, pavement layer thicknesses, assumed initial temperature distribution, and depth intervals for temperature calculation. The air model also requires solar radiation data, average wind velocity, and percent absorption of solar energy by the surface. All time-dependent variables (i.e., temperatures and solar radiation) are reported hourly.

Limited research has been conducted concerning thermal properties of asphalt concrete pavement materials, but they have not been found to have notable effects on predicted temperatures. The most critical and difficult input requirement is assumed pavement temperature at the initial hour, especially when the total period of calculation is short. Details of all inputs and sources for some of them are discussed later in this manual.

The air model must predict pavement surface temperature from thermal equilibrium at the surface-air interface, by considering all three forms of heat transfer. Equilibrium involves many factors and accuracy of each factor affects the results. The air model thus is less accurate than the surface model where surface temperatures are directly measured. From the researcher's viewpoint, the surface model is recommended if pavement surface temperature can be measured. From a design standpoint, however, monthly or seasonal average pavement temperatures (flexible pavement) and pavement temperature gradients (rigid pavement) for predicting long-term pavement performance are legitimate concerns (see Applications 3 and 4 in Section B of this Chapter). Long-term air temperature is usually easier to obtain than surface temperature. For these reasons, the air model is more applicable for pavement design than the surface model.

D. Equipment Required

To run NYTEMP, the following equipment is needed:

1. An IBM XT, IBM AT, PS/2, or compatible computer,

2. A hard disk is desirable, but not essential,

3. A 640-k system memory,

4. A DOS operating system, Version 2.1 or higher,

5. A computer graphics card (CGA, EGA, or VGA) and compatible monitor (EGA

or VGA are preferred),

6. A math co-processor is recommended, and

7. A dot-matrix printer.

Figure 1. The model choice menu.

```
A   I   R

press the up arrow key to select air model
the down arrow key to select surface model

S U R F A C E

press the END key to exit the program
```

Figure 2. The main menu.

```
                    S U R F A C E   M O D E

FILE   MODIFY   RUN   PRINT   PLOT   EXIT



Use <-, -> to select and press [ENTER] | Data File Transfer | 14:8:22
```

Table 1. Description of main menu options.

Option	Description
FILE	Input data file transactions, including creating, retrieving, and saving a file
MODIFY	Modifying an existing input data file
RUN	Running a data file, i.e., perform temperature calculations
PRINT	Print out the result in numerical values
PLOT	Graphical presentation of the result
EXIT	Quitting the surface model to model choice menu

Figure 3. File transaction selections.

```
                    S U R F A C E   M O D E

FILE   MODIFY   RUN   PRINT   PLOT   EXIT
Create
Retrieve
Save
Exit
```

II. STARTING THE PROGRAM AND INPUTTING DATA

A. Installation

NYTEMP can be run from either a floppy or hard disk, the difference in speeds being minor. To run on hard disk, simply copy all files from the floppy disk containing the program to a newly created hard disk subdirectory. For example, if the floppy disk is in A drive, then type A: <ENTER>, COPY *.* C:\NYTEMP <ENTER>. If the computer's graphics card or monitor is CGA, one more step is needed before running NYTEMP. A configuration file named CONFIG.TP in the diskette must be changed. Use a proper word processor to change the file's one-line content from "grDriver=EGA" to "grDriver=CGA."

B. Starting NYTEMP

To start the program, type NYTEMP and <ENTER> from the floppy drive or hard disk subdirectory where NYTEMP resides. For example, type C: <ENTER>, CD \NYTEMP <ENTER>, and then NYTEMP. After a NYSDOT logo screen, a title screen appears, and an introductory message screen. Press <ENTER> to continue, and a model choice menu appears as shown in Figure 1. There are three choices: 1) air model, 2) surface model, or 3) quit the program. Use the up or down arrow key to select the desired model, or press the END key to exit.

C. The Surface Model

Press the down arrow key to select this model. The main menu for surface model will appear on the screen as shown in Figure 2. (A brief description of each option in the main menu is given in Table 1.) Select the FILE option by positioning the cursor on FILE and hitting <ENTER>, or typing the letter F. Several choices will appear on the screen under FILE, as shown in Figure 3. (Table 2 gives a brief description of the options under FILE.)

Table 2. Description of file transactions.

Transaction	Description
Create	Creating a new input data file
Retrieve	Retrieving an existing input data file on disk for modifying and/or running
Save	Saving a created or modified data file onto a disk
Exit	Quitting the FILE option to the main menu

Figure 4. Entering file name.

```
                         Create File

 Type in the path of the data file :

 Drive       :     d
 Directory   :     temp
 Filename    :  >  example.sur

 d:\temp\*.sur

 INDATA.SUR      I87AU.SUR

  >>  Enter Filename With Extension [.sur]  <<
```

To create a new file, type C or move the cursor bar over to CREATE and press <ENTER>. File name specifications will be asked. Type in the disk drive and subdirectory you want for the new file and then the file name, with the extension SUR denoting that the file is for the surface model. All files with the SUR extension in the specified drive/subdirectory will be shown on the screen. An example of entering the name of a new file is shown in Figure 4.

After entering the file specification, the main input data menu will show on the screen as in Figure 5. Ten input items are in the menu. To select one, move the highlighted bar to that item and press <ENTER>. It is recommended that users follow the order in this menu to enter input data. (All input items are described in Table 3.)

Figure 5. The main input data menu.

```
                         Create File

  Title
  Date/Hour
  Pavement Layers
  Diffusivity
  Conductivity
  Thicknesses
  Time Interval
  Depth Interval
  Surface Temperature
  Initial Temperature
  EXIT to main menu

              CREATE d:\temp\example.sur
```

Table 3. Description of input items.

Item	Description
Title	A description of the problem
Date/Hour	The starting and ending time of the temperature prediction period
Pavement Layers	Number of layers in the pavement sys.
Diffusivity	Thermal diffusivity of each layer
Conductivity	Thermal conductivity of each layer
Thicknesses	Thickness of each pavement layer
Time Interval	A specified interval for temperature calculation
Depth Interval	Depth/locations in pavement where temperatures are calculated
Surface Temperature	Hourly pavement surface temperatures during the prediction period
Initial Temperature	Pavement temperature(s) at the starting hour

Figure 6. Entering problem title.

```
                         Create File

Title:        Type in the title between [ ]

 [Rt. 29, Saratoga County, Conc. Pavement, Surface Model   ]

               CREATE d:\temp\example.sur
```

Each problem should be identified by a title. Select the TITLE item from the main input data menu, type it in, and hit ENTER when finished. The screen will look like Figure 6.

The next input item is "Date/Hour," which specifies the date(s) and hours during which pavement temperature is to be calculated. This program was designed to handle a maximum of 49 hours duration. Preferably the duration selected will be no less than 5 hours to minimize the inaccuracy associated with the initial temperature assumption. Type in the starting and ending times (month, day, year, and hour). The program will calculate the total hours specified (i.e., elapsed hours plus 1 hour). After entering this information, if any mistakes were made answer "N" to the "exit(Y/N)?" prompt. This will take the cursor back to the first line. Make any necessary corrections and hit ENTER for correct information. Then Type Y to the exit prompt and proceed to the next input item. Figure 7 shows this input screen.

Select "Pavement Layers" to input the total number of layers in the pavement (Fig. 8). Subgrade soil should be included as one layer. This program was designed to handle a maximum of five layers. Similar layers, such as asphalt overlay, asphalt wearing course, binder course, and base course, may be combined together.

Figure 7. Entering starting and ending times.

```
                         Create File

  Date/Hour:               Maximum 49 hours

   start month : 6
         day   : 15
         year  : 88
         hour  : 19                 exit (Y/N) ?
   end   month : 6
         day   : 16                             > Y
         year  : 88
         hour  : 19

   total hours : 25
```

Figure 8. Entering pavement layer numbers.

```
                         Create File

  Pavement Layers:

                Enter the number of Layers (max. 5)
                   > 3
```

Figure 9. Entering thermal diffusivity.

```
                         Create File

  Thermal Diffusivity:        (sq. ft. per second)

  Top Layer
                                        AC            = 0.00000747
    Layer 1 = 0.00000452                PCC           = 0.00000452
                                  GRAN. SUBBASE       = 0.00001925
    Layer 2 =                          SOIL           = 0.00000495
                                USER DEFINE DATA      input data
    Layer 3 =                       NEXT LAYER        skip to next
                                       EXIT           stop process
  Bottom Layer
                                Select layer  2 >
```

Figure 10. Entering thermal conductivity.

```
                         Create File

  Thermal Conductivity:       (btu per ft-sec-@f)

  Top Layer
                                        AC            = 0.0002089
    Layer 1 = 0.0001478                 PCC           = 0.0001478
                                  GRAN. SUBBASE       = 0.0003616
    Layer 2 = 0.0003616                SOIL           = 0.0001546
                                USER DEFINE DATA      input data
    Layer 3 =                       NEXT LAYER        skip to next
                                       EXIT           stop process
  Bottom Layer
                                Select layer  3 >
```

The next item on the input data menu is "Diffusivity" of each pavement layer. At the lower right corner of the input screen for thermal diffusivity, the current layer to be input is indicated. Typical values for asphalt concrete, portland cement concrete, granular subbase, and soil are listed, and can be chosen by positioning the highlight bar over these values and hitting ENTER. Users can also input any value by selecting USER DEFINE DATA. Choose either NEXT LAYER for changing data, or EXIT to go to the next item when finished. This is shown in Figure 9.

The input screen for thermal conductivity (Fig. 10) is the same as for diffusivity. Input conductivity for each pavement layer by using either the typical values provided or typing in other values from top layer to bottom. Choose EXIT when no editing is necessary. (Appendix A of this manual provides more guidelines on thermal properties of common paving materials.)

The next input item is thickness for each layer (Fig. 11). Like the previous two screens, the bottom corner indicates the layer, from top to bottom, whose thickness is to be entered. No thickness is required for the subgrade layer.

From the main input menu, select TIME INTERVAL as the next input item (Fig. 12). The program calculates pavement temperatures for every time interval selected. Although only those occurring on the hour will be reported, the time interval will affect accuracy of calculation. For thin pavement layer(s), such as 1.5- or 2.0-in. overlay, a smaller "depth interval" (which is the next input item) may

Figure 11. Entering layer thickness.

```
                          Create File

 Layer Thicknesses:  (unit inches - exclude the subgrade)
 Top Layer
   Thickness 1 =  9.00
   Thickness 2 =  0.00
 Bottom Layer                Enter Thickness 2 :
                                       >  12
```

Figure 12. Entering time interval.

```
                          Create File

 Time Interval:            (unit in minutes)
        Select Time Interval
            i.e.  2, 3, 4, 5, 6, 7.5, 10, 12, 15, 20, 30
                  > 4
```

Figure 13. Entering depth interval.

```
                         Create File

  Depth Interval:             (unit in inches)

      Select Depth Interval
         i.e.   1, 1.5, 2, 2.5, 3

                  > 2
```

Figure 14. Entering surface temperature.

```
                         Create File

 Surface Temperature:        Total hrs : 25

 Date:  6/15        A        Date:  6/16        B
 Hr.  Temp   Hr.  Temp.      Hr.  Temp.   Hr.  Temp.

                              0)  0.00   12)  0.00
                              1)  0.00   13)  0.00
                              2)  0.00   14)  0.00
                              3)  0.00   15)  0.00
                              4)  0.00   16)  0.00
                              5)  0.00   17)  0.00
                              6)  0.00   18)  0.00
             19)  0.00        7)  0.00   19)  0.00
             20)  0.00        8)  0.00
             21)  0.00        9)  0.00
             22)  0.00       10)  0.00
             23)  0.00       11)  0.00

 Enter [I] for Input, [M] for Modify, [E] for Exit   >I
```

Figure 15. Entering initial temperature.

```
                         Create File

 ·Initial Temperature:        (maximum 10 temperatures)

     1) 102.57

    Number of
    Initial Temperature : 1

 Enter [I] for Insert,[M] for Modify,[D] for delete,[E] for Exit  >
```

be selected. In that case, the time interval also must be small, so that calculation(s) can converge. Usually a range of 3 to 10 minutes is practical. If the numbers chosen are other than suggested on the screen (e.g., 7 or 11 minutes were selected), the program will ask the user to re-select the time interval.

"Depth Interval" is the next item (Fig. 13). The program will calculate and report pavement temperatures at each pavement depth interval. It will also automatically calculate temperatures at interfaces of any two adjacent layers. For example, if the first layer is 5 in. thick and the depth interval selected is 2 in., then depth configuration of this setting will be 0 in. (i.e., the surface), 2 in., 4 in., 5 in., 7 in., 9 in., and so on. Depth interval must be small enough for a clear picture of pavement temperature gradient, but large enough that calculations can converge. If the selection is inappropriate (i.e., too small) the program will ask the user to re-select. Any value other than suggested on the screen (as long as it's greater than 1 in.) can be selected.

To run the surface model, pavement surface temperatures measured on or near each hour are needed. Select SURFACE TEMPERATURE from the main input menu, and the input/edit screen for surface temperature will appear as in Figure 14. Type I for input on the bottom line. Then type in temperature for each hour specified earlier in the Date/Hour input. If any errors were made and changes are needed, users can either press ENTER twice, or finish typing all temperatures and select M for modify on the bottom line. Follow instructions on the screen by using letters A, B, or C to denote the first, second, or third day, followed by the hour of that day to reach the desired hour needing change. Exit to the main input menu when done by selecting the E option.

The last input item is Initial Temperature. This is temperature distribution from top to bottom within a pavement at the initial hour. Temperatures at locations specified by the selected depth interval are supposedly known as inputs, but are difficult to obtain. Data show that at 8 or 9 o'clock in the morning and 7 to 9 o'clock in the evening, temperatures are most likely to be uniform throughout the pavement depth. It is thus recommended that starting time be one of those hours, when deciding the Date/Hour input. Measured surface temperature at the initial hour may then be the only input for this item. The program will assume temperatures at the other locations to be the same as the surface temperature. At the bottom of the screen, choose I to insert an initial temperature, M to modify temperatures already typed in, D to delete temperature entries, or E to finish this input item. Figure 15 shows this screen.

After all inputs are in, choose "EXIT to main menu." Then choose the SAVE option under FILE to save the information. Next time when running with the same set of data, simply "Retrieve" the file. If any changes are necessary, choose the MODIFY option from the main menu. Modification screens for all input items are the same as those in creating the file, as shown in Figures 5 through 15.

D. <u>The Air Model</u>

Input data for this model are mostly the same as for the surface model. Instead of surface temperature, the air model requires hourly values for air temperature

Figure 16. Main input data menu for air model.

```
A I R   M O D E L

Title                      Absorption
Date/Hour                  Time Interval
Pavement Layers            Depth Interval
Diffusivity                Air Temperature
Conductivity               Solar Radiation
Thicknesses                Initial Temperature
Avg. Wind Velocity         EXIT to main menu

MODIFY:d:\temp\indata.air
```

Figure 17. Entering wind velocity.

```
A I R   M O D E L

Wind Velocity:          (unit in mile/hour)
          Enter the wind velocity
          > 10.00

MODIFY:d:\temp\indata.air
```

Figure 18. Entering absorption.

```
A I R   M O D E L

Absorption
     Enter the absorption in decimals
     > 0.85
```

Figure 19. Entering air temperature.

```
                         A I R   M O D E L

 Air Temperature:              Total hrs : 39

 Date:  08/13      A   | Date:  08/14       B   | Date:  08/15       C
 Hr. Temp  Hr. Temp.   | Hr. Temp.   Hr. Temp.  | Hr. Temp.   Hr. Temp.
                       |  0) 50.61   12) 80.65  |  0) 53.95   12) 83.33
                       |  1) 49.25   13) 80.19  |  1) 52.53
                       |  2) 47.36   14) 88.19  |  2) 51.66
                       |  3) 48.20   15) 88.63  |  3) 50.37
                       |  4) 47.54   16) 81.95  |  4) 49.57
                       |  5) 46.16   17) 83.49  |  5) 48.07
                       |  6) 45.15   18) 88.19  |  6) 48.24
                       |  7) 47.50   19) 78.33  |  7) 50.15
                       |  8) 52.24   20) 62.38  |  8) 56.24
                       |  9) 58.99   21) 57.65  |  9) 62.77
            22) 56.43  | 10) 66.97   22) 57.45  | 10) 70.88
            23) 55.64  | 11) 75.39   23) 55.66  | 11) 77.37

       Enter [I] for Input, [M] for Modify, [E] for Exit  >M
```

and solar radiation. It also asks for average wind velocity during the calculation period, and percent energy absorbed by the surface.

Select the air model by pressing the up-arrow key from the model choice menu, at the beginning of the program or after exiting the surface model. The main menu, FILE submenu, and file-specifying procedure are the same as previously illustrated. The main input data menu for file creation or modification contains 13 items. To select one, move the highlight bar over it and hit ENTER. Since all other items are virtually the same, only those four different or new items are illustrated here. Figure 16 is the main input data menu in the MODIFY mode.

Select "Avg Wind Velocity" from the screen and input the value. Wind velocity is usually available from weather information. Appendix B of this manual lists some weather publications. Figure 17 shows the screen. When modifying previous files or values, simply type the new numbers over the existing ones, without hitting the space bar.

"Absorption" (r) is also a single-value item, accounting for the portion of solar energy absorbed by the pavement surface. For AC surfaces (blacktop), r values range from 80 percent (worn) to 90 percent (new), and for concrete surfaces the percentage range is from 75 (new) to 85 (worn) depending on shade. Type the values in decimals -- 0.9 or 0.85 as shown in Figure 18.

The procedure and screen to input/edit "Air temperature" is the same as for surface temperature in the surface model. Hourly air temperature may be obtained from nearby weather stations or on-site measurements. Note that temperatures <u>on or near the hour</u>, not average hourly temperatures, should be input, if possible. Actual ambient air temperatures above pavement surfaces may be a little higher

Figure 20. Selecting solar radiation type.

A I R M O D E L

Solar Radiation Data Type

Select the Type of Solar Radiation Data

One-Hour Irradiation (ending at local std. time)

Intensity (on each hour, local std. time)

than those measured elsewhere due to heat generated by passing vehicles. Figure 19 is the screen for air temperature.

After selecting the "Solar Radiation" input, a screen will appear to ask for the type of solar radiation data to be input. From this screen, as shown in Figure 20, select either "One-Hour Irradiation (ending at local std time)" or "Intensity (on each hour, local std time)" by moving the highlight bar over it and hitting ENTER. The input screen will then appear. Figure 21 shows the solar radiation input screen, which is similar to those for air and surface temperature with the same procedure. Details of solar radiation and available data are discussed in Appendix B of this manual.

Figure 21. Entering solar radiation.

A I R M O D E L

Solar Radiation: (unit in watt-hour/m2) Total hrs : 39

Date: 08/13 A

Hr	Solar	Hr.	Solar
		22)	0.0
		23)	0.0

Date: 08/14 B

Hr.	Solar	Hr.	Solar
0)	0.0	12)	1013.1
1)	0.0	13)	1050.5
2)	0.0	14)	1006.5
3)	0.0	15)	895.3
4)	0.0	16)	650.1
5)	2.2	17)	454.3
6)	47.3	18)	289.3
7)	194.7	19)	94.6
8)	355.3	20)	4.4
9)	589.6	21)	1.1
10)	777.4	22)	0.0
11)	948.2	23)	0.0

Date: 08/15 C

Hr.	Solar	Hr.	Solar
0)	0.0	12)	1018.6
1)	0.0		
2)	0.0		
3)	0.0		
4)	0.0		
5)	1.1		
6)	56.1		
7)	156.2		
8)	359.7		
9)	597.3		
10)	737.1		
11)	852.5		

Enter [I] for Input, [M] for Modify, [E] for Exit >

III. PRINTING/PLOTTING RESULTS

After all input information is properly created or modified, the next step is to obtain results by running the program. Select the RUN option from the main menu by moving the highlight bar over it and hitting ENTER, and the screen shown in Figure 22 will appear. Running time is usually less than 30 seconds. If the calculation does not converge, the program will stop and exit to the DOS prompt. Type NYTEMP to restart the program and modify the data. Possible reasons for divergence are improper depth interval, time interval, or some combination with inaccurate temperatures. When running is complete, users will be notified by the screen (Fig. 23).

Press ENTER and the main menu will appear. The next step is to examine the results. The PRINT option lists numerical values of predicted temperatures at each hour and prespecified location. The PLOT option is a graphic representation of the results. Both options can either be observed on the screen or printed out on the printer. After selecting the PRINT options, the screen shown in Figure 24 will appear.

Figure 22. The "program running" screen.

```
Executing ...
   Please Wait ...
```

Figure 23. The "program running completed" screen.

```
Execution completed ...
    Press Enter to continue ...
```

Figure 24. The "print result" menu.

```
P R I N T   R E S U L T

Depth  (1  -  9)
Depth  (10 - 18)
Depth  (19 - 27)
Depth  (28 - 35)
Set Printer OFF
Exit
```

Figure 25. The output-predicted temperatures.

PRINT RESULT

Route 29, Saratoga County, Concrete Pavement, Surface Model

THE TIME INTERVAL SELECTED IS : 4.0 MIN. init. hr: 19 6/15/88
THE DEPTH INTERVAL SELECTED IS : 2.0 INCH. final hr: 19 6/16/88

LAYER 1 : D = 9.0 IN, AR = 0.00000452 K = 0.0001478
LAYER 2 : D = 12.0 IN, AR = 0.00001925 K = 0.0003616
LAYER 3 : D = INFINITE AR = 0.00000495 K = 0.0001546

T\D	0.0"	2.0"	4.0"	6.0"	8.0"	9.0"	11.0"	13.0"	15.0"
19	100.03	100.03	100.03	100.03	100.03	100.03	100.03	100.03	100.03
20	96.45	99.30	99.92	100.02	100.03	100.03	100.03	100.03	100.03
21	92.06	97.55	99.39	99.89	100.00	100.01	100.02	100.03	100.03
22	88.49	95.37	98.43	99.55	99.89	99.94	99.99	100.01	100.02
23	86.25	93.34	97.23	99.00	99.65	99.79	99.90	99.96	100.00
0	84.37	91.59	95.99	98.29	99.30	99.55	99.75	99.87	99.94
1	82.52	89.98	94.77	97.51	98.86	99.22	99.52	99.72	99.84
2	80.71	88.44	93.58	96.68	98.35	98.84	99.24	99.51	99.70
3	79.92	87.14	92.42	95.83	97.79	98.40	98.90	99.26	99.51
4	78.16	85.89	91.35	94.99	97.21	97.94	98.53	98.97	99.28

press RETURN to continue

On this PRINT RESULT menu, users can choose to print out the result by turning the printer ON, or view the result on the screen by turning the printer OFF. Simply move the highlight bar over the printer item and hit ENTER to switch it on or off. Users are also asked to select the output depth level. Due to the constraints of screen and paper widths, only temperatures at nine depth locations can be listed at one time. In most cases, the upper temperatures (i.e., depths 1 to 9) are of most interest. Temperatures at lower locations are generally constant across the depth.

Move the highlight bar to DEPTH (1-9), press ENTER, and the resulting screen will look like Figure 25, which shows temperatures at various hours and depths. All temperatures are in degrees Fahrenheit. Material properties and thicknesses, as well as other selected parameters, are also listed at the top. When finished printing, choose EXIT from the PRINT RESULT menu, and return to the main menu. To plot the results choose PLOT from the main menu and the PLOT RESULT menu will appear, as in Figure 26. Two kinds of plots are available: temperature vs depth at certain hours, and temperature vs hour at certain depths. The former gives temperature gradients, and the latter shows hourly fluctuations in pavement

Figure 26. The "plot result" menu.

PLOT RESULT

Select Hours
and/or Plot
Temp. vs. Depth

Select Depths
and/or Plot
Temp. vs. Hour

Color : Normal

Printer : off

Exit

Figure 27. Selecting the temperature vs depth plot.

P L O T R E S U L T

Select Hours and/or Plot Temp. vs. Depth

Select Depths and/or Plot Temp. vs. Hour

Color : Normal

Printer : off

Exit

Maximum 3 hours :

Hour1: B1 Hour2: B13 Hour3:

Select A -day1, B -day2, or C -day3 followed by the hour. e.g. A15

Enter Hour3 A19-B19 : B16

temperature. Like the PRINT RESULT menu, the printer can be turned on or off from this menu. The "Color" item in this menu can be either Normal or Reverse. Some graphics settings show better graphs in the Normal color, and some are better in the Reverse color.

Move the highlight bar to the first option, hit ENTER to select the temperature vs depth plot, and then select the hour(s) desired. (A maximum of 3 hours can be plotted on one graph.) The letters A, B, and C denote the first, second, and third days, respectively. After typing in the hour(s), users may choose to enter P for plotting if no errors were made, M to modify the hour(s) just typed in, or E to exit to the PLOT RESULT menu. Figure 27 shows the screen for this option.

The temperature-depth plot shows predicted temperatures from the pavement surface down, at up to 10 locations, specified by depth interval and pavement layer thickness. It will also calculate temperature gradient (in degrees F per inch) for the first layer, which is useful for concrete slabs. Selected hours of the surface model example are shown in Figure 28.

Figure 28. Temperature vs. depth plot.

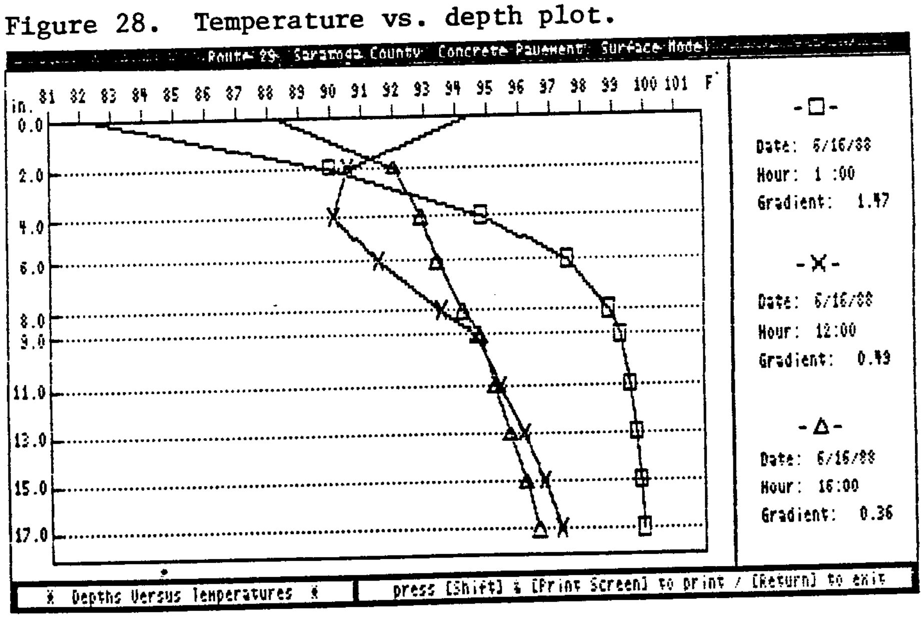


Figure 29. Selecting the temperature vs hour plot.

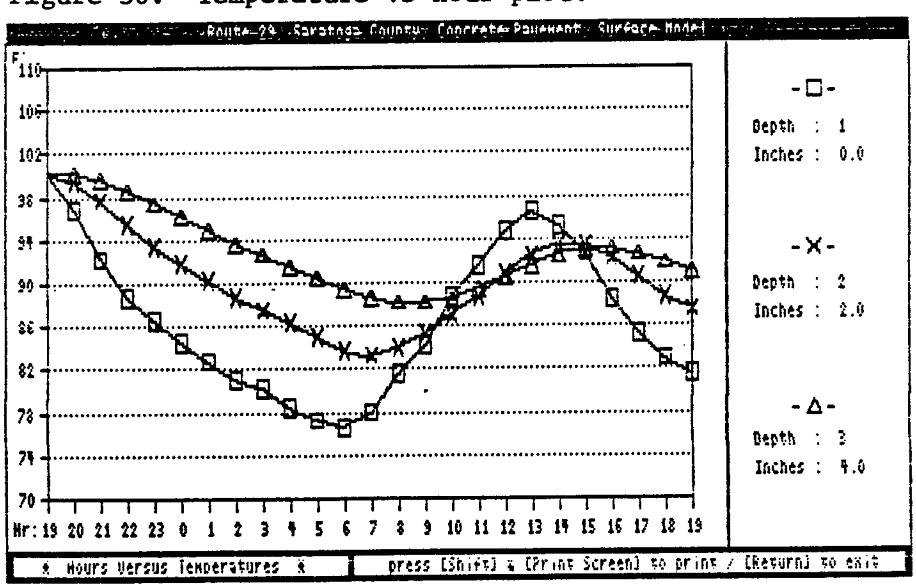
```
                         P L O T    R E S U L T

  Select Hours
   and/or Plot
 Temp. vs. Depth          Maximum 3 depths :
 ------------------
  Select Depths            Depth1: 1   Depth2: 2   Depth3: 3
   and/or Plot
 Temp. vs. Hour
 ------------------
 Color : Normal
 ------------------        Enter P -plot, E -menu, M -modify P
 Printer : off
 ------------------
 Exit
```

To select the temperature-vs-hour plot, move the highlight bar to that option and hit ENTER from the PLOT RESULT menu. The screen will ask for depth(s) at which temperatures are desired, as illustrated in Figure 29. Temperatures at up to three depth locations can be plotted on a single graph. Note that inputs are in "depth numbers," not depth in inches. Depth Number 1 corresponds to the surface, and so forth.

Press P and ENTER to plot. The resulting graph shows hourly temperature variation for the period specified in the DATE/HOUR input -- an example in shown in Figure 30. The real depth corresponding to each depth number is displayed at the right. To print the graph, either set off the printer earlier in the PLOT RESULT menu, or press PRINT SCREEN when it is on the screen.

Choosing EXIT from the PLOT RESULT menu will take the program back to the main menu. Type E or choose EXIT to leave the main menu, either to choose another model or quit the NYTEMP program.

Figure 30. Temperature vs hour plot.



ACKNOWLEDGMENTS

This work was initiated and conducted under supervision of Dr. Robert J. Perry, Director of Engineering Research and Development. Jack Poon, then a student intern, was the NYTEMP programmer who translated it from its original FORTRAN language, designed the program structure and input screens, and added all graphic features. Dr. Joe Michalski, Senior Research Associate at the SUNY Atmospheric Sciences Research Center, provided this study his computer program for calculating the sun's position and much other essential information concerning solar radiation.

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APPENDIX A. DIFFUSIVITY/CONDUCTIVITY OF MATERIALS

Thermal conductivity of a substance is the quantity of heat flowing in unit time through unit area of a layer of a substance of unit thickness, with unit difference of temperature between its faces. It measures capability or speed of a substance to conduct heat within its body. Thermal conductivities for most metal materials are assumed to be isotropic and constant, although they vary slightly with temperature. Thermal conductivity of concrete may either increase or decrease with temperature, depending on temperature range and mix type. Soil's thermal conductivity usually increases with temperature. Common units for thermal conductivity are Btu/ft•hr•°F and cal/cm•sec•°C. The unit used in the NYTEMP program is Btu/ft•sec•°F, which can be obtained by dividing thermal conductivity in Btu/ft•hr•°F by 3600, or in cal/cm•sec•°C by 14.88.

Diffusivity of a substance is often defined by its thermal conductivity divided by its density and specific heat, or

$$\alpha = K/\rho c \tag{1}$$

where α = diffusivity, (cm^2/sec or ft^2/hr)

K = thermal conductivity, (cal/cm•sec•°C or Btu/ft•hr•°F)

ρ = density, and (g/cm^3 or lb/ft^3)

c = specific heat. (cal/g•°C or Btu/lb•°F)

Diffusivity, as its name indicates, measures the rate at which a substance can diffuse or spread heat within its body. It can be viewed as the area (perpendicular to the direction of heat flow) of the substance affected by the heat in unit time. Although it is one thermal property of a substance, the unit does not contain any heat or temperature component. Common units are ft^2/hr and cm^2/sec. NYTEMP uses ft^2/sec as the diffusivity unit, which can be converted from ft^2/hr by dividing by 3600 or from cm^2/sec by dividing by 929.

Published thermal properties are mostly for metals. Little information could be found for thermal properties of typical paving materials. Following is a compilation providing either values or relations regarding the two properties (conductivity and diffusivity) for asphalt concrete, portland cement concrete, gravel, and soil. References 2, 3, 4, 5, and 6 provided this information. Like most other non-metals, thermal properties of these materials vary greatly by samples, mix properties, grain sizes, moisture contents, and temperatures.

Preceding page blank

1. Asphalt Concrete

Conductivity	$2 - 4 \times 10^{-4}$	Btu/ft•sec•°F
Diffusivity	$7 - 12 \times 10^{-6}$	ft^2/sec

2. Portland Cement Concrete

Conductivity	$1.2 - 2.2 \times 10^{-4}$	Btu/ft•sec•°F
Diffusivity	$4.5 - 7.5 \times 10^{-6}$	ft^2/sec

3. Granular Subbase and Subgrade Soil

Conductivity (Btu/ft•sec•°F)

Marble stone	4.4×10^{-4}	
Granite stone	$2.7 - 6.4 \times 10^{-4}$	
Sandstone stone	$2.5 - 3.8 \times 10^{-4}$	
Limestone stone	$2.0 - 3.5 \times 10^{-4}$	
Mica stone	$5.8 - 9.5 \times 10^{-5}$	
Average rock	2.8×10^{-4}	
Limestone, coarse-grained	$1.3 - 1.6 \times 10^{-4}$	
Limestone, fine-grained	$1.0 - 1.2 \times 10^{-4}$	
Sandy dry soil	$4.2 - 5.2 \times 10^{-5}$	
Sandy soil (7-8% moisture)	$0.9 - 1.8 \times 10^{-4}$	
Average soil, dry	$2.5 - 4.5 \times 10^{-5}$	
Average soil, wet	$0.8 - 1.5 \times 10^{-4}$	
Frozen gravel or sand	$K = [0.076(10)^{0.013\gamma_d} + 0.032(10)^{0.0146\gamma_d}\, w]/12$	(2)
Unfrozen gravel or sand	$K = [(0.7 \log(w) + 0.4) \cdot 10^{0.01\gamma_d}]/12$	(3)
Frozen silt or clay	$K = [0.01(10)^{0.022\gamma_d} + 0.085(10)^{0.008\gamma_d}\, w]/12$	(4)
Unfrozen silt or clay	$K = [(0.91 \log(w) - 0.2)10^{0.01\gamma_d}]/12$	(5)
Saturated frozen silt/clay	$K = (1.007 \cdot 1.0054^{w/100})^{\gamma_d} \cdot 0.5778$	(6)

where K = thermal conductivity (Btu/ft•hr•°F),

γ_d = dry density of the soil (pcf), and w = percentage moisture content by weight.

Eqs. 2 and 3 are valid for moisture contents from 1 percent up to saturation. Eqs. 4 and 5 are valid for moisture contents from 7 percent up to saturation. These equations are accurate at ± 25 percent.

<u>Diffusivity</u> (ft^2/sec)

Marble stone	$1.2\text{-}1.5 \times 10^{-5}$
Granite stone	$0.86\text{-}2.0 \times 10^{-5}$
Limestone stone	$6.1\text{-}7.0 \times 10^{-6}$
Sandstone stone	$1.1\text{-}1.4 \times 10^{-5}$
Average rock/gravel	1.3×10^{-5}
Coarse sand	8.2×10^{-6}
Sandy dry soil	2.1×10^{-6}
Sandy soil (8% moisture)	3.6×10^{-6}
Sandy loam	1.5×10^{-5}
Sandy clay	5.5×10^{-6}
Average dry soil	3.3×10^{-6}
Average soil	4.9×10^{-6}

The following equations are used to calculate volumetric heat capacities of common soils:

Frozen $$C = \gamma_d\ [c + 0.5(w/100)] \tag{7}$$

Unfrozen $$C = \gamma_d\ [c + 1.0(w/100)] \tag{8}$$

where C = volumetric heat capacity ($Btu/ft^3 \cdot {}^\circ F$),

γ_d = dry density of soil (pcf),

c = specific heat of dry soil (0.175 Btu/lb•°F), and

w = percent moisture content by weight.

Diffusivity can then by obtained by dividing conductivity by volumetric heat capacity.

ERRATUM

On page 24, Equations 2 through 6 should read as follows:

Frozen gravel or sand	$K = [0.076(10)^{0.013\gamma_d} + 0.032(10)^{0.0146\gamma_d}\, w]/12$	(2)
Unfrozen gravel or sand	$K = [(0.7 \log(w) + 0.4)\cdot 10^{0.01\gamma_d}]/12$	(3)
Frozen silt or clay	$K = [0.01(10)^{0.022\gamma_d} + 0.085(10)^{0.008\gamma_d}\, w]/12$	(4)
Unfrozen silt or clay	$K = [(0.91 \log(w) - 0.2)10^{0.01\gamma_d}]/12$	(5)
Saturated frozen silt/clay	$K = (1.007\cdot 1.0054^{w/100})^{\gamma_d} \cdot 0.5778$	(6)

APPENDIX B. SOLAR RADIATION

All matter emits electromagnetic radiation by molecular and atomic agitation. Thermal radiation, commonly called heat and light, is emitted by agitation associated with the matter's temperature. Most solar radiation reaching the earth's surface, which is of interest here, is in the thermal radiation range. Thermal radiation encompasses wavelengths ranging from 0.2 to 1000 μm, and consists of the following spectrum: a portion of the ultraviolet, visible, and near- and far-infrared.

Several terms are used to describe solar radiation incident on a surface on earth. Irradiation refers to quantity of solar energy arriving at a surface during a given time period. Irradiance, or radiant flux density, or radiant flux, indicates the rate of solar energy arriving at a surface per unit time and per unit area. Intensity of radiation, strictly speaking, means irradiance from a particular direction and contained within a unit solid angle. However, "intensity" in this report and other documents is loosely employed as being equivalent to radiant flux.

The three types of solar radiation most commonly measured are global, direct, and diffuse. The first, also called "total horizontal radiation," is solar radiation received from a solid angle 2π on a horizontal surface. It includes radiation directly from the sun (direct radiation), and that scattered by clouds, dust, etc. (diffuse radiation). Obviously, this radiation is relevant for calculation of pavement temperatures.

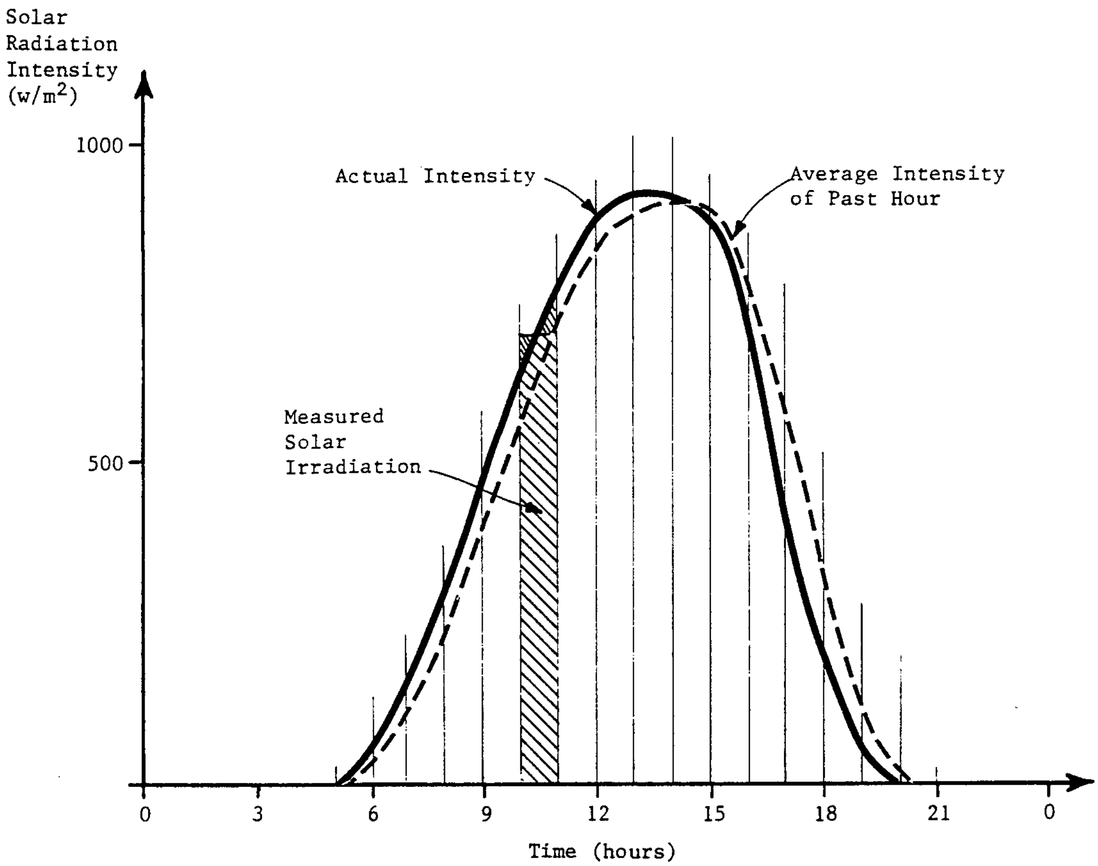
Common units for solar radiation as energy incident upon a unit surface (over a particular time period) are: cal/cm^2 (Langley), watt-hr/m^2, K Joule/m^2, and Btu/ft^2. The SI unit for solar radiation intensity is watt/m^2. NYTEMP uses Btu/ft^2•sec as the intensity unit in calculation, but takes the solar radiation input as the watt-hr/m^2 unit, because most measured solar radiation data, which are introduced later, are reported hourly. To be more specific, they measure solar energy for a 1-hr period, ending at the reported local standard time. Average intensity during the hour is obtained by simply dividing measured irradiation by 3600. If the radiation intensity value (in watt/m^2) for each hour on the hour is known, NYTEMP can also accept it as an alternative input. Some conversion factors between SI and USCS are as follows:

1 watt-hr/m^2 = 0.317 Btu/ft^2

1 K Joule/m^2 = 0.088 Btu/ft^2

1 K Joule/m^2 = 0.278 watt-hr/m^2

Figure 31. Solar irradiation vs intensity.



Since NYTEMP requires solar radiation intensity to calculate temperature, there is an associated inaccuracy when using measured hourly irradiation as the input instead. Figure 31 is a typical graph of solar radiation intensity versus time of day (the solid line). Input values are the areas under the curve for each past 1-hour interval. The dotted line represents hourly average intensity, which is less during temperature rise and greater during temperature drop than the actual intensity. This explains the often-encountered results in running temperature models -- i.e., predicted temperatures rise and also drop more slowly than those actually measured. NYTEMP corrects this shortcoming by solving for approximate ordinate values, assuming continuous linear increase or decrease at the beginning or end of the calculation period.

Another important category of solar radiation is extraterrestrial radiation, which is the amount of solar radiation incident upon the top of the atmosphere. Extraterrestrial radiation on a horizontal surface, which is the "global radiation" immediately outside the atmosphere, theoretically can be calculated for any given time, date, and location. It is obtained by dividing the solar constant by the distance (between the sun and top of the atmosphere, in astronomical units) squared, and then multiplying by the sine of solar elevation (or cosine of the zenith angle).

Because few weather stations measure solar radiation, for most geographic areas solar radiation data could be obtained only by interpolation from the nearest stations, permitting considerable possible variations from true solar radiation values. This problem may be solved if measured global radiation can be related to extraterrestrial radiation (which can be readily calculated for any location, as just described). Many devices and models requiring accurate solar radiation as input thus may have available data for many geographic locations. For example, this pavement temperature model may be applicable to all New York State highway locations. Scientists have been trying to develop models to predict solar radiation received on the ground for various weather and atmospheric conditions, but this is difficult. The greatest factor affecting solar radiation apparently is cloud cover. But even under perfectly clear conditions, many variables still will affect solar radiation to some extent, such as content of vapor, carbon dioxide, nitrogen, and aerosol. The ratio of measured to extraterrestrial radiation on perfectly clear days ranges from 70 to 80 percent, depending on locations and the factors just listed. Following are some widely used simple models (1,7):

$$H/H_o = a + b\ S \tag{9}$$

where H = average daily global radiation,

H_o = average daily extraterrestrial irradiation,

a and b = coefficients, and

S = average daily fraction of possible sunshine, given by

$$S = n/N_d \tag{10}$$

where n = average total instrument-recorded bright sunshine hours per day, and

N_d = average day length in hours.

Eqs. 9 and 10 are valid for long-term averages, with monthly averages being the most common. Many researchers have presented values for the a and b coefficients for many parts of the world, or have modified Eq. 9 for site dependency. Iqbal (7) found that Rietveld's correlation is generally superior, particularly for cloudy conditions (S<0.4):

	a	b
Rietveld (worldwide)	0.18	0.62
Iqbal (Montreal)	0.295	0.371

The foregoing correlations are not valid for estimating global radiation for a particular day, but some work has been done to make such estimations, using the same model as in Eq. 9. "S" in Eq. 9 now becomes the percent of possible daily sunshine, and this information is recorded by some weather stations and is thus ready to be used in this model. Following are two studies on the a and b coefficients for this particular "single-day" application:

	a	b
Dempsey (Midwest)	0.202	0.539
Chen (Albany)	0.15	0.556

With these models, global radiation can be estimated at locations where stations exist that measure hours of sunshine. Another category of models relates average daily global radiation to cloud cover (also called "sky cover"), because stations that have cloud-cover data are more numerous than sunshine stations. Black (7) presented the following model:

$$H/H_o = 0.803 - 0.34\ C - 0.458\ C^2 \quad (C \leq 0.8) \tag{11}$$

where C = average fraction of daytime sky obscured by clouds.

Models based on a cloudiness index are known to be less reliable than previous correlations with percent sunshine. More sophisticated models have been developed to predict global radiation using many meteorological inputs, some of which are briefly introduced at the end of this appendix.

NYTEMP users have two choices to input solar radiation: 1) use measured hourly global irradiation obtained (or interpolated) from nearby stations, or 2) use calculated extraterrestrial radiation intensity exactly on each hour, and the models just cited (sunshine or cloud cover obtained or interpolated from nearby stations) to estimate global radiation intensity. The Engineering Research and Development Bureau has obtained a program from the SUNY Atmospheric Sciences Research Center (ASRC) to calculate the sun's position, and from that program has developed a separate program called NYETRI to calculate extraterrestrial radiation intensity on any given day(s) in any of New York State's eleven DOT regions or major cities.

Following is a summary of available solar and weather information:

A. Solar Radiation

1. The National Oceanic and Atmospheric Administration (NOAA) re-established a solar radiation network in 1977, and publishes a "Monthly Summary, Solar Radiation Data" as well as producing "SOLMET Tapes (TD-9736)" containing hourly global radiation from all those stations. Observed data are checked by the Machta Clear Sky Model developed by NOAA) before publication (8). The nearest station is at Burlington, Vermont.

2. ASRC at Albany measures solar radiation. They formerly published a quarterly "Solar Climatological Summary" in hourly format, but no longer do so. Unedited observed data are available by minutes on request.

3. The New York Power Authority measures solar radiation at nine stations, all downstate (NYSDOT Regions 8, 10 and 11). Data are available, on request, on diskettes for every 10 minutes or as printouts in daily summaries.

4. NOAA derived average daily global solar radiation for 200 U.S. stations from 1952-76 data, covering all of New York's major cities (8).

5. NOAA has another set of modeled data, called the "National Solar Radiation Database." It was recently developed by the National Renewable Energy Laboratory and takes into account many meteorological factors. It covers the years 1961 to 1990, and 239 stations in the U.S. Currently it is available in hourly format and will have daily, monthly, and yearly statistics available in 1993. Although data continue to be collected, the database is to be updated only every 5 years.

B. Other Weather Information

1. "Local Climatological Data" published by NOAA is a useful source of information. New York now has nine stations publishing local climatological data: Albany, Binghamton, Buffalo, Islip (Long Island), NYC Central Park, NYC Kennedy Airport, NYC LaGuardia Airport, Rochester, and Syracuse. Burlington and Erie are nearest outstate stations. Air temperature, wind speed, and sky cover are available in daily averages as well as every 3 hours. The percent possible sunshine and sunshine minutes are included only in daily summaries. All this information, together with other weather data are also available in monthly and annual summaries.

2. "Climatological Data" published by NOAA have much less information (only temperature and precipitation), but cover some 230 stations across New York State. Although published data contain only daily information, most stations collect air temperature hourly. Raw or hourly data may be requested directly from each station.

3. The National Weather Service has about 50 stations in New York, about 30 of which are not associated with the NOAA system. ASRC also collects temperature and wind data.

All NOAA publications and products can be ordered from the National Climatic Data Center. The Engineering Research and Development Bureau Library subscribes to "Climatological Data" for New York State and "Local Climatological Data" for Albany.