THERMALLY INSULATED TEST ROAD: STATE ROAD 26 FINAL PERFORMANCE AND TEMPERATURE PREDICTION STUDIES

NOVEMBER 1972 — NUMBER 39

BY

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JHRP

JOINT HIGHWAY RESEARCH PROJECT
PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Final Report

THERMALLY INSULATED TEST ROAD: STATE ROAD 26 FINAL PERFORMANCE AND TEMPERATURE PREDICTION STUDIES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

November 9, 1972

Project: C-36-16G

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-10-7

Attached is the Final Report on the JHRP Study titled "Thermally Insulated Test Road: State Road 26". This Report has the further title of "Final Performance and Temperature Prediction Studies" and has been authored by Mr. James A. Horton, Graduate Assistant in Research on our staff under the direction of Professor C. W. Lovell, Jr. Mr. H. R. J. Walsh, Director of the ISHC Research and Training Center, supervised all phases of the field study and members of his staff collected and reduced the data.

Recommendations from this study include that the ISHC should consider insulated pavement design as a proven alternative to other special designs in areas where frost action problems are anticipated and that the ISHC might develop a standard design procedure for thermally insulated pavements. Guidance for such a standard is included in the Report. The Report does suggest that the experimental pavement of this Study be monitored for evidence of differential pavement icing over two more winters. The suggestion is also made that a formal investigation of the structural adequacy of the pavement should be made.

The Report is submitted for acceptance as fulfillment of the objectives of this Study.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Associate Director

HLM:ms

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Graduate Assistant in Research

Joint Highway Research Project

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Conducted by
Joint Highway Research Project
Engineering Experiment Station
Purdue University

In cooperation with

Indiana State Highway Commission

Purdue University
West Lafayette, Indiana
November 9, 1972

ACKNOWLEDGMENTS

The writer wishes to thank Dr. C. W. Lovell, Jr., Professor of Civil Engineering, Purdue University, for his guidance throughout the project.

Financial assistance for the project was provided by the Joint Highway Research Project, Dr. J. F. McLaughlin, Director.

Mr. H. R. J. Walsh, Director of the Research and Training Center, Indiana State Highway Commission, West Lafayette, Indiana, deserves credit for the supervision of all phases of the project. Thanks is also given to the numerous employees of the Research and Training Center who collected and reduced the data.

The writer wishes to thank Mr. A. Mohan for his work with the computer simulation of the project.

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ABSTRACT

The analysis of the performance of the test road during the 1971-72 season is presented. A qualitative study of the icing problem on the test road is discussed. Also various studies are presented concerning the sensitivity of the computer simulation of the 2-D heat flow model to various input parameters.

The design, construction, and analysis of previous data have been reported by Stulgis [5], Toenniessen [6] and Bowers [2] and are not covered in detail in this report.

INTRODUCTION

This report, the fourth in a series, is a final and summary one. The research, a study of thermal pavement insulation for the State of Indiana, was begun in 1967 with the Joint Highway Research Project (JHRP) Board's approval of a plan to construct an insulated test road. The test installation was part of a 3.1 mile[1] flexible pavement construction project, located just west of Rossville, Indiana, on State Road 26. Stulgis in July, 1968, recommended [5][2] the thermal design of the test road, which was based upon a one-dimensional heat flow model. The development of a two-dimensional heat flow model by Ho [3] in late 1968 permitted a superior prediction and the pattern of temperature sensors (thermistors) for the test site was altered somewhat from the original plan proposed by Stulgis.

The instrumentation system was designed by the Indiana State Highway Commission Research and Training Center under the direction of Mr. H. R. J. Walsh. After experimenting with different potting materials, the thermistors were wired and potted in a complete assembly. Each sensor was then calibrated by immersion in water of a known temperature.

Construction of the site was begun in July, 1969, and the first data were collected on November 12, 1969. The construction of the test road and the installation of thermistors were reported by Toenniessen [6] in May, 1970.

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[1] English units are used in this report. A table for conversion to International System (SI) units is located in Appendix A.

[2] Numbers in brackets refer to items in the Bibliography.

As the study progressed, additions were made to the original study plan. Since the two-dimensional heat flow model was available, it was used to produce predictions to be compared with observed temperatures. A report on the analysis of first year data (1969-70) and the results of the comparisons was submitted by Bowers [2] in March, 1972.

Because of lack of manpower, data were not collected for the winter of 1970-71. The final study phase started in September, 1971. Benefiting from past results, this phase was divided into three areas: 1) more performance evaluation, utilizing a second year of data collection; 2) further modification of the computer simulation with the objective of producing a practical design tool; and 3) a survey of the possibility of preferential pavement icing on the insulated sections.

LOCATION AND DESIGN

The test site is located just west of the Rossville town limits on Indiana State Road 26, approximately 13 miles east of Lafayette.

Plan and profile views of the test sections are shown in Figure 1 and Figure 2, respectively. Section C is a normal design (control) section. Section A is a normal design with a 1-inch thick layer of insulation[1] placed on the subgrade surface. The insulation extends 17 feet on either side of centerline. The 6-inch subbase was eliminated

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[1] The insulation is Styrofoam HI brand plastic foam manufactured by the Dow Chemical Company of Midland, Michigan.

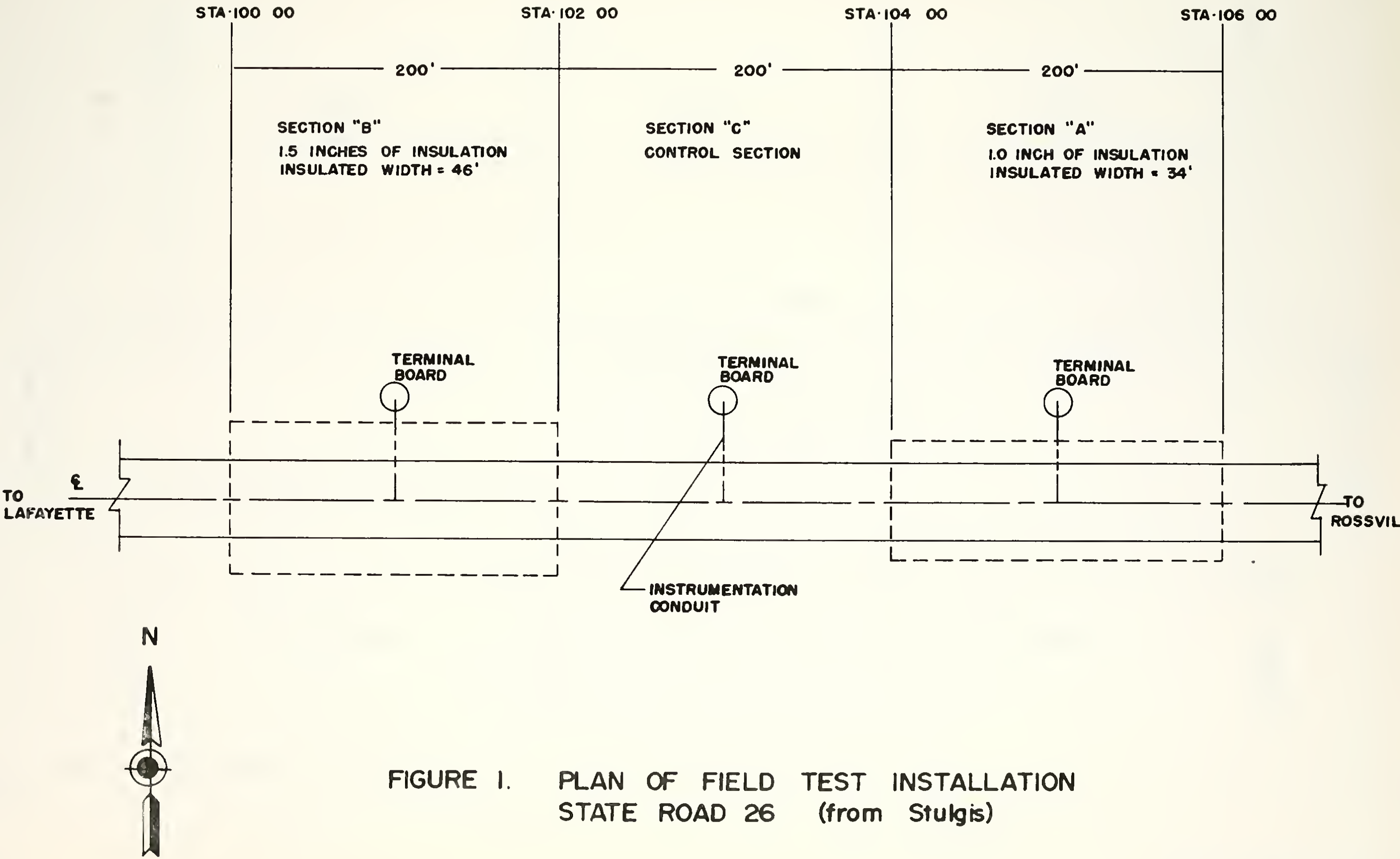
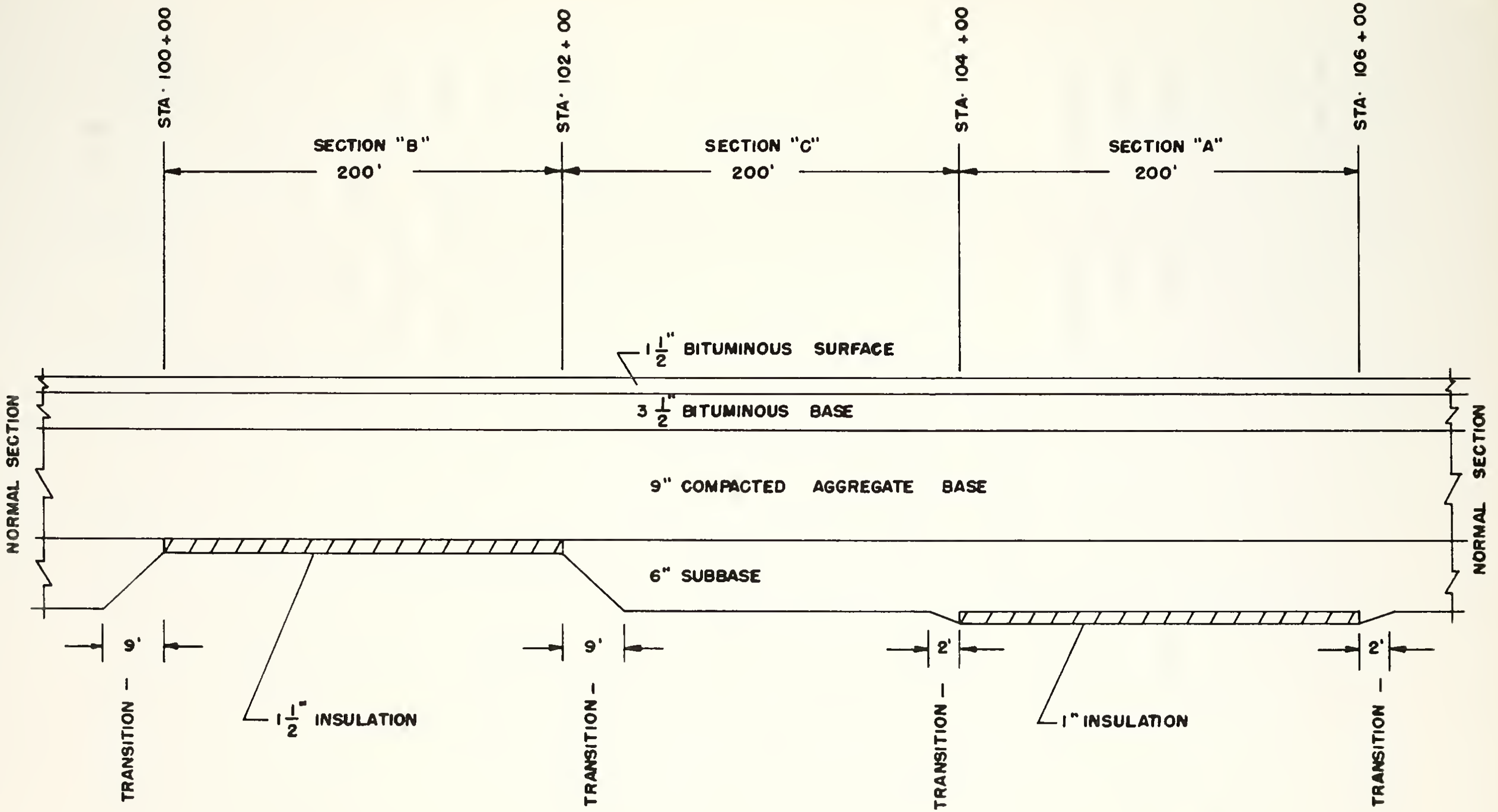


FIGURE I. PLAN OF FIELD TEST INSTALLATION STATE ROAD 26 (from Stulgis)

NOT TO SCALE



NOTE: ALL TRANSITIONS AT 1/2" PER FT.

FIGURE 2 TEST SECTION PROFILE
(from Stulgis)

NOT TO SCALE

in Section B and a 1.5-inch thick layer of insulation was placed on the subgrade extending 23 feet on either side of centerline. The thermistors are placed only in the northern half of the test road and are located at the center of each 200-feet long section. The thermistor positions for Sections A, B, and C are shown in Figures 3, 4, and 5, respectively. Section A has 42 thermistors; Section B, 38 thermistors; and Section C, 24 thermistors; for a total of 104 thermistors.

SITE CONDITIONS

Soil borings were taken at the site on July 2, 1969. These borings were located on the northern half of the highway at stations where the thermistors were placed. Also, soil samples were obtained at the time of thermistor installation from the sides of the installation trench, which was 4 feet in depth. From these investigations the soil profile and moisture conditions were determined.

The subgrade soils of Section A are 4 feet of A-2-4 soil (AASHO classification) overlying more than 8 feet of A-1-b soil. The water contents of the soils were found to be about 5% to 6%. The water table in Section A was found about 14 feet below the pavement surface. The borings in Section A were the only borings in which the water table was encountered. The borings in each section were from 11 feet to 15 feet deep. Section B soils consist of 1 foot of A-2-4 soil overlying 3.5 feet of A-4 soil which overlies an A-6 soil. The water contents were 5%, 13% and 17%, respectively. Section C soils generally consist of 1.5 feet of A-2-4 soil overlying A-1-b soil. There is an additional layer of A-1-a soil about 6 inches thick located 2 feet below the top of the subgrade. The Section C water contents were 5% to 7%.

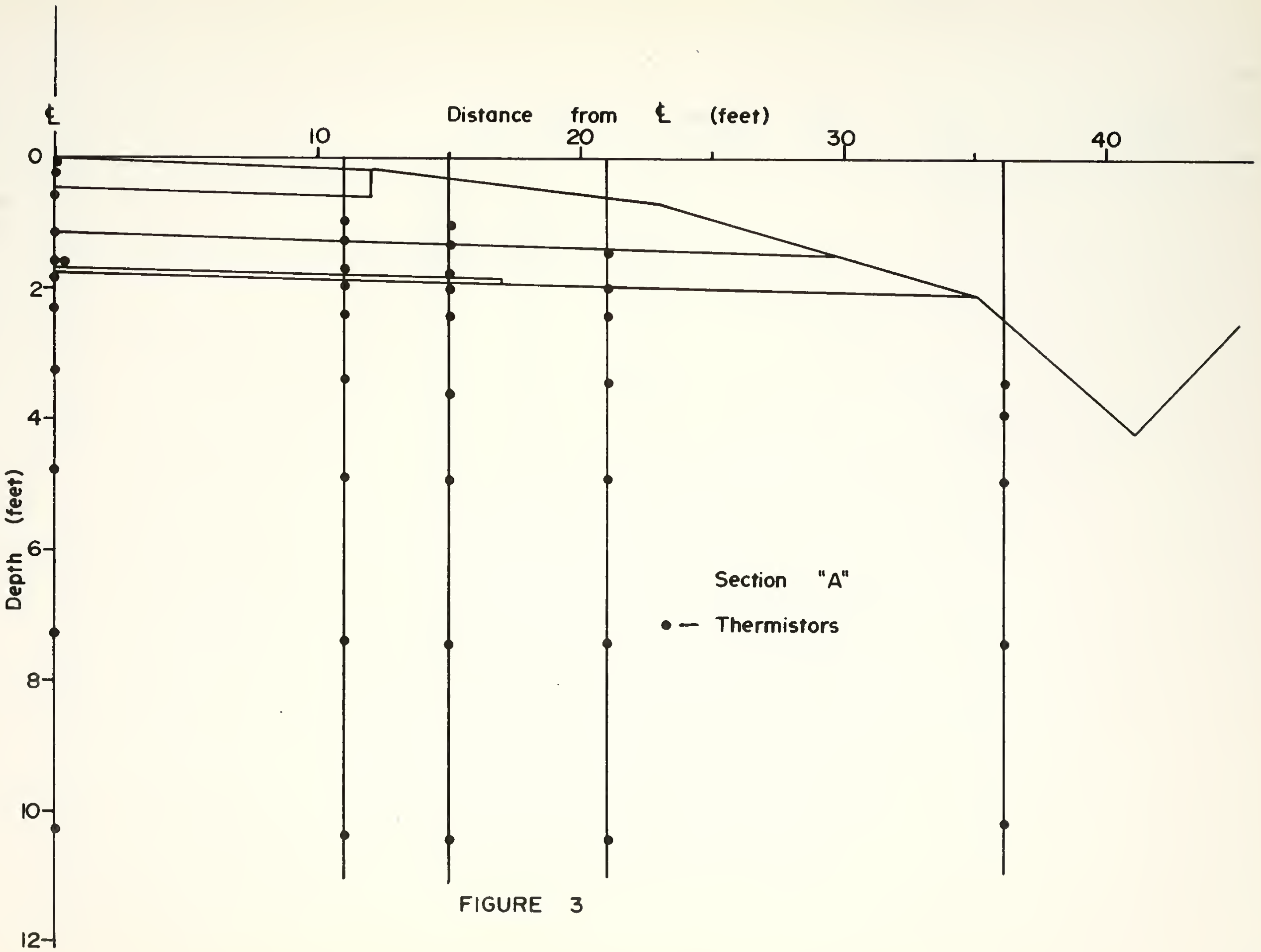

℄
Distance from ℄ (feet)
10
20
30
40
0
2
4
6
8
10
12
Depth (feet)
Section "A"
● — Thermistors

FIGURE 3

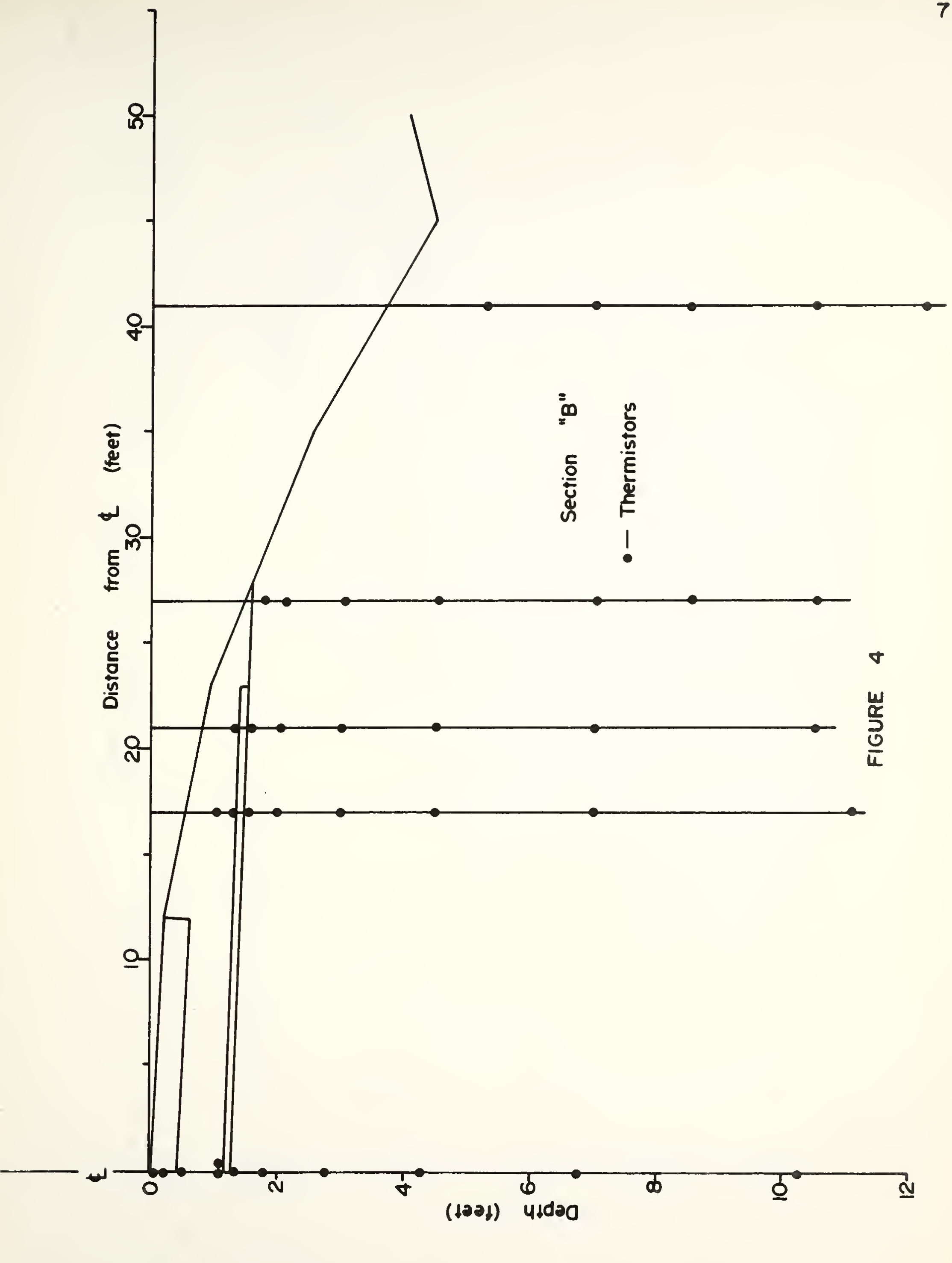

Distance from ℄ (feet)
10
20
30
40
50
Depth (feet)
0
2
4
6
8
10
12
℄
Section "B"
● — Thermistors

FIGURE 4

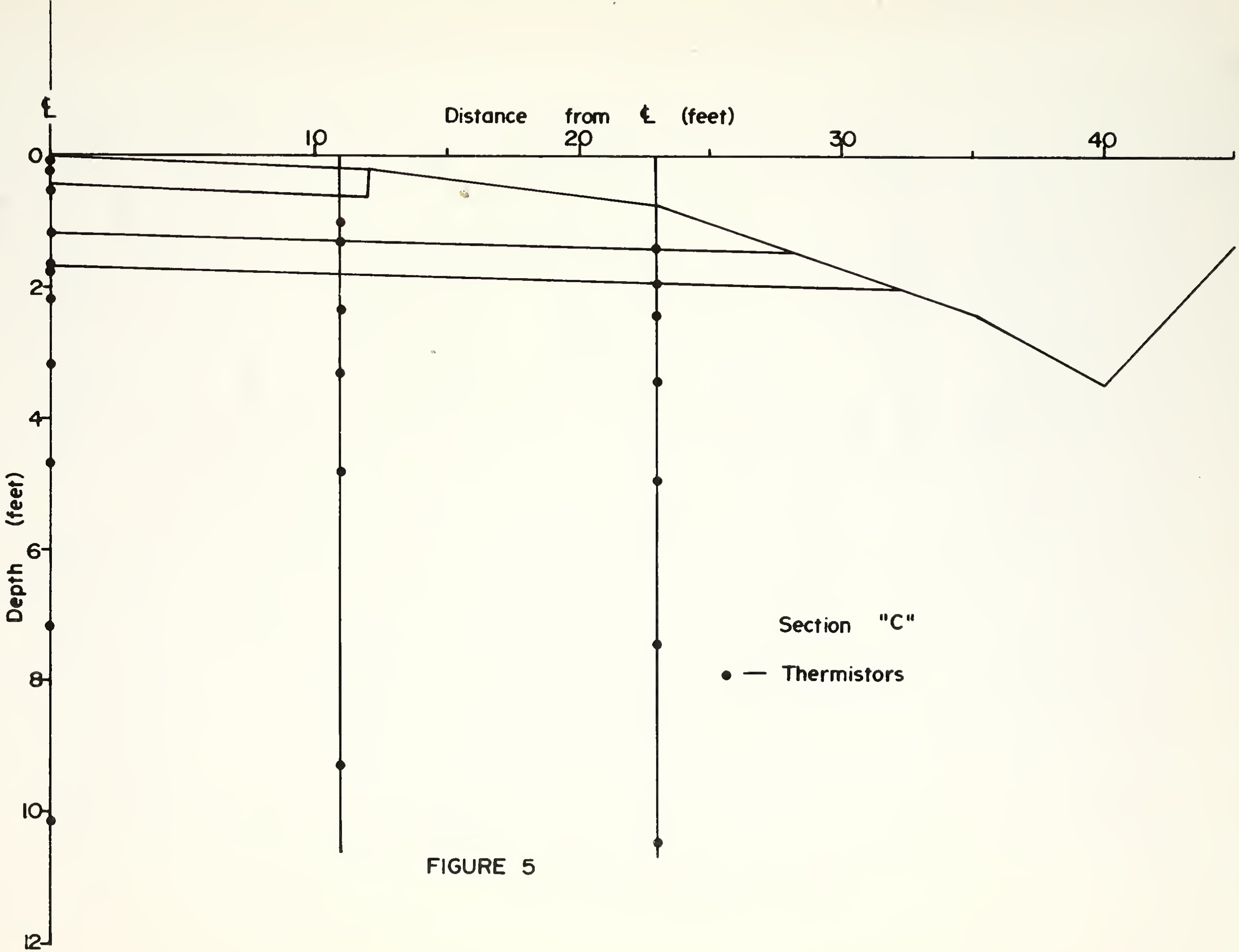

℄
Distance from ℄ (feet)
0
10
20
30
40
Depth (feet)
0
2
4
6
8
10
12
Section "C"
● — Thermistors

FIGURE 5

The site was selected in an area of generally silty soils, and was placed in a cut to increase the wetness (relative to a fill). Unfortunately, neither soil nor water condition were such to produce the hoped for high-frost-damage potential. In spite of this, nearly all the objectives of the study were realized.

PART I - PERFORMANCE EVALUATION

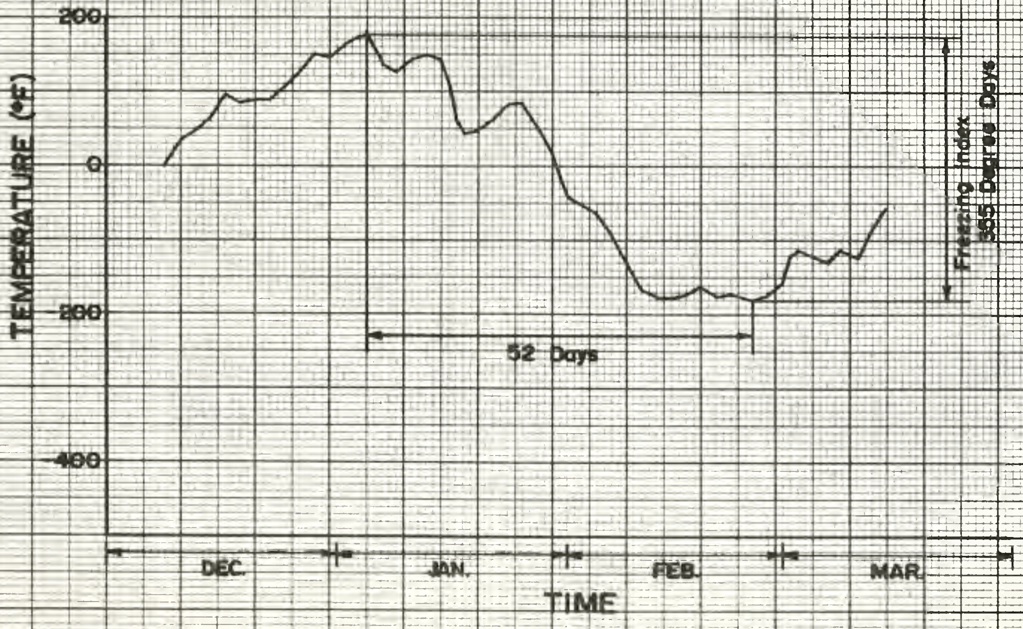
SEVERITY OF THE FREEZING SEASON

The design year for the test installation was 1962-63, the coldest winter in the 10 years preceding 1968, having a freezing index of 1274 degree days over a freezing season of 89 days. The freezing index was calculated in the usual manner using the mean daily air temperature and $32^{\circ}F$ as a reference temperature. A short discussion of the relationship between freezing index and the severity of the winter with respect to structural performance is given by Bowers [2] and is not repeated in this report.

The design criterion for the insulated sections was to prevent penetration of the $32^{\circ}F$ isotherm through the insulation (Stulgis [5]). When the proposed design was analyzed with respect to the design year, it was found that there would be some penetration of the $32^{\circ}F$ isotherm into the subgrade in the insulated sections. However, the design was accepted with the concession that some penetration of the 32° isotherm into the subgrade could be tolerated.

The winter of 1971-72 was not a severe test for the insulation when compared to the design year. An unusually mild December shortened the freezing season considerably. As shown in Fig. 6, the freezing

FIGURE 6
DEGREE - DAY CURVE
1971 - 72



index was 355 degree days over a freezing season of 52 days. It should be noted that most of the degree day accumulation occurred in a 17-day period from January 25 to February 12. A season with this type of freezing index curve would not be critical with respect to large moisture accumulation and high ice contents which result in poor structural performance. However, it is still possible to see the effects of the styrofoam as a thermal insulator.

DATA COLLECTION AND METHOD OF ANALYSIS

The data collected in December gave an indication of the number of thermistors that were still functioning properly. By plotting the measured subsurface temperature versus depth with regard to previously determined curves (Bowers [2]), it was possible to determine which thermistors were erratic. Figures 7, 8, and 9 show the functioning thermistors during the winter of 1971-72 for Sections A, B, and C, respectively.

Generally, data were collected twice a week by the Research and Training Center. The 1969-70 analysis showed that this amount of data could properly define the trends except in periods of sudden or extreme cold. Accordingly, when these particular conditions occurred, additional readings were requested.

The study of subsurface temperature is a five-variable problem. Temperature is the dependent variable with time and with the 3-dimensional subsurface space. The analysis in this report is conducted by holding three of the independent variables constant and studying the effect of the fourth on temperature. As the properties of each section change

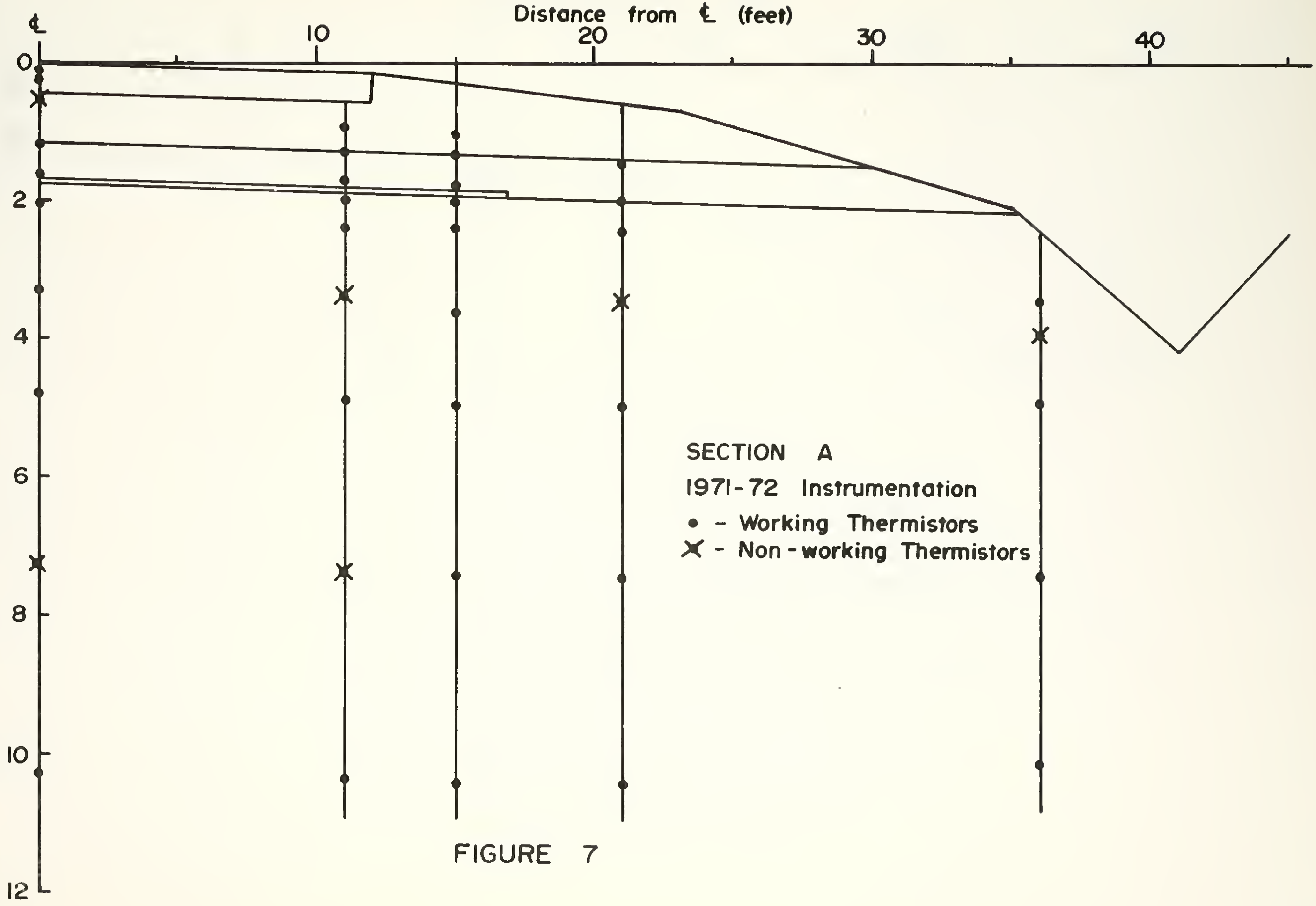

Distance from ℄ (feet)
℄
10
20
30
40
0
2
4
6
8
10
12
SECTION A
1971-72 Instrumentation
● - Working Thermistors
✕ - Non-working Thermistors

FIGURE 7

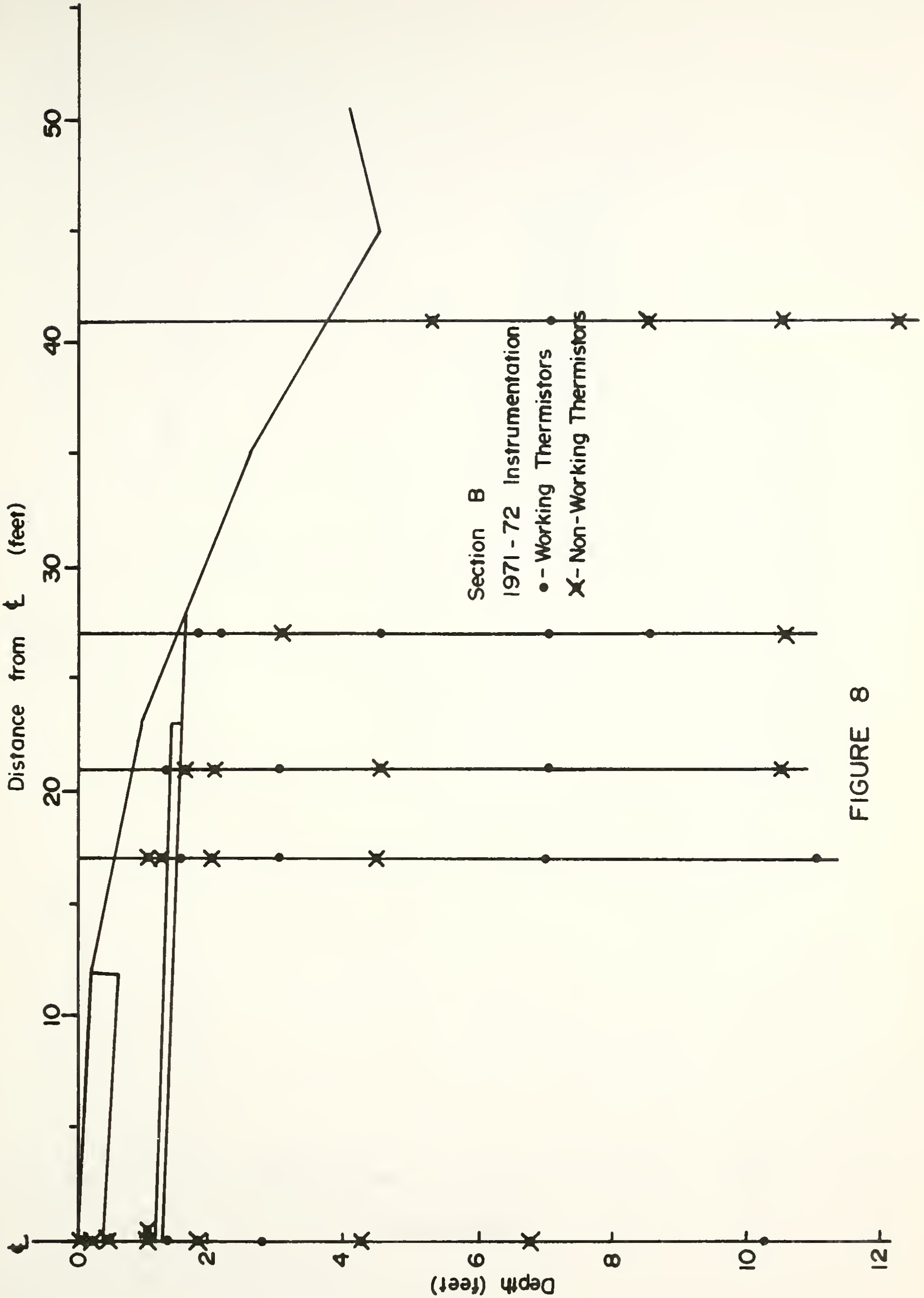

Distance from ℄ (feet)
℄
10
20
30
40
50
Depth (feet)
0
2
4
6
8
10
12
Section B
1971-72 Instrumentation
• - Working Thermistors
X - Non-Working Thermistors

FIGURE 8

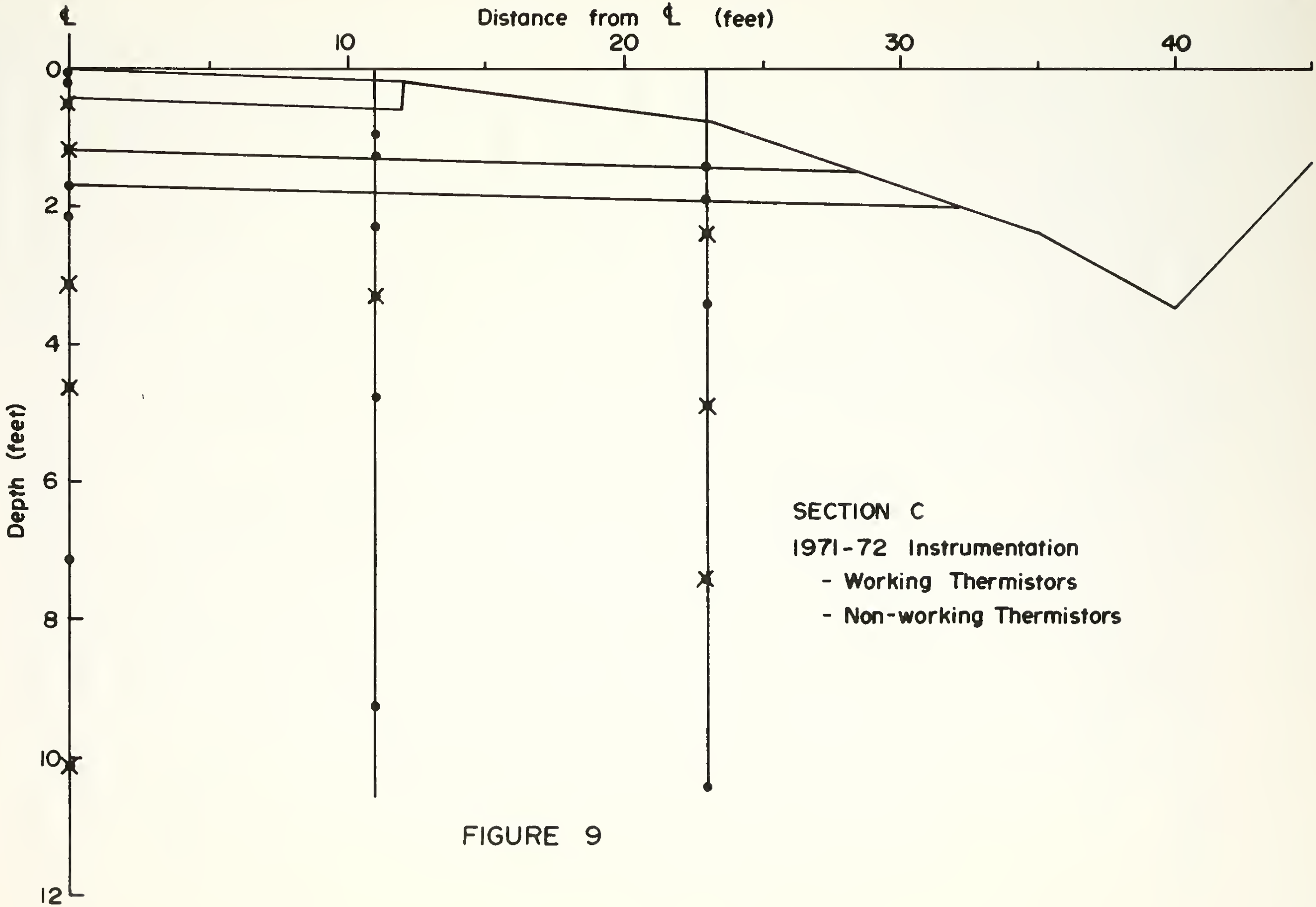

Distance from ℄ (feet)
℄
10
20
30
40
Depth (feet)
0
2
4
6
8
10
12
SECTION C
1971-72 Instrumentation
- Working Thermistors
- Non-working Thermistors

FIGURE 9

with depth, the reader is reminded to be aware of the general relationship between the sections as shown in Figure 2 and as discussed under "Site Conditions". Any differences in the sections that affect the analysis will be noted throughout the report.

PERFORMANCE COMPARISONS OF THE SECTIONS

As previously discussed there are a number of ways of looking at the five variable problem, depending upon which variables are held constant. One of these ways is to hold position (3-D subspace) constant and consider the variation of temperature with time. This is shown in Figures 10, 11, and 12. Figure 10 compares the temperature just below the insulation in Section A and Section B with the temperature at approximately the same depth in Section C. As shown, Section B remains the warmest during the winter even though it is closest to the surface, i.e., 1.37 feet from the surface as compared with 2.25 from the surface for Section A and 1.73 feet from the surface for Section C. Direct comparison of Section A and Section C is difficult because, while Section A is warmer throughout the winter, the point at which the temperature is known is deeper than the corresponding point in Section C. Consequently, it is difficult to separate the effect of the insulation and the effect of different depths. Likewise, when comparing Section B with either Section A or Section C, it should be noted that due to the elimination of the subbase in Section B the materials are not the same with depth. This is shown in Figure 2. In this case there are also two effects to be considered. The effect of the different thicknesses of insulation and the effect of different materials interact to complicate direct comparison.

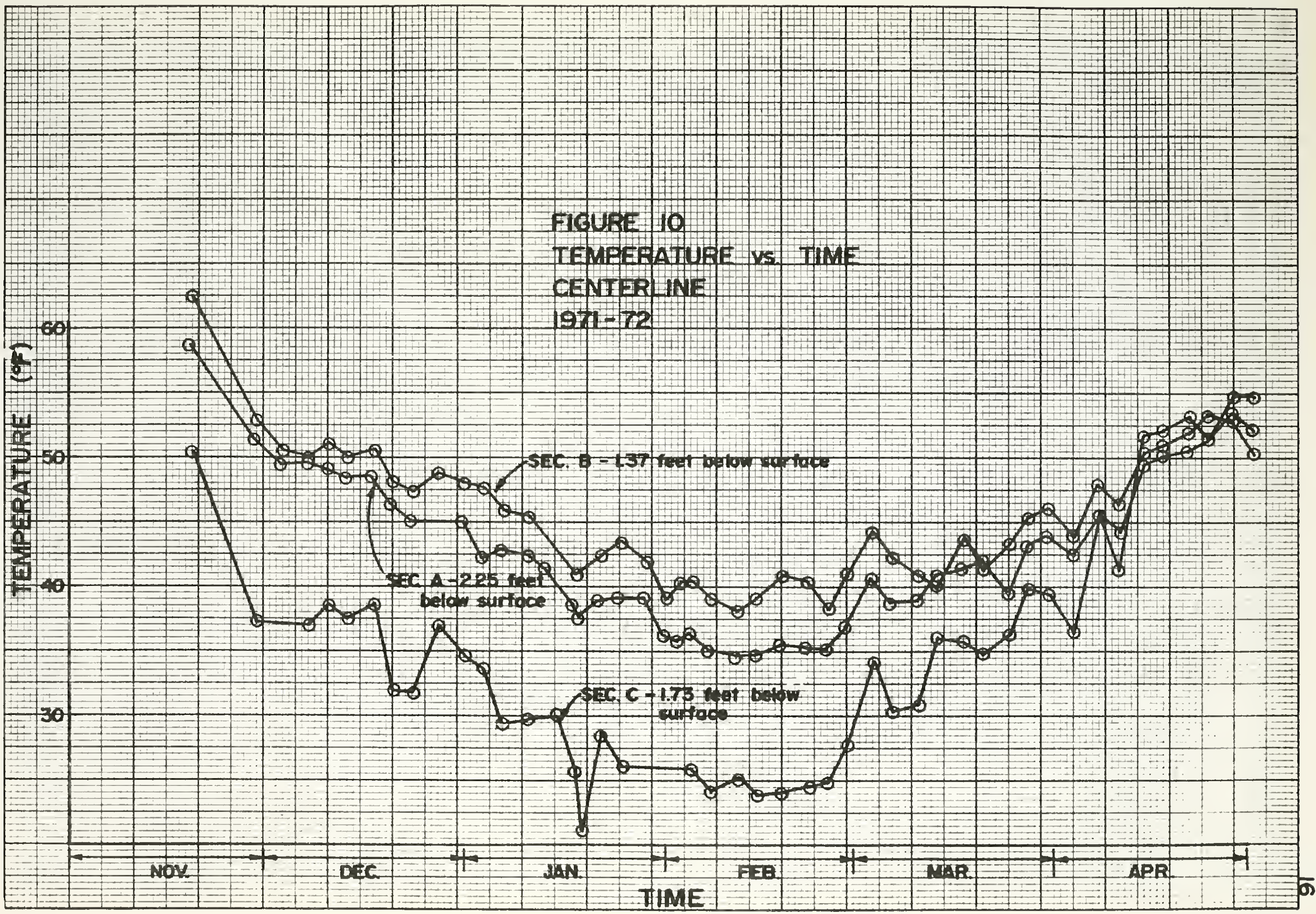


FIGURE 10
TEMPERATURE vs. TIME
CENTERLINE
1971-72

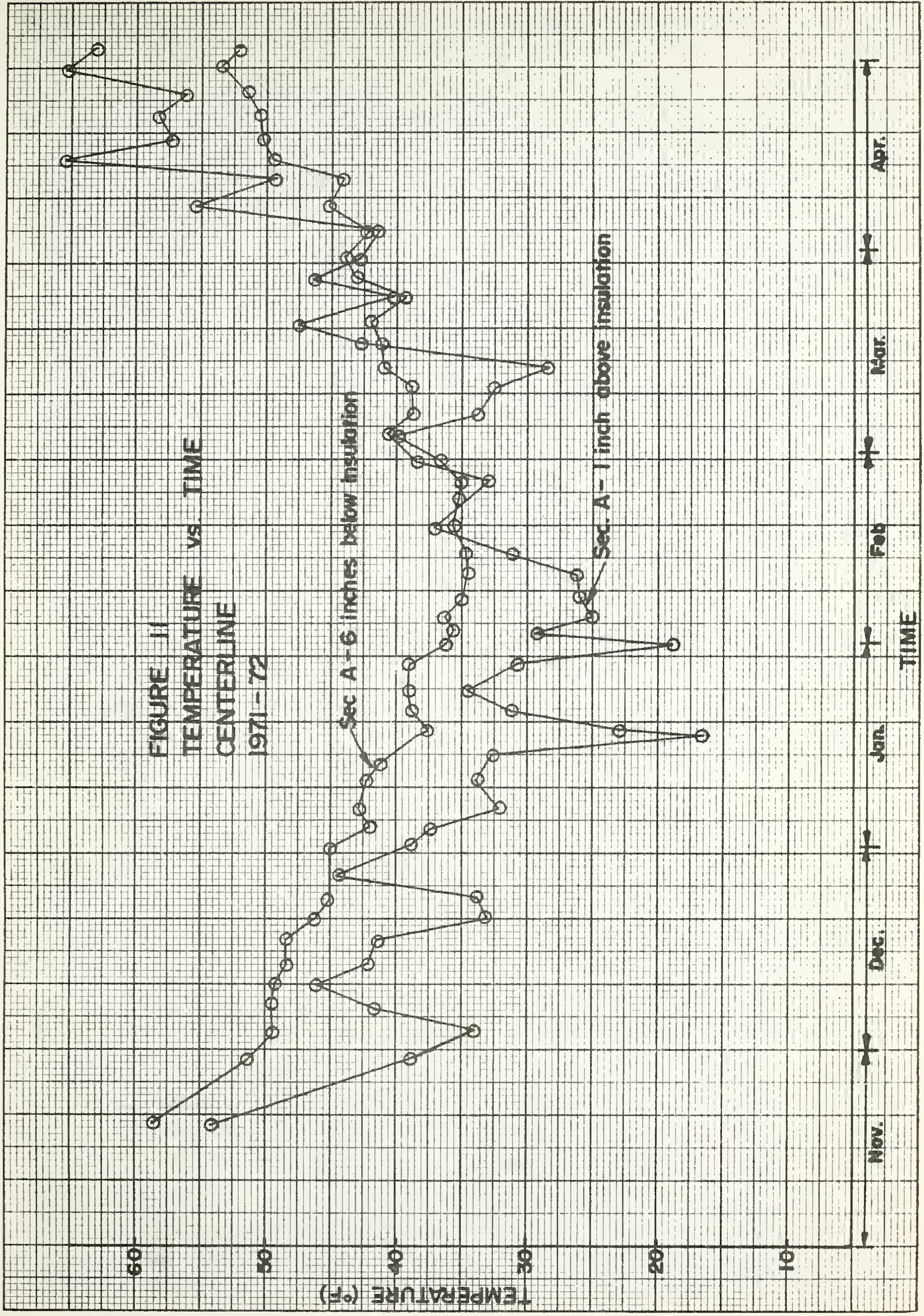


FIGURE 11
TEMPERATURE vs. TIME
CENTERLINE
1971 - 72

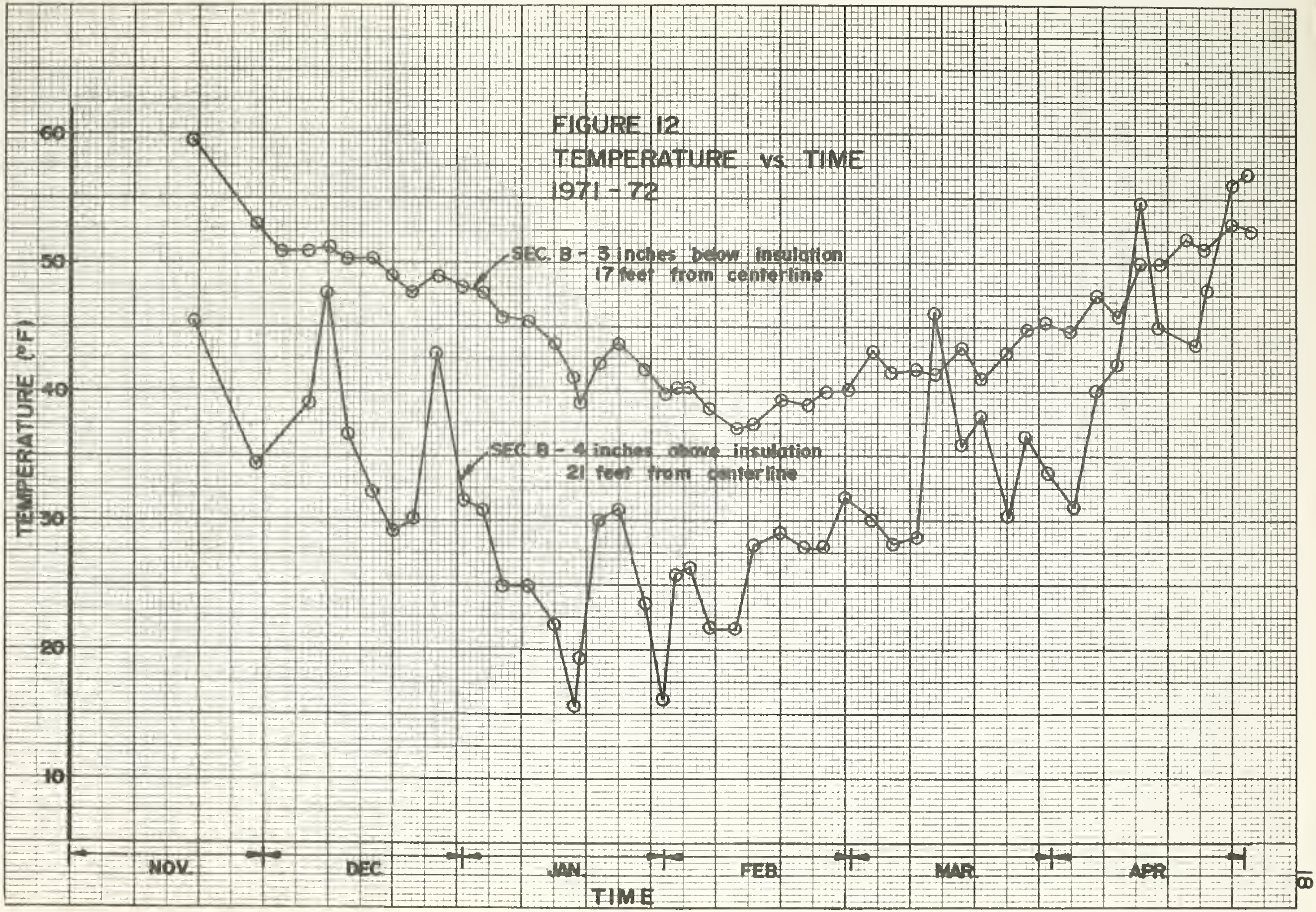


FIGURE 12
TEMPERATURE vs. TIME
1971 - 72

Hypothetically, if the thermal properties of the materials do not greatly change with temperature, 6 inches of subbase material could be placed beneath the insulation to isolate the effect of the insulation. The temperatures in the replaced section would be lower than those in the actual section, an effect similar to the increased depth of frost penetration when frost susceptible material is replaced by non-frost susceptible material. However, again referencing Figure 10, if the temperature just below the insulation is assumed to remain constant through the replaced section, viz., there is no gradiant, to the same depth as considered in Section A or Section C it is apparent that Section B is warmer throughout the winter.

The insulating effect of the styrofoam can also be seen in Figures 11 and 12, which compare the temperatures above and below the styrofoam in Sections A and B, respectively. For Section A the temperature 1 inch above the styrofoam is compared with the temperature 6 inches below the styrofoam at centerline. For Section B the temperature 4 inches above the styrofoam and 21 feet from centerline is compared with the temperature 3 inches below the styrofoam and 17 feet from centerline. The comparison of temperatures at different lateral distances is necessitated by the lack of working thermistors in Section B as shown by Figure 8. The trends are the same. The insulation creates a greater temperature differential than would normally exist over 7 inches. Also, the insulation damps the effect of any temperature change.

It is convenient to hold time constant and view the variation of temperature with depth. The sections are compared in this manner in Figures 13, 14, and 15, for December 23, February 4, and March 20, respectively. Again the subgrade in Section B remains warmer than the

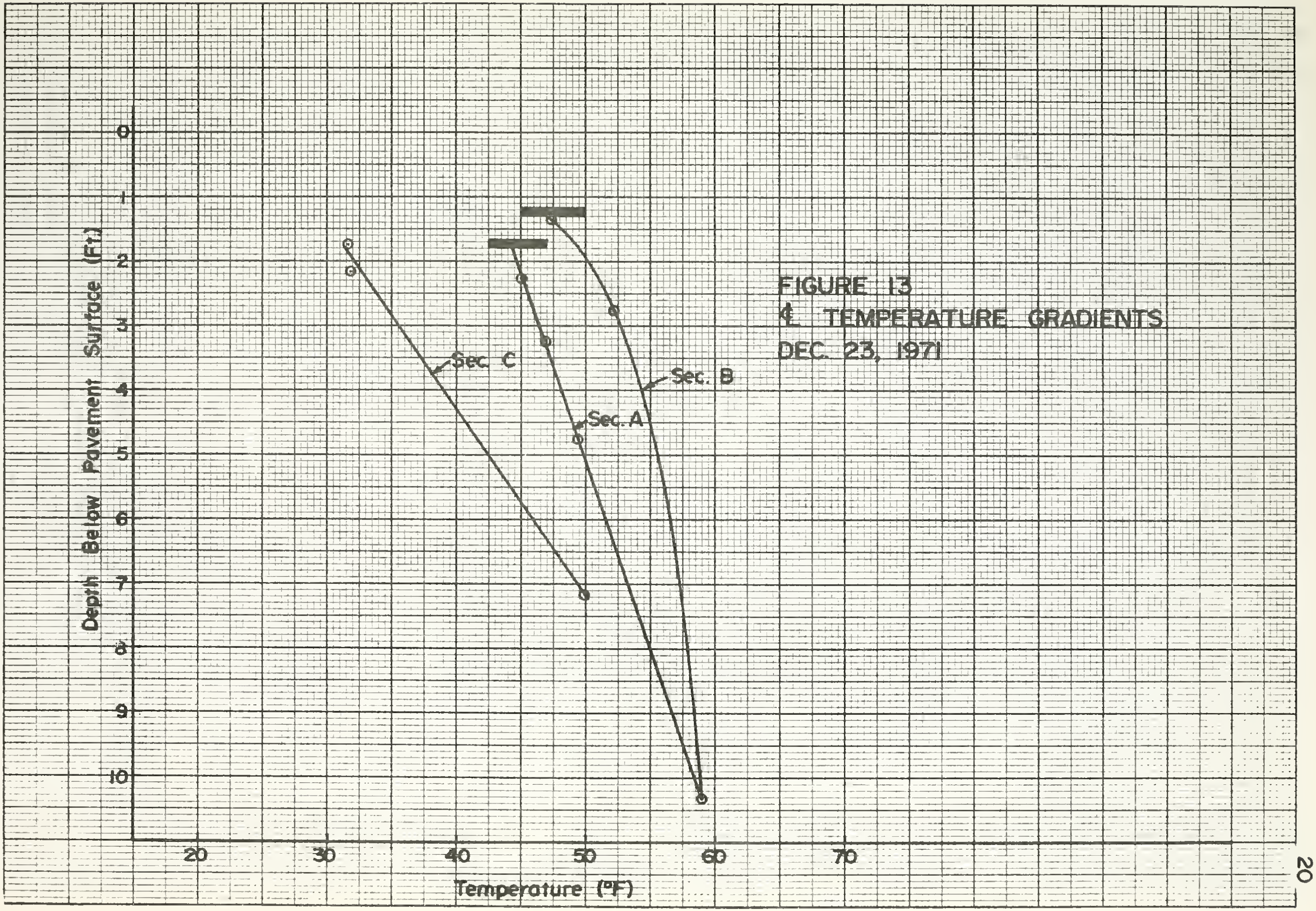


FIGURE 13
℄ TEMPERATURE GRADIENTS
DEC. 23, 1971

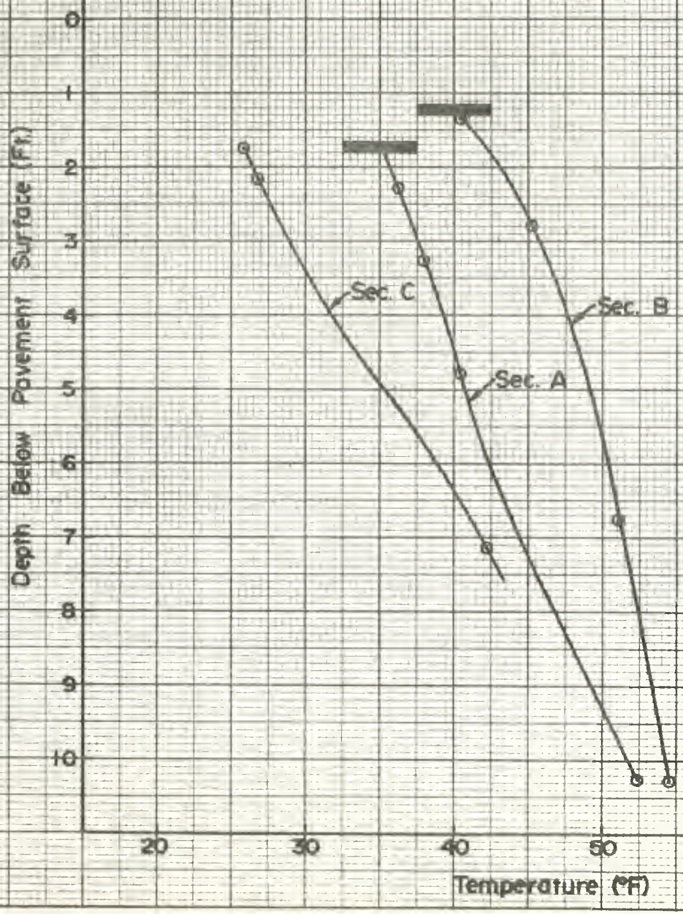


FIGURE 14
℄ TEMPERATURE GRADIENTS
FEB. 4, 1972

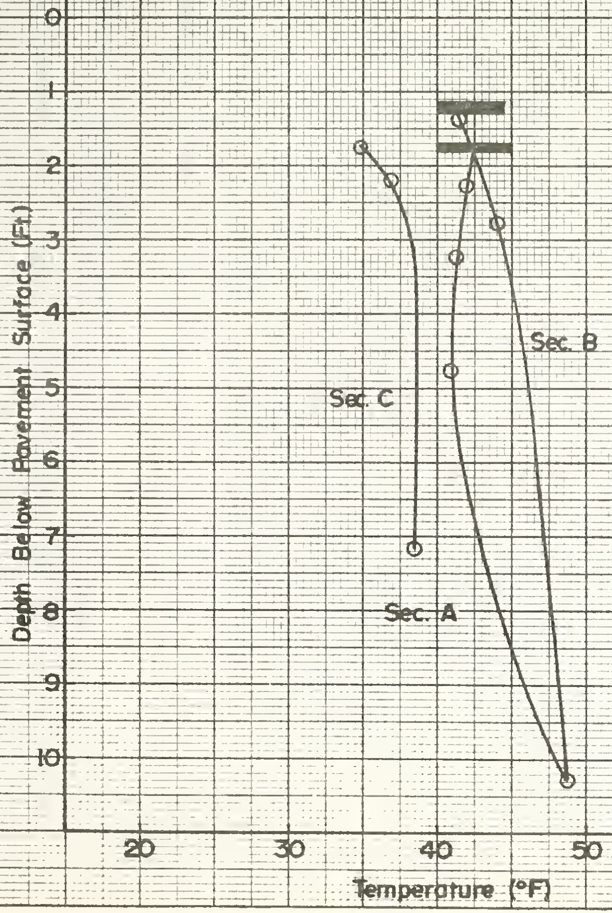


FIGURE 15
℄ TEMPERATURE GRADIENTS
MARCH 20, 1972

other two sections throughout the winter with the Section A subgrade being warmer than that of Section C. It should be noted that the soil type in Section B would cause it to be warmer than the other two sections if no insulation were present in any of the sections. Section A and Section C soil types and water contents are about the same so direct comparison is possible. The change in thermal gradient throughout the winter can be seen by comparing the three figures. Due to the spring warming trend the gradients are almost zero in Figure 15 which is for March 20.

An overall view of the subsurface condition can be seen by plotting isotherms for a constant time for each of the sections. This is done in Figures 16 through 21. Figures 16, 17, and 18 are for Sections A, B, C, respectively for December 23, while Figures 19, 20 and 21 are for February 4. The effect of the insulation can plainly be seen, especially in Figure 20, from the sudden change in curvature in the isotherms at the edge of the insulation. In Section C, the isotherms are parallel to the surface as would be expected. Again, the temperatures in the insulated sections are higher than in the control sections.

Shown in Figure 22 is the depth of the 32° isotherm beneath the subgrade of Section C throughout the winter. As shown, there is a possibility of up to three feet of frost penetration. In comparison, the 32° isotherm did not penetrate the insulation in either Section A or Section B during the winter.

PART II - ICING POTENTIAL SURVEY

A potentially troublesome side effect of subgrade insulation when used in sections is a differential in the temperature of the pavement

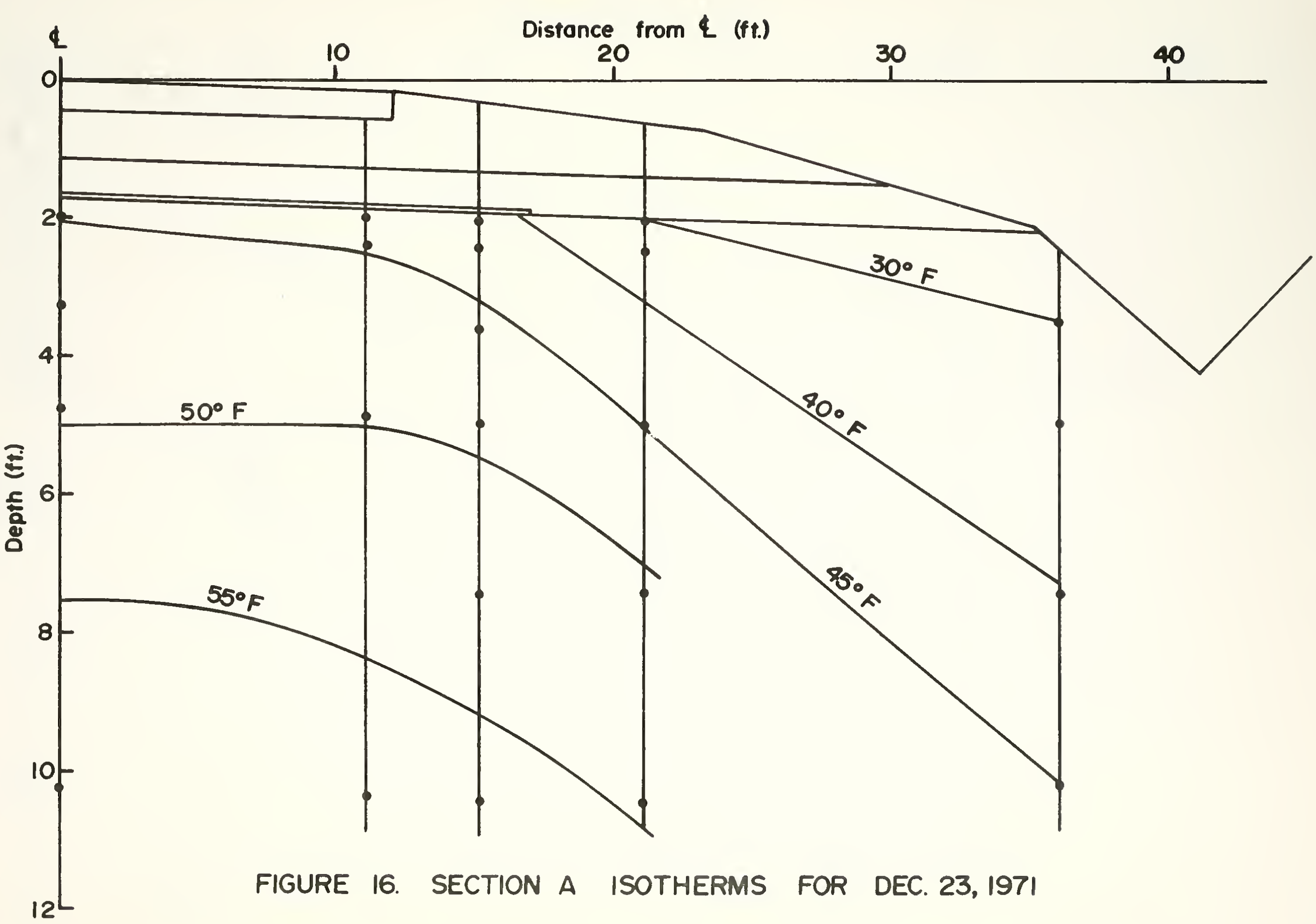


FIGURE 16. SECTION A ISOTHERMS FOR DEC. 23, 1971

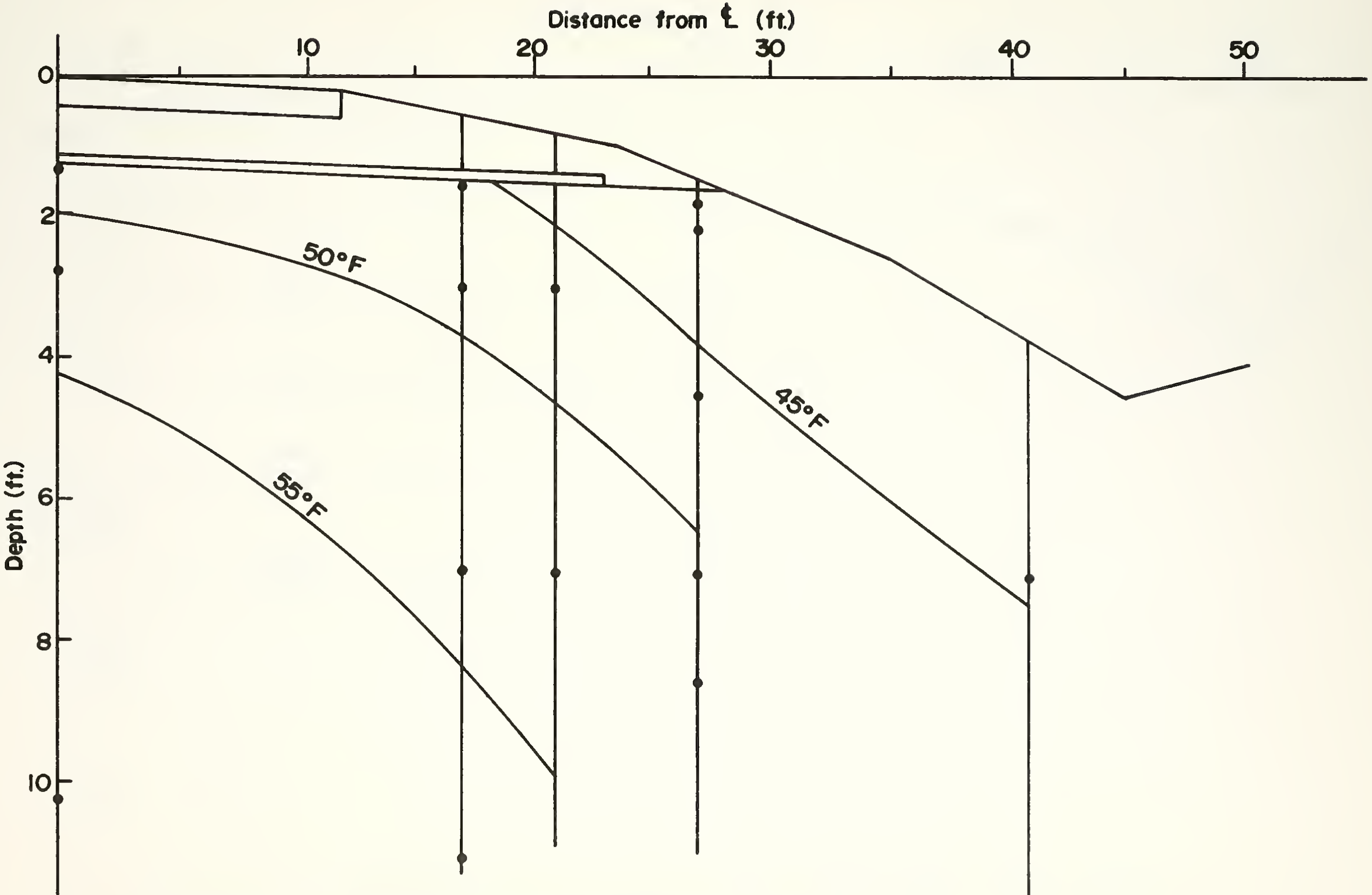


FIGURE 17. SECTION B ISOTHERMS FOR DEC. 23, 1971

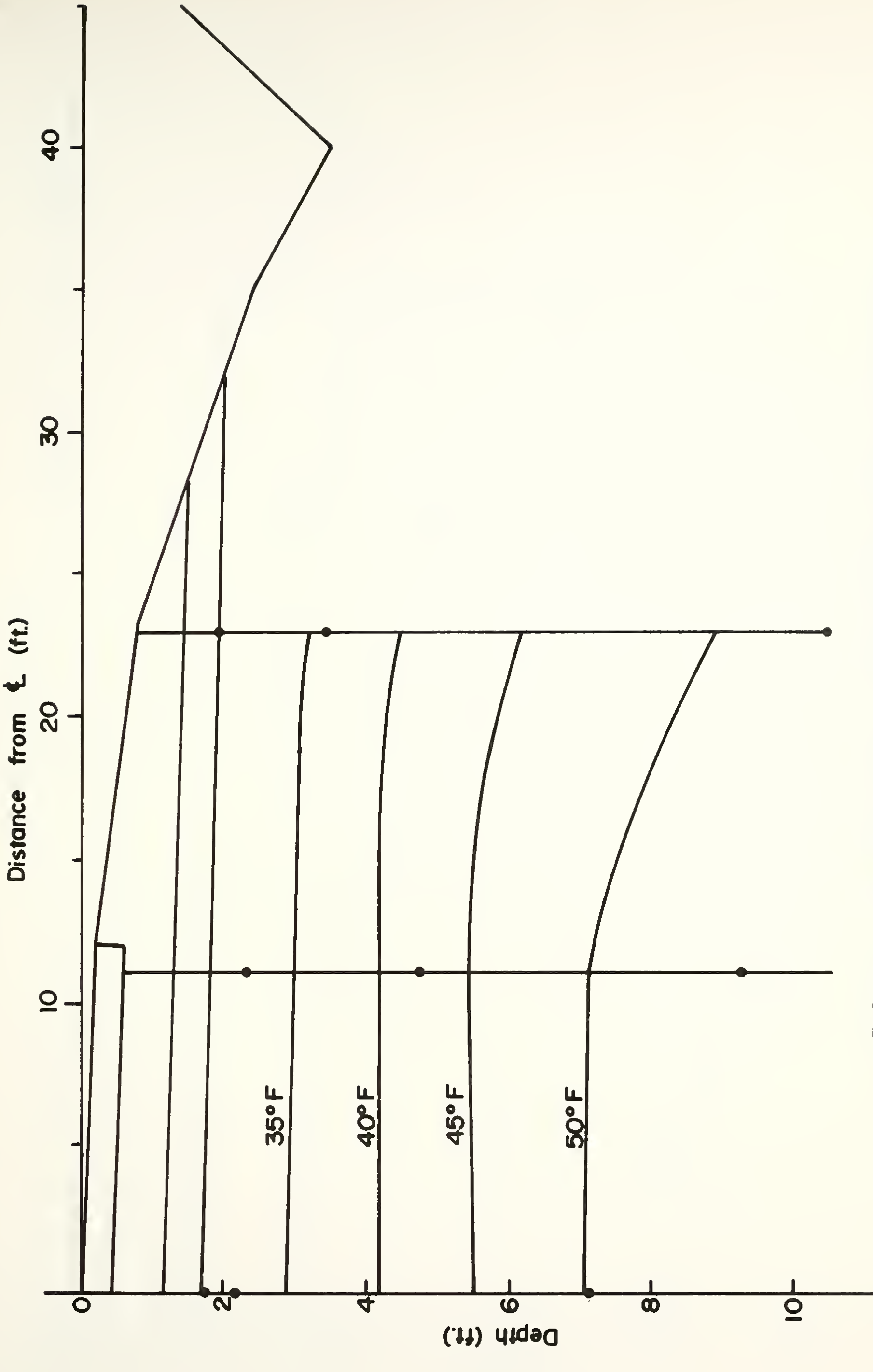


FIGURE 18. SECTION C ISOTHERMS FOR DEC. 23, 1971

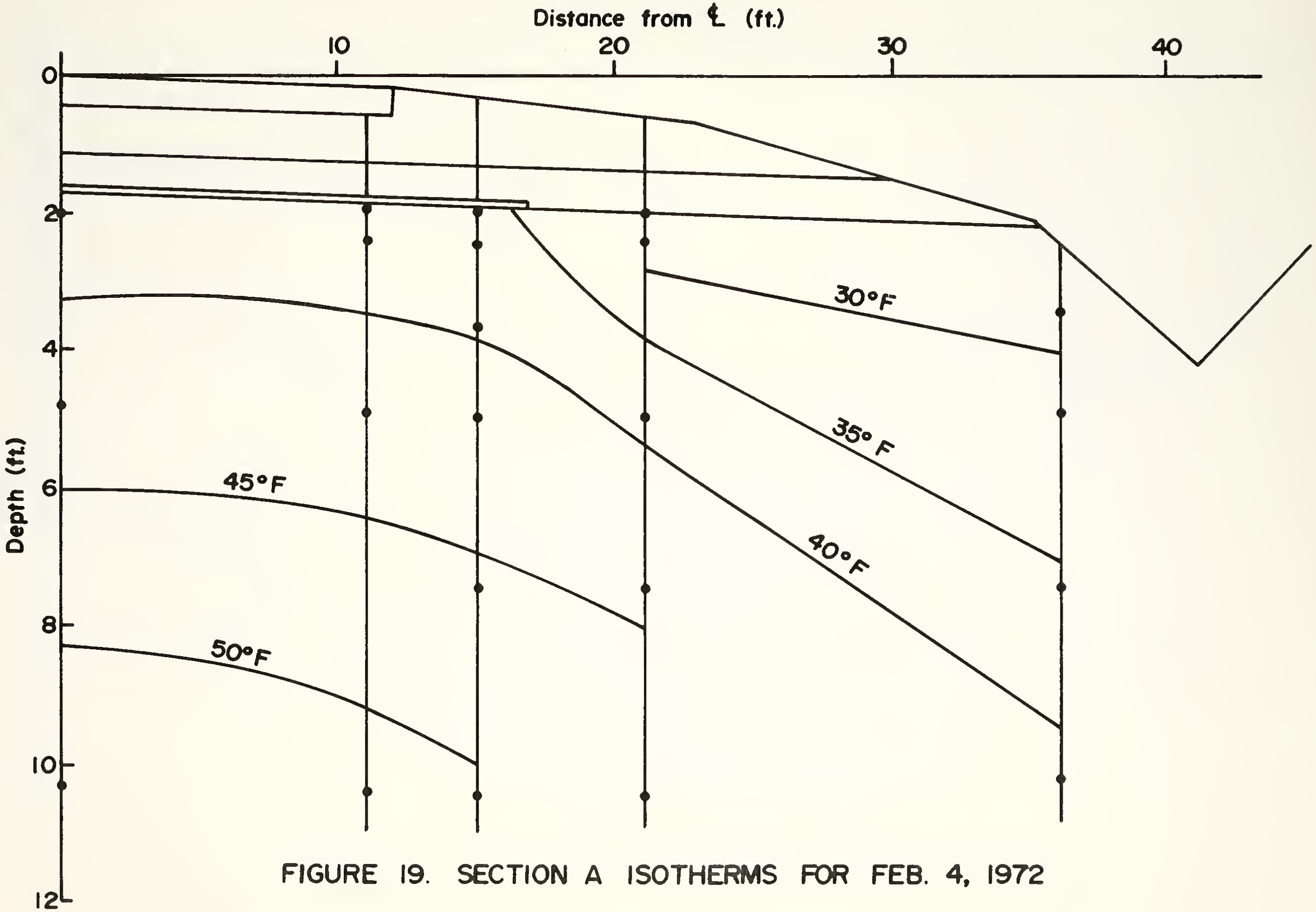


FIGURE 19. SECTION A ISOTHERMS FOR FEB. 4, 1972

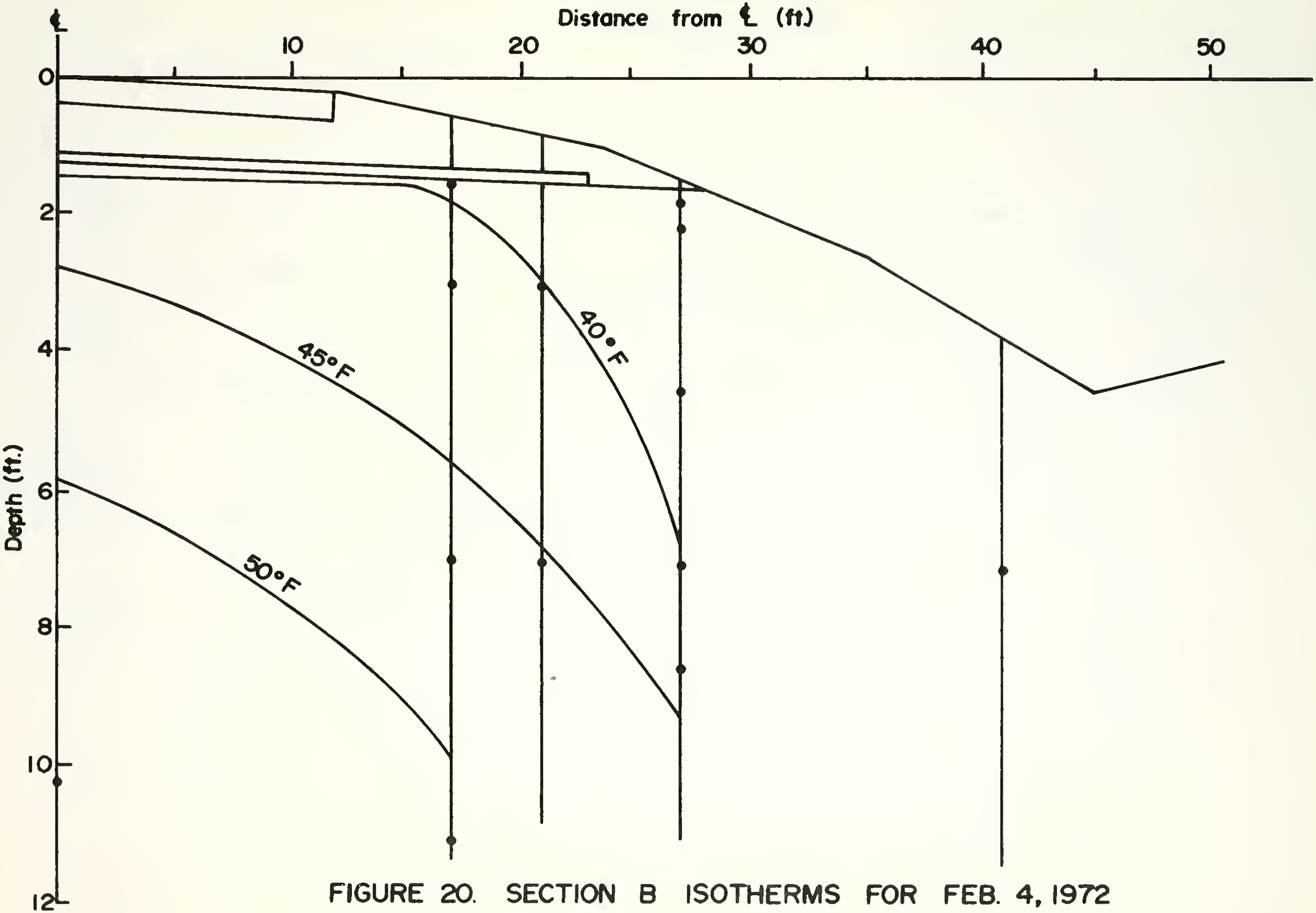


FIGURE 20. SECTION B ISOTHERMS FOR FEB. 4, 1972

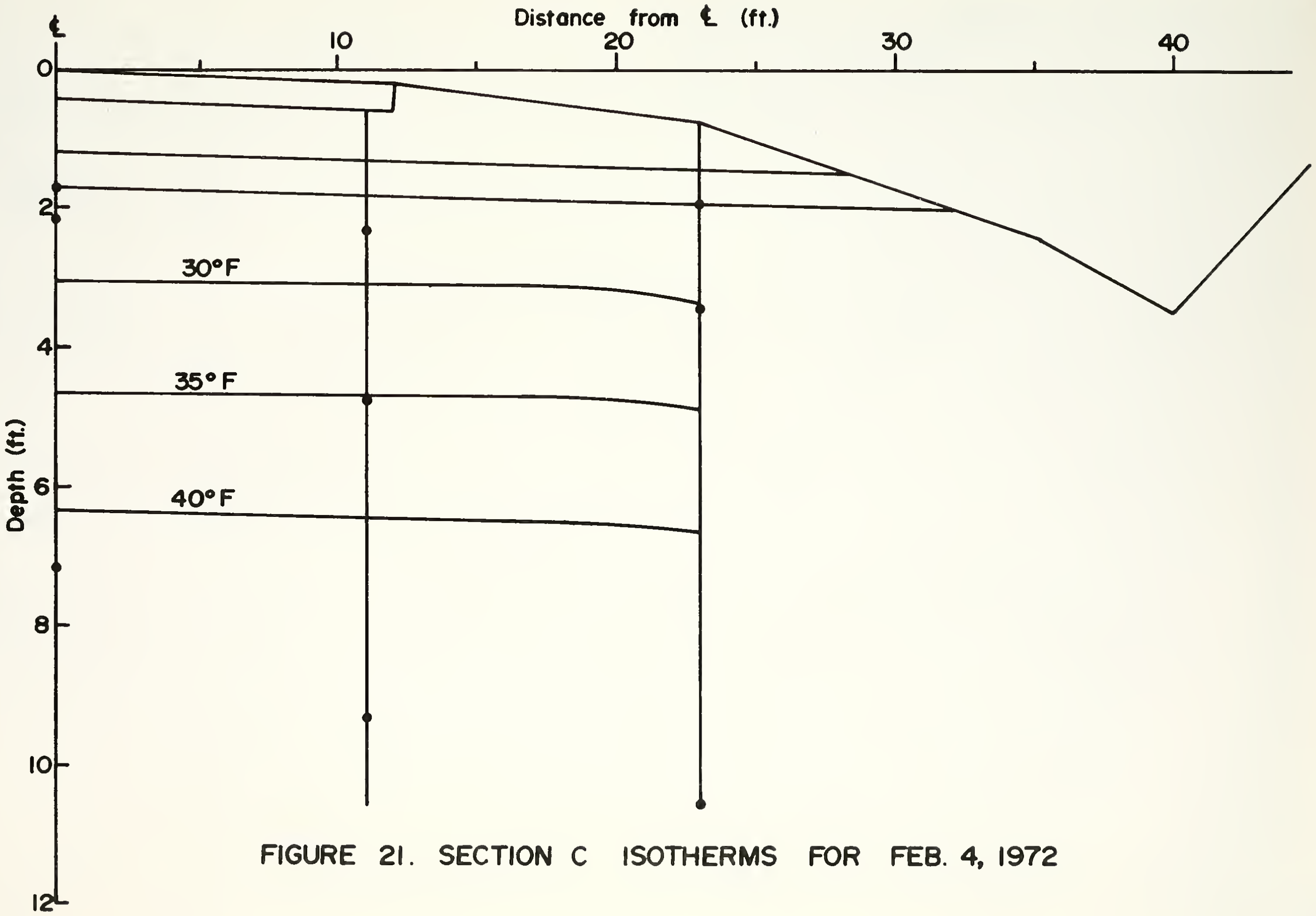
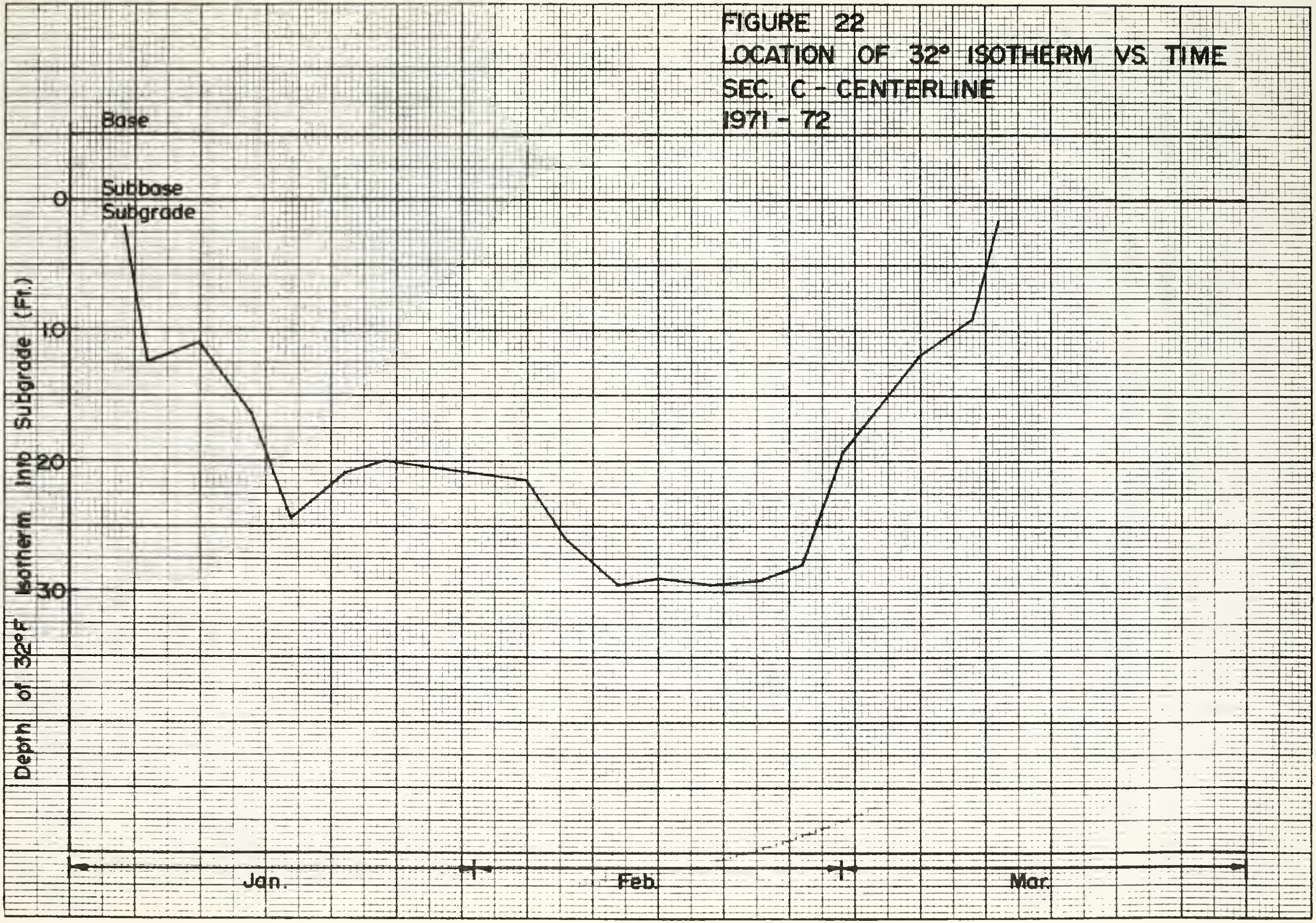


FIGURE 21. SECTION C ISOTHERMS FOR FEB. 4, 1972

FIGURE 22
LOCATION OF 32° ISOTHERM VS. TIME
SEC. C - CENTERLINE
1971 - 72



surfaces of insulated and uninsulated sections which can lead to preferential icing of these surfaces. The pavement system above the insulation may be either cooler or warmer than a similar uninsulated system depending upon whether the air temperature is in a general cooling trend or a general warming trend. Bowers [2] showed that the insulated section pavement systems were colder in the winter months than the uninsulated section pavement system, presumably because the insulation prevents upward heat flow from the warmer subgrade soils. Likewise, during the spring warming trend it is possible for the uninsulated section pavement to be colder because of the frozen subgrade beneath. As a result of the varying pavement temperature, it is possible for an insulated section pavement surface to ice while an adjacent uninsulated section pavement surface does not ice, and vice versa.

An attempt was made to determine the degree of differential icing on the test road during the winter of 1971-72. This study was limited by two factors. The first was that the instrumentation system was not designed to record pavement surface temperatures. Secondly, the distance of the test installation from Purdue prohibited more than a random daily visual observation of the pavement condition.

Figure 23 is a plot of the temperature with time at the centerline and 1 inch below the surface in Section A and Section C. Data from Section B are not shown because of erratic thermistors. Previous work has shown (Bowers [2]) that comparison of Section B with Section C would give the greater difference. The reader should also note that the times of available temperature readings are sometimes different. Comparisons are most valid where both sections have readings on the

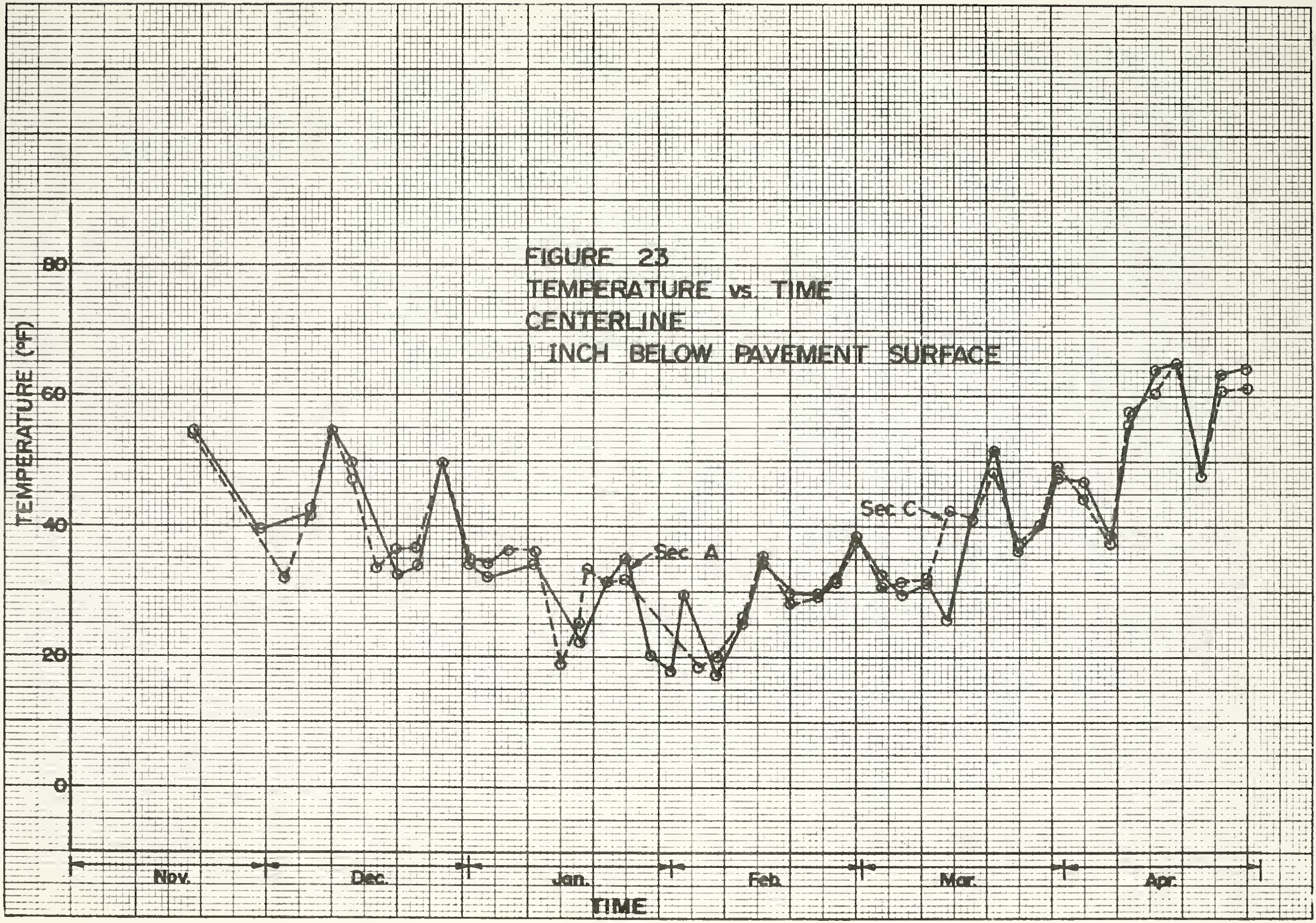


FIGURE 23
TEMPERATURE vs. TIME
CENTERLINE
1 INCH BELOW PAVEMENT SURFACE

same days. However, the figure does show the expected trend, viz., the insulated pavement (Section A) is cooler than the uninsulated one (Section C) during a cooling trend and vice versa during a warming trend.

Daily observation of the pavement condition began January 13, 1972 and continued until March 2, 1972. The survey consisted of completing a Form (Appendix B) which noted certain facts about the pavement surface condition, e.g., the traction condition, the extent and location of any non-dry areas, and comparisons of the test sections with the rest of the highway. These observations were usually made in the morning.

No differential icing was encountered during the survey, but some difference in behavior was observed. On three occasions a distinct color difference between the sections was noticed. Two blocks of darker color could be seen, which coincided exactly with the two insulated sections. Closer examination revealed this darker color was the result of moisture, which had either condensed or had not dried, in the minute surface cracks of the asphaltic surface. The actual traction surface of the insulated sections was dry. A reverse situation was also seen during a light snowfall with the air temperature around 30°F. The uninsulated section was wet and slick while the insulated sections were dry. The condition resulted from the uninsulated section pavement being warm enough to melt the snow while the snow was not melted on the cooler insulated sections pavements and was blown off.

The fact that the icing survey consisted of only daily observations should be re-emphasized. Consequently, it is inadvisable to conclude that differential icing is a minor problem in Indiana, although evidence of this study would support such a conclusion.

It is also well to restate the findings of Bowers [2]. The tendency for an insulated section to ice with respect to an uninsulated one (or vice versa) depends upon the general trend of air temperatures. In a general cooling trend, the insulated sections are more likely to have surface ice, while in a general warming trend, the uninsulated sections are more likely to have ice.

PART III - DESIGN APPROACH

TWO-DIMENSIONAL HEAT FLOW MODEL PREDICTION METHOD

Besides a material that adequately insulates the subgrade, it is necessary to have a workable design procedure for its use. There are both empirical and theoretical methods available. The test installation for this project was designed using a theoretical approach (Stulgis [5]). If accurate subsurface temperatures can be predicted, the theoretical method will naturally render the most economical design. It would also be possible to compare alternate designs quickly and easily. Accordingly, the objective of this phase is to demonstrate the use of a theoretical method as a design tool and discuss the results of varying its input.

The theoretical approach utilizes a two-dimensional finite difference technique developed by Ho [3] to predict temperatures in a layered "soil"-water system. There are three general areas of required input: 1) geometric details of the system, 2) material properties, and 3) boundary conditions.

The primary geometrical consideration is prescribing the solution mesh which corresponds to the shape of the system. Figure 24 is an example of the mesh used for Section A. Each of the cells must be

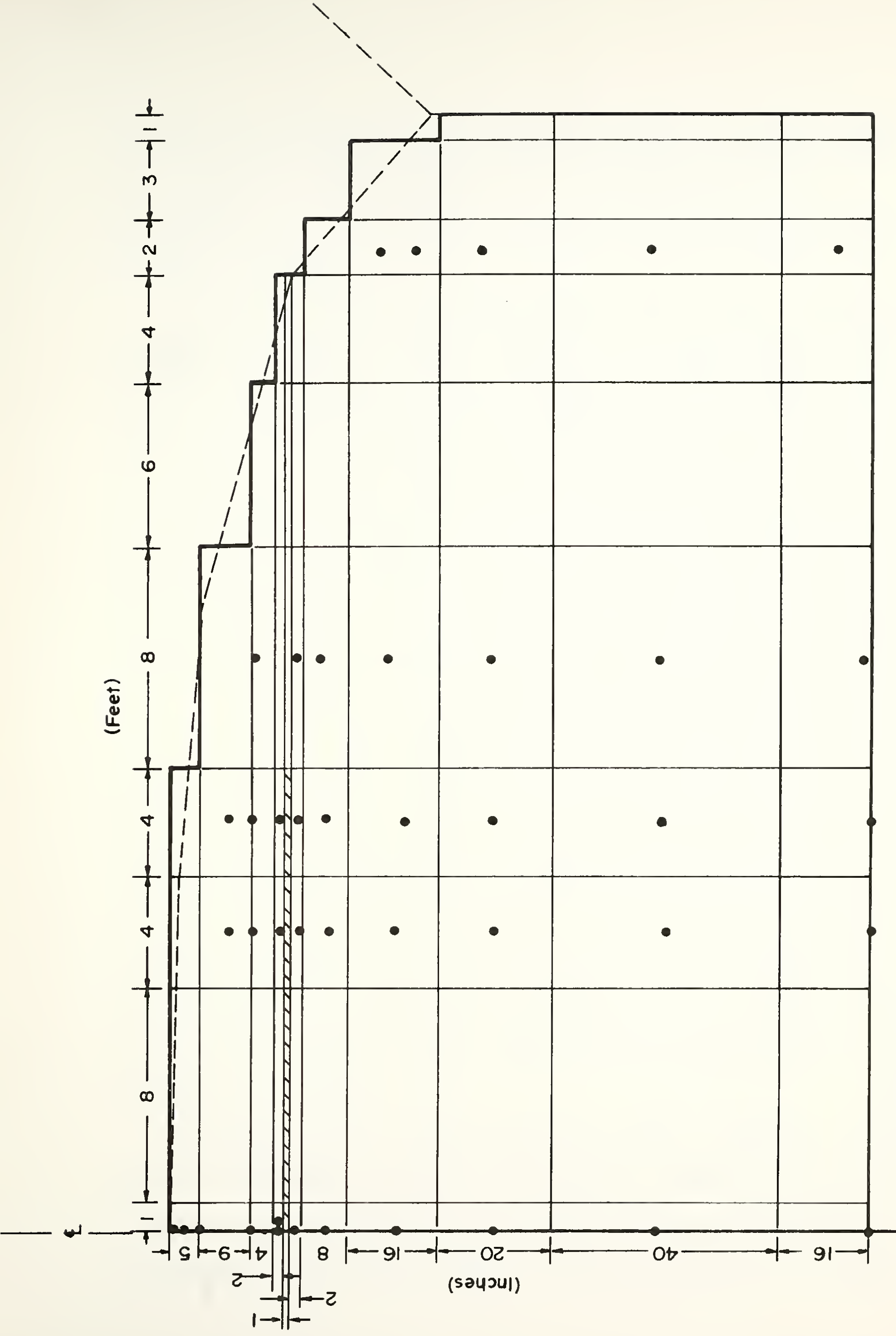


FIGURE 24

Section A Mesh

rectangular and contain only one type of material. As seen in Figure 24, because of the rectangular cells the side slopes can only be approximated. A more detailed discussion on the selection of the mesh is given by Bowers [2].

The required material properties are the unit weight, water content, thermal conductivity, volumetric heat, and ice formation characteristics for each cell in the mesh. The unit weights and water contents are either found from borings for the foundation materials or from specified design valves for the compacted materials. The volumetric heat input consists of the individual volumetric heats of water, ice and dry soil. The volumetric heats used for water, ice and dry soil are 1.0 BTU/LB-DEG F, 0.5 BTU/LB-DEG F and 0.2 BTU/LB-DEG F, respectively. The water in the soil is assumed to freeze according to the relation:

$$\text{Percent Frozen} = C5 - C^{C6\cdot\text{Temperature}+C7} \qquad \text{Ho [3]}$$

where C5, C6, and C7 are constants. Their value depends upon the temperature range over which the pore water is assumed to freeze. For the materials at the test installation, the pore water is assumed to be completely frozen at 25°F. The thermal conductivities of the soil completely frozen and unfrozen are the input for the cells thermal conductivity determinations. An interpolation is made for a partially frozen soil. The frozen and unfrozen thermal conductivities are determined from curves given by Kersten [4].

Assumptions have to be made about the system's temperature boundaries. The upper boundary is defined by the mean daily temperature, coupled with a surface transfer coefficient. For this study the side boundaries temperatures for the next calculation in time are taken as the same as the temperatures of the adjacent cells from the current time calculation. There are a number of ways to handle the lower boundary. The various methods will be discussed in more detail later in the report.

Initial Conditions

For the solution process to begin, each cell must have a known temperature. The accuracy of these initial conditions determines how quickly the solution converges to the real situation. Ho [3], during the development of the 1-D heat flow program which preceded the 2-D heat flow program, assumed a constant temperature, 50°F, throughout the profile, and found that the temperature 1 inch below the insulation took almost two months to converge. The initial difference in temperature at this point was 8°F.

Bowers [2] recommends that even for the test sections where measured temperatures are available, temperature predictions be started 10 to 15 days before the date comparisons are to be made.

The effect of improper initial conditions can be seen in Figure 25. Three cases of different initial condition methods are compared with the observed temperature at a point six inches below the insulation in Section A. From these results, it seems that the quickest convergence results from an initial condition determination which fits a curve to experimental values. The amount of computational convergence lead time will of course depend upon the number of known points and the accuracy of the temperatures at these points.

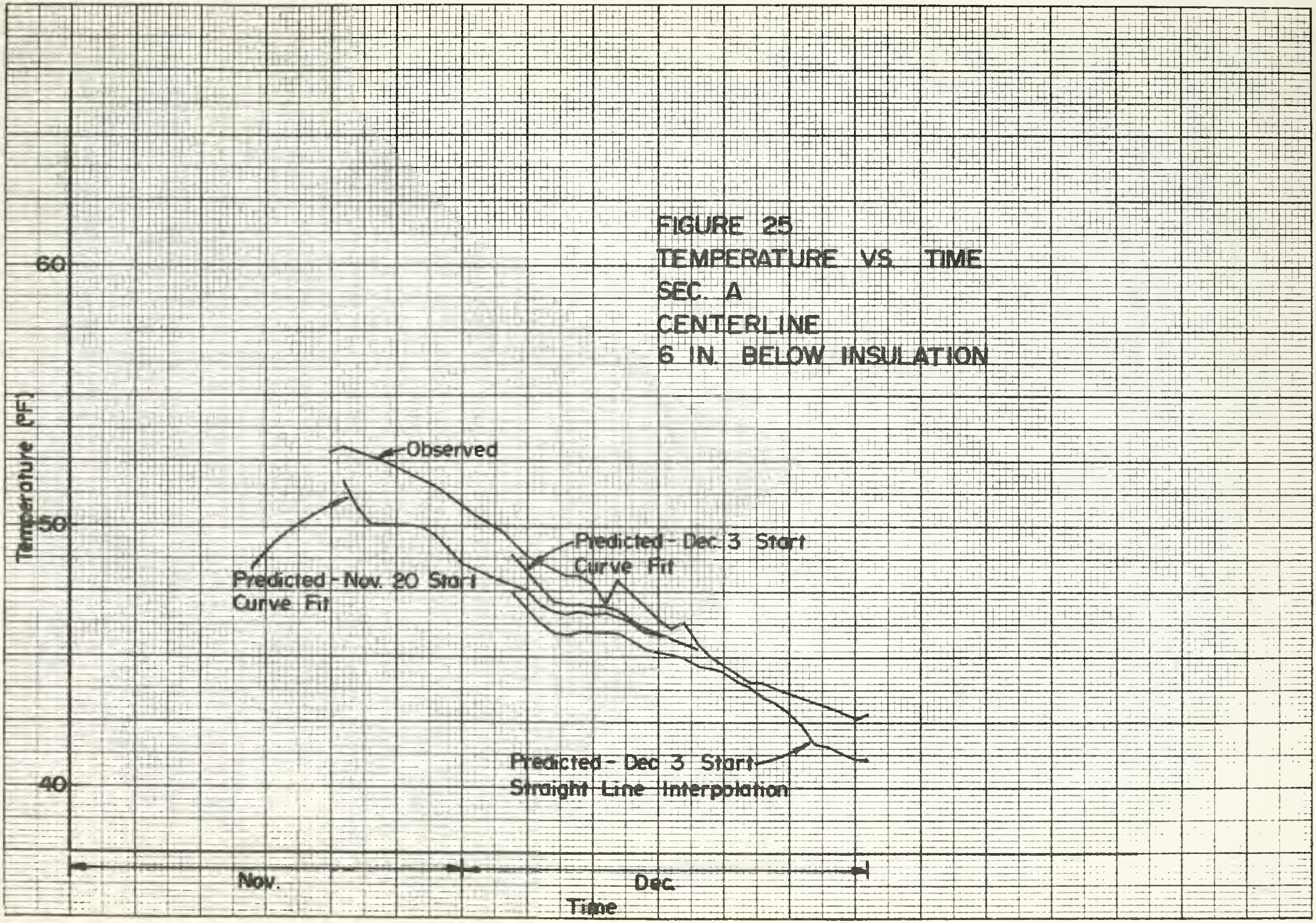


FIGURE 25
TEMPERATURE VS. TIME
SEC. A
CENTERLINE
6 IN. BELOW INSULATION

Upper Boundary

The 24-hour mean air temperatures in the form of a step function are used as the system upper boundary. The program is generalized such that a step of any length could be used, with the constraint that it be a multiple of the program time increment. As it is not feasible to have temperature data recorded at every design location, it is desirable to know the effect of a change in the upper boundary when all other factors are held constant.

Ho [3] did some study of the sensitivity of the solution to the upper boundary for the 1-D heat flow model. The study considered two cases, using data from another test installation. Constant upper boundary temperatures that resulted in the same degree-day value as the actual condition were used. In the first case, a constant temperature of 19.5°F for 99 days was used and in the second case a temperature of -18.4° for 25 days coupled with a temperature of 32°F for 74 days was used. The temperature at 1/2 inch below the insulation was compared for each of these cases with the actual measurements. It was found that the minimum temperature predicted deviated as much as 7°F at this point.

In the study for this report another form of the same problem was considered. The upper boundary temperature was varied a constant amount each step to determine the effect with depth of a small but continuous error in the upper boundary. In Section A, 5°F was first added to the upper boundary temperature and then subtracted as shown in Figure 26. In Section C, as shown in Figure 27, 5°F was added to the upper boundary temperature.

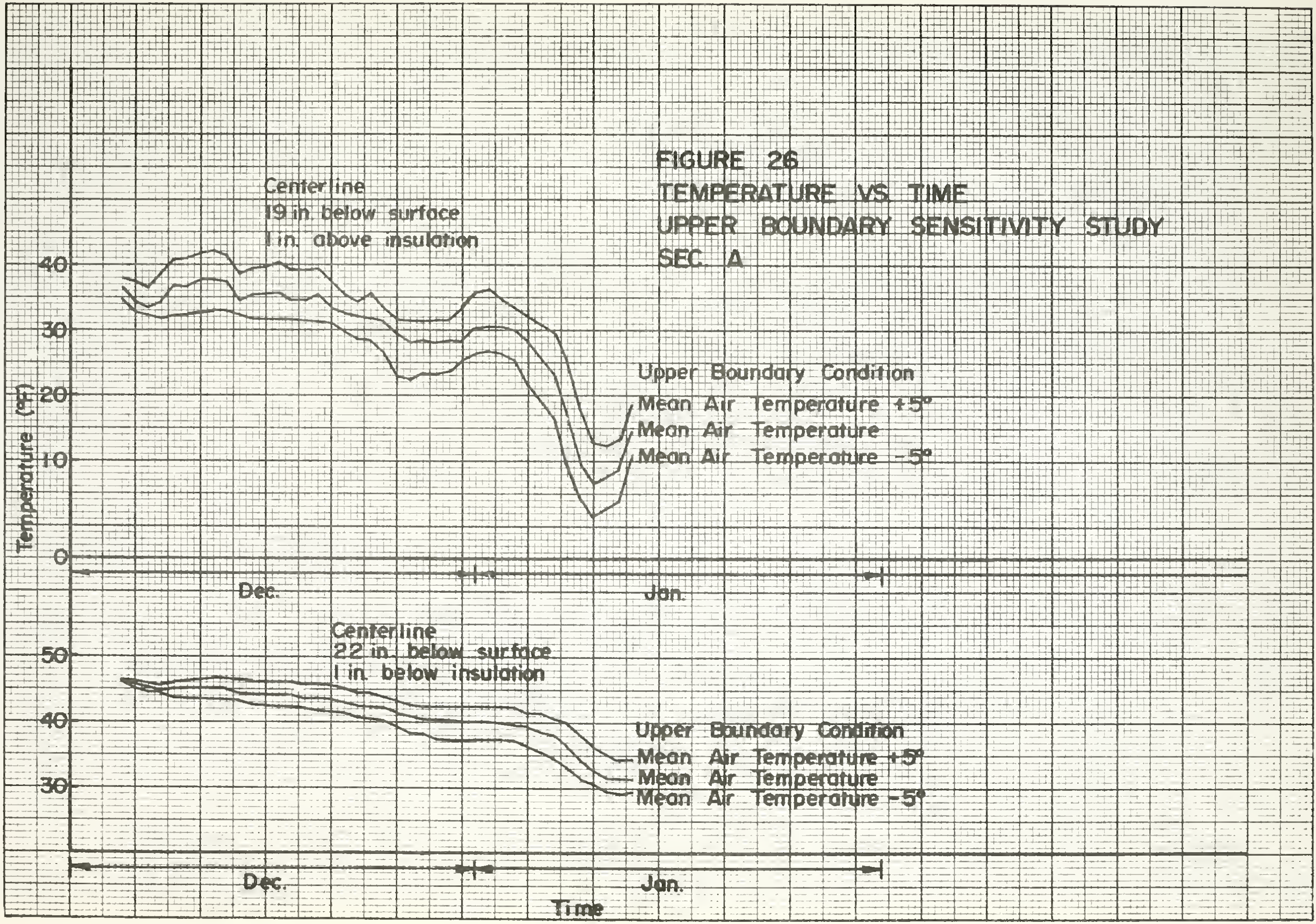


FIGURE 26
TEMPERATURE VS. TIME
UPPER BOUNDARY SENSITIVITY STUDY
SEC. A

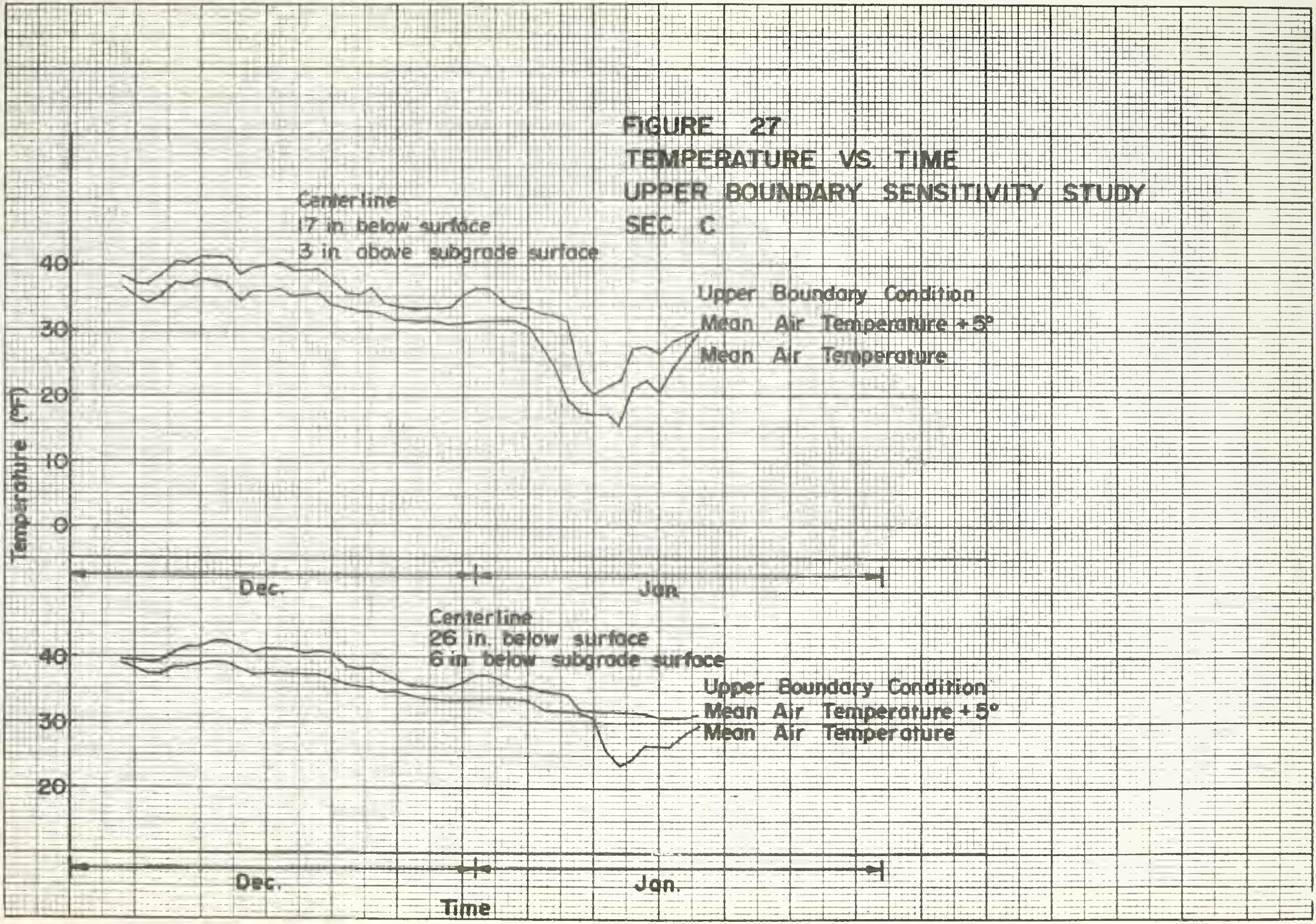


FIGURE 27
TEMPERATURE VS. TIME
UPPER BOUNDARY SENSITIVITY STUDY
SEC. C

Above the insulation in the granular material, the change in temperature is almost equal to the change in boundary temperature. Below the insulation, the change in temperature is less than the change in boundary temperature, but the difference is fairly constant. An exception occurs when there is a phase change. This is especially evident for the uninsulated section shown in Figure 27. The effect of the phase change is to dampen the change in temperature.

Water Content

The water contents of the materials have a large effect upon the thermal properties of the system. Generally, the thermal conductivity and volumetric heat of the material both increase with an increase in water content. These two factors have reverse effects on the rate of temperature change, so the resultant effect may be small. However, the latent heat of the system is greatly changed with a change in water content.

Shown in Figures 28 and 29 are the results of doubling the subgrade water contents of Section A and Section C, respectively. At the points considered, the effect of the increased water content is to increase the temperature. The reader is reminded that the actual water contents of these subgrade soils are low, from 5% to 7%. The difference in temperature becomes much greater when a phase change occurs because of the latent heat effect.

From these results, it seems that an error in water content becomes a very important factor in the accuracy of the prediction when a phase occurs. This happens a number of times above the insulation during a freezing season.

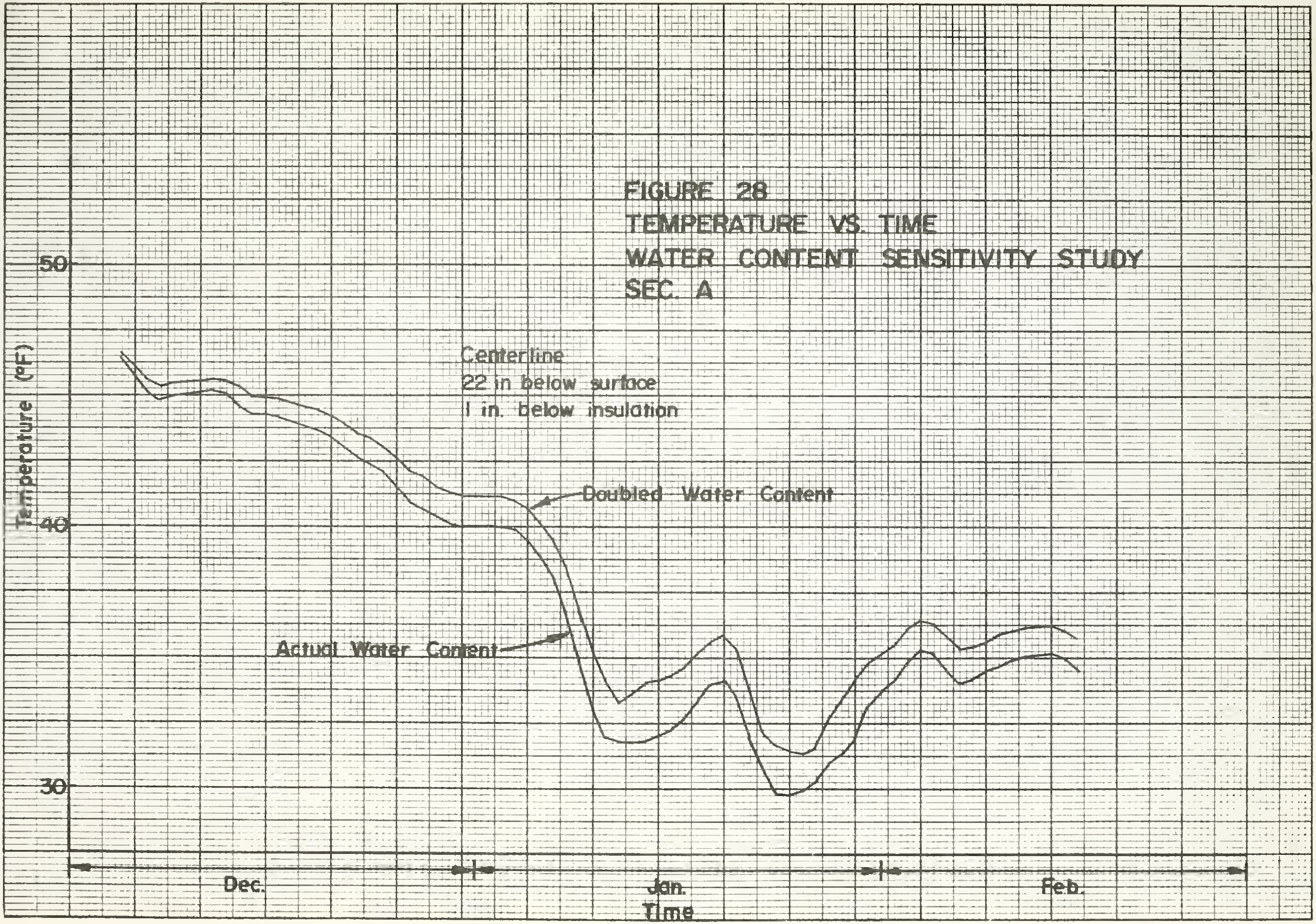


FIGURE 28
TEMPERATURE VS. TIME
WATER CONTENT SENSITIVITY STUDY
SEC. A

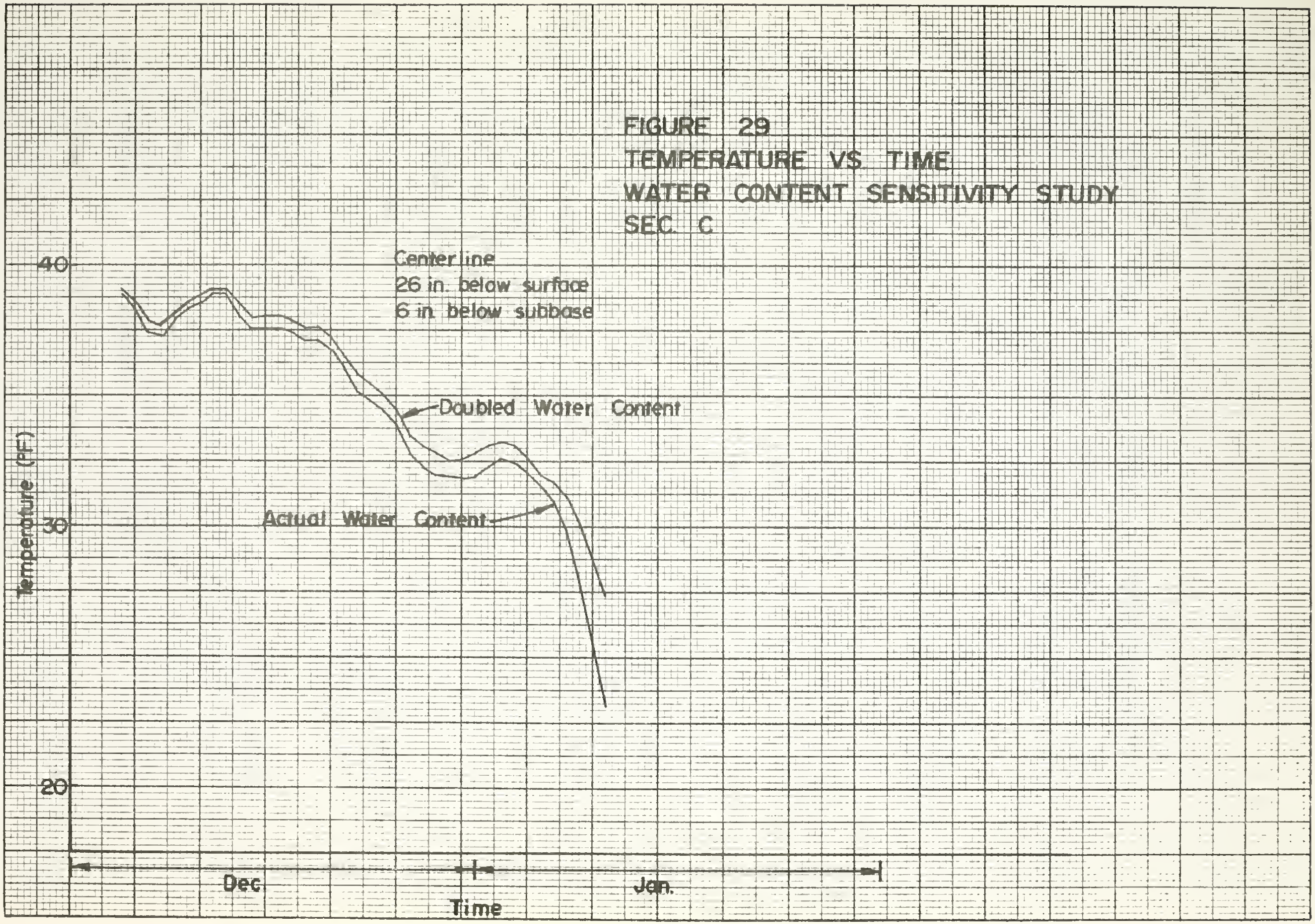


FIGURE 29
TEMPERATURE VS. TIME
WATER CONTENT SENSITIVITY STUDY
SEC. C

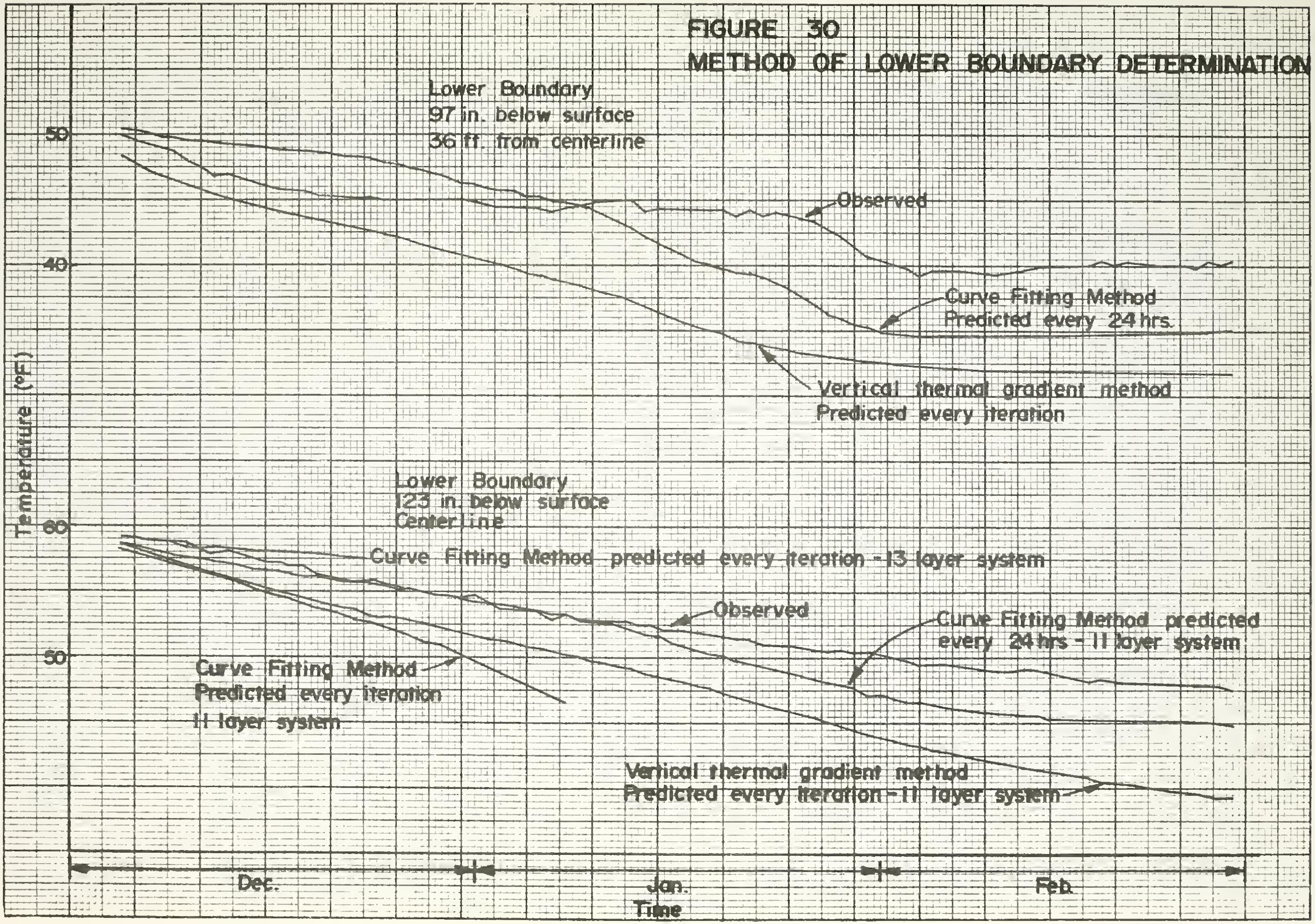
Lower Boundary

Bowers [2] showed that the temperature predictions can be significantly improved with a correct, or nearly correct, lower boundary condition, e.g., using the measured temperatures as input. However, it is not feasible to use measured lower boundary temperatures in a design situation. One approach that has been previously investigated (Ho [3]) is the assumption that the temperature at a given depth shows no seasonal variation, i.e., is constant. However, as shown in Figure 30, the temperature as deep as 10 feet below the surface (even in an insulated section) may vary as much as 10°F over the freezing season. The problem space would have to extend to a much greater depth than this before the lower boundary could be suitably approximated by a constant temperature. Consequently, a method of calculating the lower boundary temperature is needed within the program.

The method used in earlier predictions (Bowers [2]) consisted of assuming a vertical thermal gradient, i.e., no temperature difference, between the centers of the lowest cells and the lower boundary. It was assumed that the error produced by this gradient was small when the thickness of the lowest layer was small, in this case 2 inches. However, this method produced divergence of the predictions from the experimental measurements, as seen in Figure 30.

There are several possible alternatives to the method discussed above. Some of them are:1) assume a linear time-temperature relationship for the lower boundary over the freezing season, as seen in Figure 31; 2) assume the lower boundary time-temperature relationship as part of

FIGURE 30
METHOD OF LOWER BOUNDARY DETERMINATION



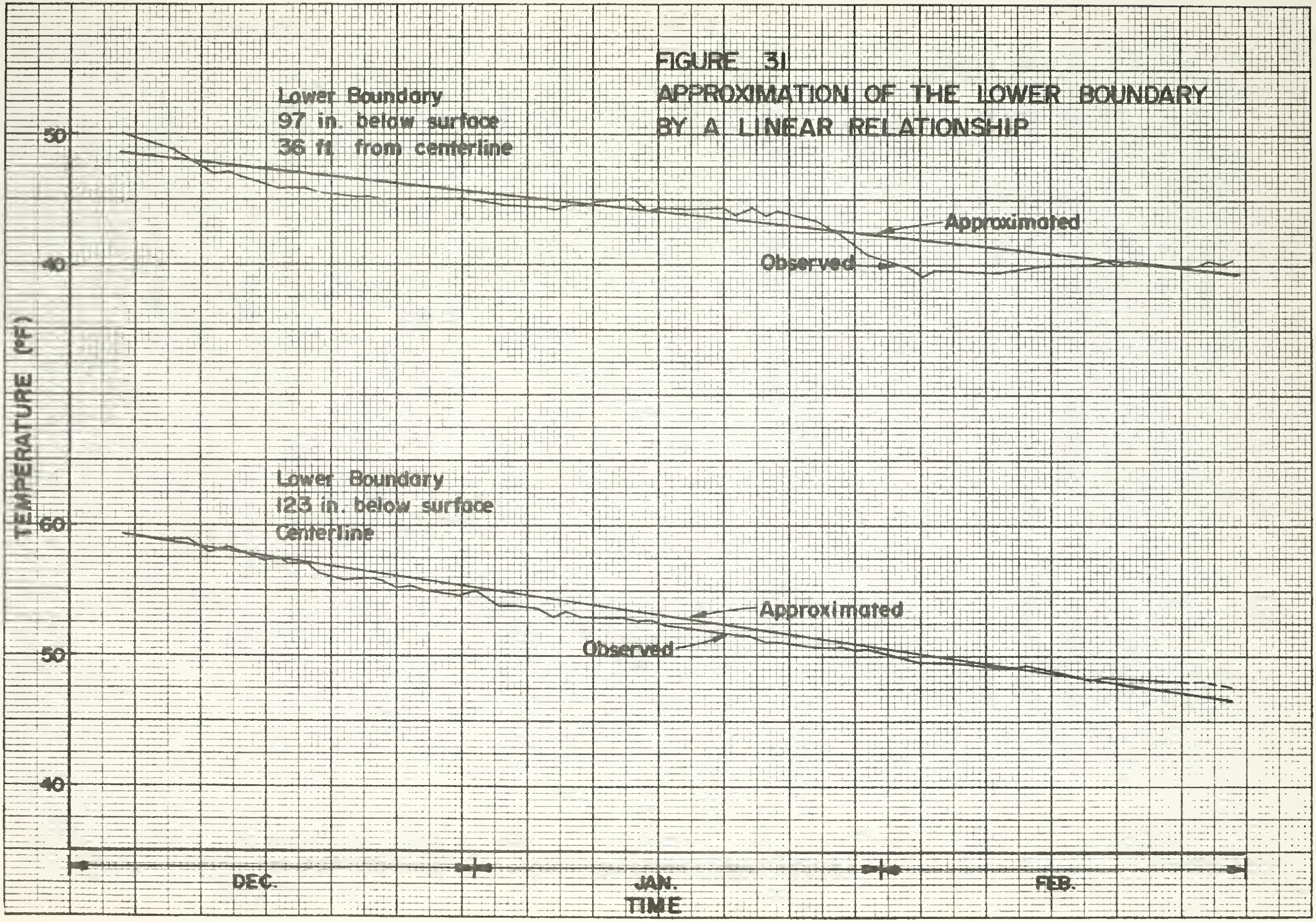


FIGURE 31
APPROXIMATION OF THE LOWER BOUNDARY
BY A LINEAR RELATIONSHIP

a sine curve that has a period of one year, as seen in Figure 32; and 3) calculate the lower boundary using an equation determined by a least squares fit of a curve through points of known temperature. These points of known temperature would correspond to the centers of the solution mesh cells. The first two methods require different input for each design location. This input may be difficult to estimate for situations other than those previously studied in detail. Therefore, alternate 3, involving curve fitting, seems to be the most practical one.

For this study, the temperatures of the cells in the lowest three layers were used in a least squares fit to determine a second order equation that describes the temperature-depth relationship. The results of the calculations are shown in Figure 30. As seen in the lower plot, the curve fitting method was an improvement over the vertical thermal gradient method when the lower boundary temperatures were calculated every 24 hours. Also shown are two cases in which the predictions diverged rather quickly. In the first case, the lower boundary temperatures were predicted every iteration, viz., 96 times in a 24 hour period. Thus, many small errors apparently accumulate. In the second case, some of the lower layers in the 11-layer system were subdivided resulting in a 13-layer system. The lower boundary remained at the same depth. It was felt that smaller layers close to the lower boundary would better define the temperature-depth curve near the lower boundary. However, the temperatures of these lower cells defined a curve that was different from the overall depth trend, and resulted in consistantly predicting temperatures that were too high.

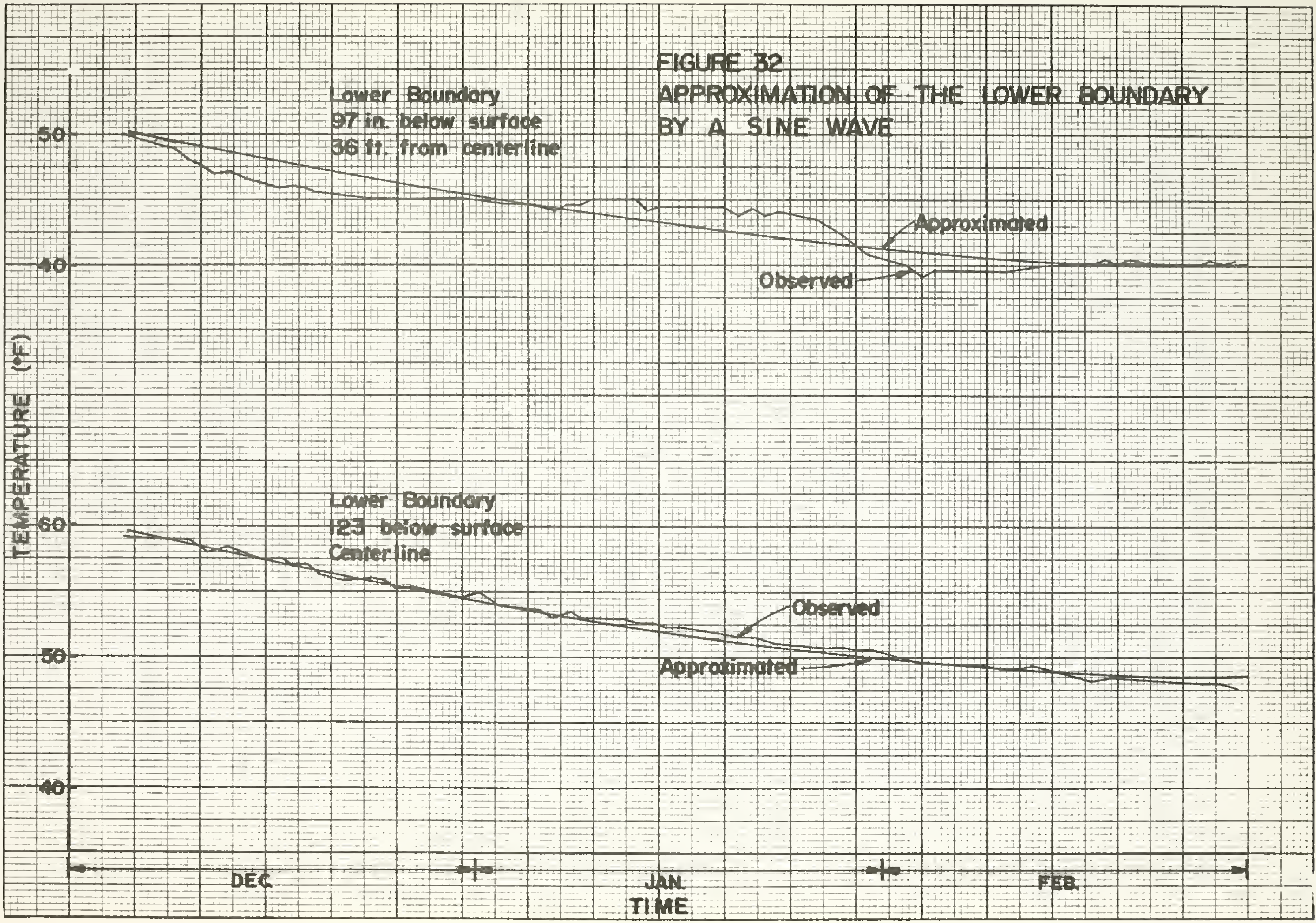


FIGURE 32
APPROXIMATION OF THE LOWER BOUNDARY
BY A SINE WAVE

The question of what points to use in defining the temperature-depth curve is a difficult one, and an intrinsic disadvantage of this curve fitting approach. As shown in the top curve in Figure 30, it is possible to produce predictions that are unconservative when using the curve fitting method. A conservative temperature prediction is considered to be one that is equal to or lower than the actual temperature, thus leading to adequate or more than adequate insulation. With reference to Figures 13 to 15, the vertical gradient method of lower boundary temperature determination will always result in a conservative lower boundary during the freezing season.

In design situations, due to the absence of measured temperature, it is not known whether the curve fitting method is calculating conservative or unconservative lower boundary temperatures. Consequently, it is recommended that the vertical thermal gradient method be used for design, but that the transfer of the lowest cell temperatures to the lower boundary be made only every 24 hours rather than every iteration. With reference to Figure 30 and Figures 13 to 15, this method of lower boundary determination should result in conservative but reasonable lower boundary temperatures.

DESIGN EXAMPLE

The work of this project may be summarized in the form of a thermal design example. It is intended that this example serve as a guide in the formulation of a standard thermal design procedure by the ISHC.

As a result of a summary study of numerous insulated subgrade test installations, a general correlation between freezing index and required thickness of insulation has been recommended [1]. This correlation is shown in Figure 33. However, this recommendation does not address itself to the question of selection of the appropriate depth of placement of the insulation. It is obvious from the work of this project that the placement depth is a function of the thermal boundary conditions, initial conditions, and material properties. Accordingly, the design procedure recommended by this report uses Figure 33 as a guide for the selection of an insulation thickness, but determines the most economical placement depth through utilization of the two-dimensional heat flow model.

This example is formulated for the Rossville test site data, and the winter of 1962-63, having a freezing index of 1274 degree days, was selected as the design year. It is important to note that it was necessary to select a specific design year. The actual daily mean air temperatures for the design year are input as the upper boundary condition.

Using a design freezing index of 1274 degree days, an initial required thickness of 1 1/2 inches was determined from Figure 33. For an initial trial, the insulation was placed on the subgrade surface of a "normal" design, i.e., one where no special frost protection was considered. Section C of the test installation was considered to represent such a design. The base and subbase materials above the insulation were assumed to be non-frost susceptible. The solution mesh for this first design check is shown in Figure 34.

Based upon the findings of this study, the following approach was taken for a thermal adequacy check of the trial thickness and placement.

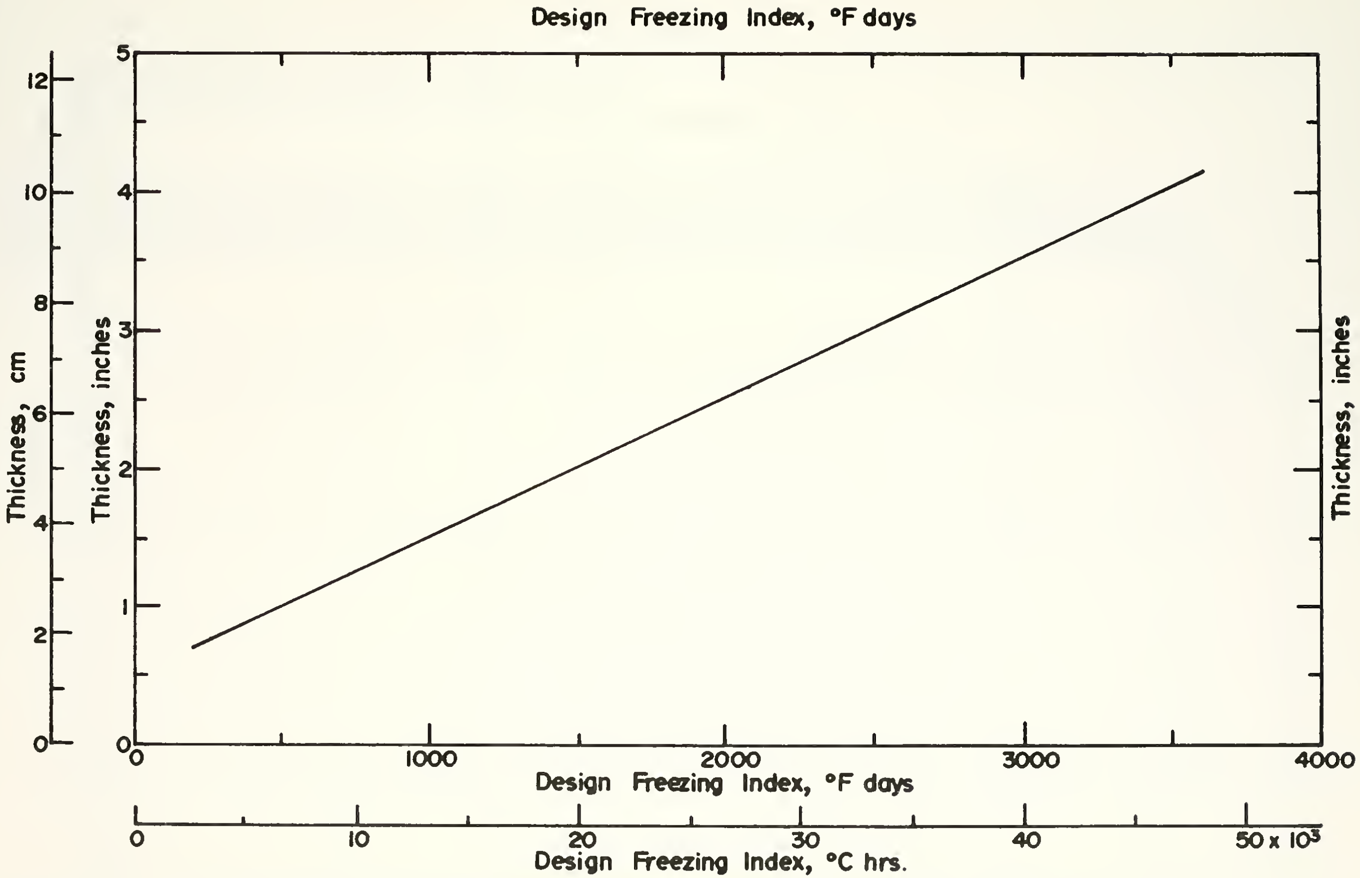


Figure 33. Approximate thickness design recommended by AASHO-ARBA for extruded polystyrene boards (1970).

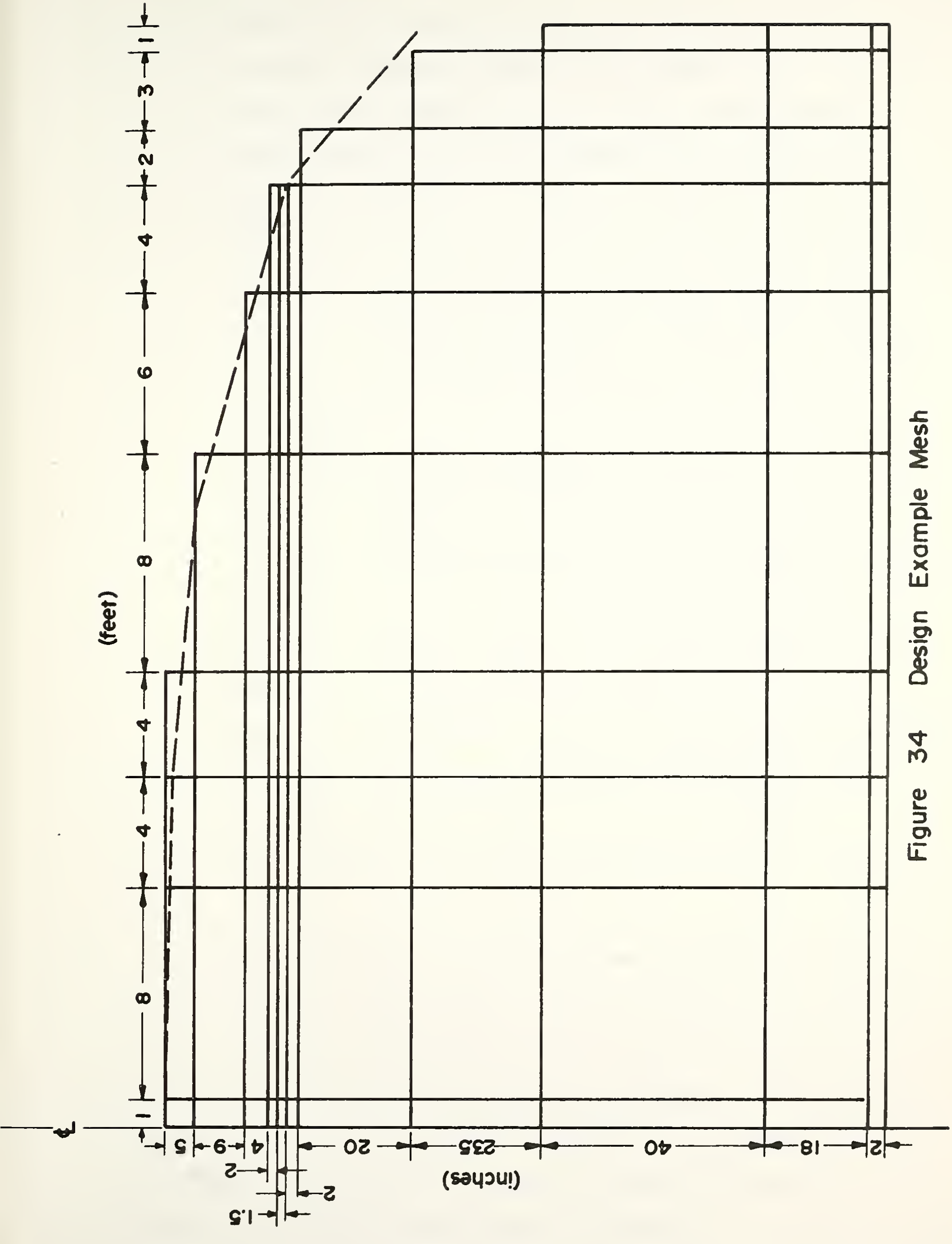


Figure 34 Design Example Mesh

1. Predictions were started on Nov. 21, 10 days before the subsurface temperature analysis was to begin.
2. Initial temperatures of the cells on Nov. 21 were estimated with: knowledge of the air temperatures of the preceding days, the assumption of a steep thermal gradient in the granular material, and, a temperature differential of approximately 15°F to 20°F through the thickness of insulation (see Figure 12).
3. The vertical thermal gradient method, as proposed in an earlier section, was used for the lower boundary temperature determination.
4. The non-clayey materials involved were assumed to freeze between 32°F and 25°F.
5. The material thermal conductivities were taken from curves by Kersten [4].
6. The design criterion was that no penetration of the 32°F isotherm below the insulation be allowed.

In keeping with this approach, the model input was prepared according to the program user manual located in Appendix C. The results of the first design adequacy check are shown in Figure 35. The design criterion for allowable frost penetration was satisfied in the first trial.

In the case where this criterion, or some less rigid criterion, was not satisfied, either a thicker layer of insulation or an increased depth of placement would be assumed, and the calculation repeated to determine the adequacy of the new choice. Conversely, if the criterion were met by the trial with what was perceived to be an excessive margin of safety, the trial would be repeated with reduced thickness of insulation or possibly a reduced depth of placement.

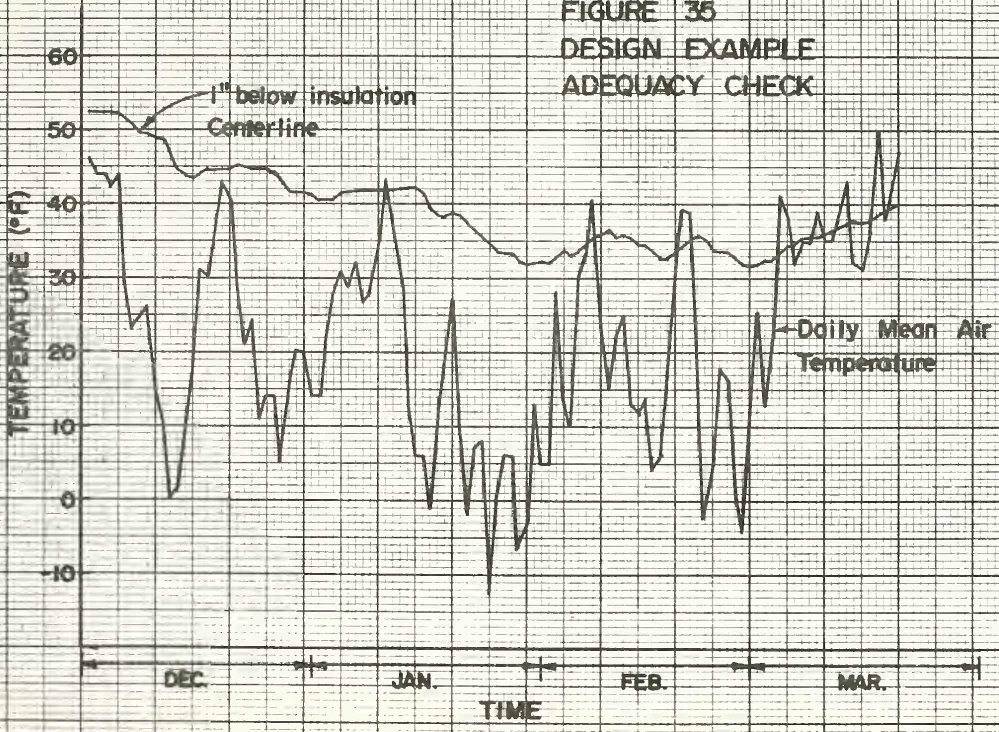


FIGURE 35
DESIGN EXAMPLE
ADEQUACY CHECK

SUMMARY AND CONCLUSIONS

The analysis of the 1971-72 freezing season data has been completed. This analysis, coupled with the analysis reported by Bowers [2], culminates two years of study on the effectiveness of highway subgrade insulation for Indiana. Although the winters in which data were collected were not as severe as hoped for, the alteration of the thermal regime by the insulation was conclusively demonstrated. Numerous two-dimensional plots have been presented to show the effectiveness of a thermal barrier of 1 to 1 1/2 inches of the insulation.

Additionally, an icing survey was conducted to determine the differential icing potential of the insulated test sections. Due to several factors, the survey was somewhat inconclusive. However, it was found that in a general cooling trend the insulated sections are likely to be colder, while in a general warming trend the uninsulated sections are likely to be colder.

Lastly, a method of design was presented from which an adequate thermal design may be formulated and checked with relative ease. This method of design utilizes a two-dimensional heat flow model, and has been checked for sensitivity to variations in principal items of input.

With this final report, and the three progress reports (2, 5, 6) previously submitted, planning, design, construction and performance of the Rossville insulated test road have been reported. The success of this experiment provides support for the acceptance of the insulated pavement method as a practical solution to the frost action problem.

RECOMMENDATIONS

1. Based upon the favorable experience of this study, as well as the positive results from other insulated pavement tests, the ISHC is justified in developing a standard design procedure for thermally insulated pavements. Guidance for such a standard is contained in this report, and is further available by contact with Purdue researchers.

2. The insulated pavement design should be considered as a proven alternative to other special designs in those areas where frost action problems are anticipated. The insulated design may often provide the most economic problem solution.

3. Although differential pavement icing does not appear to be a significant problem in northern Indiana, the performance of the Rossville test road should be monitored (by the ISHC) for such evidence over the next two winters.

4. Although the Rossville test road appears to be performing satisfactorily in a structural sense, its performance should be formally evaluated by the ISHC.

REFERENCES

1. AASHO-ARBA Subcommittee on the Development, Evaluation and Recommendation of New Highway Materials (1970) Performance Study Report on Insulation Board (Polystyrene).

2. Bowers, M. M., "Thermally Insulated Test Road: State Road 26 - Performance and Temperature Prediction Studies", Joint Highway Research Project Report No. 2, March, 1972.

3. Ho, Da-Min, "Prediction of Frost Penetration Into a Soil Water System," Ph.D. Thesis, Purdue University, August, 1969.

4. Kersten, M. S., "Thermal Properties of Soils", Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, pp. 161-166, 1952.

5. Stulgis, R. P., "Insulated Test Road - State Road 26", Joint Highway Research Project Report No. 12, July, 1968.

6. Toenniessen, J. D., "Thermally Insulated Test Road: State Road 26 - Phase II: Performance Studies", Joint Highway Research Project Report No. 10, May, 1970.

APPENDIX A

ENGLISH-SI CONVERSION FACTORS

To convert	To	Multiply by
inches (in.)	millimeters (mm)	25.40
inches (in.)	centimeters (cm)	2.540
inches (in.)	meters (m)	0.0254
feet (ft.)	meters (m)	0.305
miles (miles)	kilometers (km)	0.61
yards (yd.)	meters (m)	0.91
cubic inches (cu. in.)	cubic centimeters (cm^3)	16.4
cubic feet (cu. ft.)	cubic meters (m^3)	0.028
cubic yards (cu. yd.)	cubic meters (m^3)	0.765
pounds (lb.)	kilograms (kg)	0.453
tons (ton)	kilograms (kg)	907.2
pounds per square foot (psf)	newtons per square meter (N/m^2)	47.9
pounds per square inch (psi)	kilonewtons per square meter (kN/m^2)	6.9

APPENDIX B
TEST ROAD ICING SURVEY FORM

DATE ____________

TIME ____________

INSPECTOR ____________

Use N/A if question is not applicable	SEC A	SEC B	SEC C
1. Visual Condition of Pavement a) Dry c) Icy b) Wet D) Compacted snow			
2. Traction Condition of Pavement a) Normal b) A little slick c) Very slick			
3. Extent of wet, icy or snowy condition a) Entire section b) Large Patches c) Few small patches (If hard to determine, sketch extent and location on following page)			
4. Location of wet, icy or snowy condition a) mostly middle of road b) mostly edge of road c) no special place If choice is c, please show on sketch			
5. Is the Condition (other than dry) visible to the Driver a) Yes b) No			
6. How Does the Pavement Condition of These Sections Compare with the Highway for a Distance of 1/2 Mile to the West? a) Better b) Same c) Worse			
Additional Comments - Use Back if Necessary			

APPENDIX C

2-D HEAT FLOW PROGRAM USER MANUAL

The following information is the required sequence and format for data input when using the two-dimensional heat flow program. The data cards can not be numbered consecutively in a general sense because the number of cards required depends upon the particular solution mesh. Consequently, this manual is divided into sections of input with the number of cards required for each section given. A horizontal row of cells in the solution mesh is called a layer, while a vertical row of cells is called a column.

ID Information

10 cards	alphameric-contains information about the particular case under study. Ten cards are required, so fill in remainder with blanks.

Solution mesh information

1 card

col 1-5 [right adjusted]	integer-total number of cells in solution mesh.
col 6-10 [right adjusted]	integer-total number of layers in solution mesh.
col 11-15 16-20 21-25 continue as needed [right adjusted]	integer-number of cells for each layer, proceeding from layer 1 [top] to layer m [bottom].

General cell information

1 card for each cell in solution mesh

col 1-5 [right adjusted]	integer-layer number of cell
col 6-10 [right adjusted]	integer-column number of cell

col 11-15 [right adjusted]	integer-cell type [see page 66]
col 16-25	real-cell thickness in inches
col 26-35	real-cell width in inches
col 36-45	real-cell material density in pcf
col 46-55	real-cell material water content in percent

Thermal conductivity information

1 card per cell

col 1-5 [right adjusted]	integer-layer number of cell
col 6-10 [right adjusted]	integer-column number of cell
col 11-20	real-unfrozen cell material thermal conductivity
col 21-30	real-frozen cell material thermal conductivity

Ice formation characteristics

1 card per cell

col 1-5 [right adjusted]	integer-layer number of cell
col 6-10 [right adjusted]	integer-column number of cell
col 11-15 [right adjusted]	integer-cell ice formation characteristic Read 1- for known coefficients, C5, C6, C7 [see below] 2- for fit into an exponential function 3- for dry cell

for each card that the number in column 15 is 1, this card should follow.

col 1-10	100.0
col 11-20	C6
col 21-30	C7

C6 and C7 depend upon the range over which the soil water is assumed to freeze. For example, if 0% is frozen at 32°F and 100% is frozen at 25°F, then find C6 and C7 by solving

$$0 = 100 - \exp^{[32(C6) - C7]}$$

$$100 = 100 - \exp^{[25(C6) - C7]}$$

Initial condition information

1 card

col 1-5 [right adjusted]	integer-initial condition type Read 1 for constant temperature throughout 2 for known temperatures at center of each cell

if number in col 5 is 1, this card should follow

col 1-10	real-desired constant temperature

if number in col 5 is 2, one card for each layer should follow

col 1-6	real-cell temperature of col 1 in layer considered
col 7-12	real-cell temperature of col 2 in layer considered

continue as needed in fields of 6

a similar card should follow for the upper boundary "layer" and the lower boundary "layer".

Time information

1 card

col 1-10	real-the total period in hours to be analysed.
col 11-20	real-time increment in hours [.25 recommended, See Ho [3], pp. 64-68, for detailed discussion]
col 21-30	real-output time interval in hours [usually 24 hours]
col 31-40	real-the total time that has been already computed

1 card [if needed]

col 1-5 [right adjusted]	integer-the number of cells that require a smaller time increment. [usually the cells where material is insulation See Ho [3], pp. 64-68 for detailed discussion]

if the number in col 5 is more than zero, a card for each cell that requires a smaller time increment should follow.

col 1-5 [right adjusted]	integer-cell layer number
col 6-10 [right adjusted]	integer-cell column number
col 11-20	real-reduced time increment [.05 recommended]

Upper Boundary information

1 card

col 1-5 [right adjusted]	integer-upper boundary condition Read 1 for constant 2 for algebraic function 3 for trigonometric function 4 for step function

if the number in col 5 is 4, a card for each step should follow plus control cards.

control card 1

col 1-5 [right adjusted]	integer-number of steps [usually number of days]

card for each step

col 1-10	real-step lower limit [i.e.,0 for the first step, 1 for the second step, so on]
col 11-20	real-step upper limit [1 for the first step, 2 for the second step, so on]
col 21-30	real-step temperature [mean daily temperature if step = 24 hours]

control card 2

col 1-10	real-length of time of each step [usually 24 hours]
col 11-20	real-number of hours at start of first step

Surface transfer coefficient information
[See Bowers [2], page 61, for discussion]

1 card

col 1-6	real-surface transfer coefficient of col 1 [1.0 used for this project]
col 7-12	real-surface transfer coefficient of col 2

continue for each column in solution mesh in fields of 6

Lower Boundary information

1 card

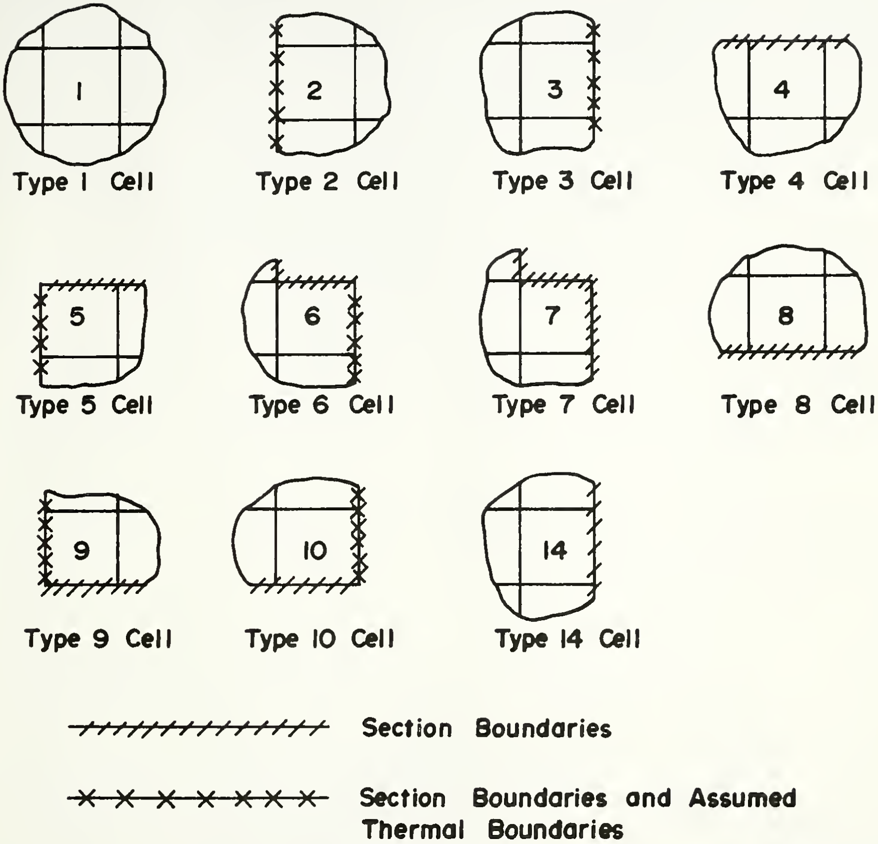
col 1-5 [right adjusted]	integer-lower boundary condition Read 1 for constant 2 for predicted from curve fit 3 for temperature same as lower boundary 4 for specified temperature 5 for daily [step] control

if the number in col 5 is 5, a card for each day [step] is needed

col 1-6	real-lower boundary temperature of col 1
col 7-12	real-lower boundary temperature of col 2

continue as needed for each column in fields of 6

Types of Cells for Solution Mesh



Cell Types 11, 12, and 13 not required for this particular problem.

Figure 36. (from Toenniessen (6))