AL03.150

3 0782 00000522 0
JOINT PIPELINE OFFICE

NORTHWEST ALASKAN PIPELINE COMPANY, INC.

PERFORMANCE PREDICTIONS

FOR

FAIRBANKS FROST HEAVE TEST FACILITY

FEBRUARY, 1980

EBA Engineering Consultants Ltd.

TA
713
P36

19800201-2

A/03.150301

LIBRARY

BUREAU OF LAND MANAGEMENT
Alaska State Office
Branch of Pipeline Monitoring
222 W. 7th Avenue, #30
Anchorage, Alaska 99513-7590

LIBRARY

THE ASSOCIATION OF
PROFESSIONAL ENGINEERS
OF ALBERTA
PERMIT NUMBER
P 245
E B A ENGINEERING
CONSULTANTS LTD.

LIBRARY

NORTHWEST ALASKAN PIPELINE COMPANY, INC.

PERFORMANCE PREDICTIONS

FOR

FAIRBANKS FROST HEAVE TEST FACILITY

LIBRARY

February, 1980

LIBRARY

EBA Engineering Consultants Ltd.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

List of Figures (cont'd)

APPENDIX A

I INTRODUCTION

Northwest Alaskan Pipeline Company (NAPLINE) and Foothills Pipe Lines (Yukon) Ltd. are jointly sponsoring the Alaska Highway Gas Pipeline project (Figure 1.1) and, to address shared concerns regarding the possible adverse effects of frost heave, they have undertaken extensive engineering studies.

Frost heave is defined as volumetric expansion of the subsurface due to freezing; this volumetric expansion results in uplift of the pipe. For this specific project, freezing will be the result of the operation of a chilled gas pipeline which for fine grained soils may cause volumetric expansion of in situ pore water and water migrating to the frost front.

Frost heave thus presents some unique problems to the proposed Alaska Highway Gas Pipeline project. The engineering studies undertaken include various field investigations to delineate the extent of the problem, the development of a numerical model to predict frost action on pipelines, structural analysis of a pipeline subjected to differential frost heave and the development of potential mitigative design measures. In addition to theoretical and laboratory studies, undertaken to understand the frost heave phenomenon and develop a model capable of predicting frost heave magnitude over the design life of the pipeline, two full scale frost heave testing facilities (Figure 1.1) are now being operated:

1. Calgary Frost Heave Test Facility, Calgary, Alberta, is presently operated by Foothills Pipe Lines (Yukon) Ltd. This facility has been in operation since March 21, 1974. The performance analysis of this test site (Reference No. 1) confirms the validity of the proposed design approach.

2. The Fairbanks Frost Heave Test Facility located near Fairbanks, Alaska, is operated by NAPLINE; operation started on October 13, 1979.

Both test sites utilize full scale 48 inch diameter pipe sections and circulate chilled air. The growth of the frost bulb and movement of the pipe sections are monitored, as they are integrated components of the frost heave phenomenon.

The primary objective of this report is to predict the performance of the Fairbanks Frost Heave Test Facility. The method of analysis utilized together with the input parameters are discussed, and the sensitivity of pertinent input variables is evaluated. Predictions emerging from the analyses are summarized, and pertinent observations are made.

II DESCRIPTION OF TEST FACILITY

2.1 Site Selection

The main criteria for the selection of a frost heave test site are as follows:

1. Soil conditions at the test site should be representative of the troublesome conditions to be encountered along the pipeline route.

2. The presence of a high water table ensures a ready supply of water to the freezing front. Water availability is a priority requirement for frost heaving.

3. As the size of the frost bulb, around the pipe, to be considered is approximately 20 feet, a sufficient depth of frost susceptible and initially unfrozen soil is necessary to ensure that the frost front will be maintained within that material over the test duration.

4. Clayey silts are traditionally the more frost susceptible soils as they possess the ability to attract water during freezing while they have a high enough permeability to permit water migration through the soil to the freezing front.

5. The soil strata should be as uniform as possible so that the interpretation of the results can be made in a definitive manner with a minimum of uncertain factors.

6. Easy access of service systems such as electricity, water and sewer, is economically desirable.

In light of the above criteria, nine sites were selected for preliminary evaluation of the subsurface soil conditions (Reference No. 2); subsequently, further subsurface investigations were conducted on five of them (Reference No. 3). Evaluation of the obtained soil samples led to the conclusion that the Gettinger site conformed most to the prescribed criteria.

The Gettinger site is located on Chena Hot Springs Road, approximately six miles north east of Fairbanks, in the north east corner of the NE ¼ of Section 28, T.1N, R.1E, Fairbanks Meridian. Figure 2.1 shows the site location together with the borehole locations and resistivity survey lines.

2.2 Geology and Subsurface Soil Properties

The Gettinger site is located adjacent to a small seasonal stream, Columbia creek. The site topography is relatively flat to gently sloping to the south and east. The subsoil consists of loess and retransported deposits that blanket much of the Yukon - Tanana uplands and are referred to as the Fairbanks silt. Typically, these soils are generally frozen and frequently contain large ground ice masses and organic debris. In this respect, the subsoil at the Gettinger site was formerly frozen and the southern portion of the site, covered by willows and undisturbed black spruce, is still frozen.

The thickness of the Fairbanks silt stratum varies from a few feet on ridges and hilltops to over 200 feet.

The generalized soil stratigraphy, obtained from detailed soil investigations (Reference No. 3), consists of a brown micaceous silt turning grey with depth to the depth of permafrost, approximately 24 feet. The organic content varies randomly from traces to abundant and the moisture content ranges from 20 to 40 percent. The consistency of the silt varies from very soft to medium stiff, and the subject soil is non plastic. The liquid limit is between 18 and 34 percent, however, for a few samples it was as high as 60 percent. Figure No. 2.2 shows the range of grain size distribution of the soils at the Fairbanks Test Site, compared with those of the Calgary Test site and Mackenzie Valley soils.

2.3 Groundwater Table

The depth to the groundwater table was monitored with piezometers installed during the site investigation. Readings were taken during 1978 and the data tends to indicate that the piezometers had not stabilized since the depth to water consistently decreases with time. During construction of the test facility, some surface stripping and site levelling was done, and at the north east corner of the facility up to 3.5 feet of soil were removed.

Piezometer readings, subsequent to construction, indicate the groundwater table to be located approximately 6.5 feet below ground surface.

2.4 Description of the Test Facility

2.4.1 General

The Fairbanks Frost Heave Test Facility (Figure No. 2.3) is comprised of eight 120 foot sections, one 400 foot section and one 70 foot section. Refrigerated air at a pressure of 670 psia has been continuously circulated through the pipe sections at a flow rate of 910 cubic feet per minute (velocity being 1.2 ft/sec) since October 13, 1979. The air inlet temperature is 8°F and the outlet is 12°F; however, almost no drop in temperature occurs over the insulated test sections, pipes No. 8,5,7 and 2.

At all the test section locations the pipes have 3.5 feet of soil cover, except for No. 5 which has 3.0 feet. The configuration of the test sections, presented as Figure No. 2.4, may be described as follows:

2.4.2 Test Section No. 1

The 48 inch diameter pipe at this test section is uninsulated and has no granular bedding. This test section is anticipated to serve as a control of the heave mitigative effect of both the gravel bedding and insulation.

2.4.3 Test Section No. 2

The pipe burial configuration is similar to test section No. 1; however, the test pipe is wrapped with two inches of urethane insulation.

2.4.4 Test Section No. 3

For test section No. 3, six inches of gravel bedding support the test pipe. In addition, the trench is lined with six inches of styrofoam insulation.

2.4.5 Test Section No. 4

The heave mitigative effect of gravel is evaluated at this test section: no insulation is utilized and a 3 foot thick gravel layer supports the pipe.

2.4.6 Test Section No. 5

A slightly different burial configuration was utilized at this test location: the test pipe is wrapped with 2 inches of urethane insulation and a 3 foot high gravel berm constitutes the overburden.

2.4.7 Test Section No. 6

The pipe burial configuration is the same as that of test section No. 1, however, heat pipes were installed on both sides of the pipe at 8 foot intervals. It is intended that this section will confirm that inducing a frozen layer by the heat pipes below a chilled pipeline,frost heave will greatly be reduced. The section is to investigate one of the possible migative measures for frost heave control.

2.4.8 Test Sections No.7 and No. 8

Two inches of urethane insulation in conjunction with one foot of granular bedding are utilized for test pipe No. 7, whereas 4 inches of urethane insulation together with 3.0 feet of gravel bedding were employed for test pipe No. 8.

2.4.9 Test Section No. 9

Half of this 400 foot test pipe is placed in permafrost and the other half in thawed silt. The test results will provide input for the evaluation of stresses and deformations which may develop at permafrost interfaces as a result of differential heave.

2.4.10 Test Section No. 10

This test pipe is buried in permafrost to investigate the magnitude of secondary frost heave (frost heave in already frozen soils).

2.5 Instrumentation

2.5.1 General

Data receiving and recording equipment is housed in the instrument room which is a separately framed and insulated room located within the equipment building. Unless otherwise noted, readings from all instruments are automatically scanned by a micro-processor and recorded on tape. In order to avoid the possibility of losing data, two tape recorders are used simultaneously. Heat tracing is placed between the air supply pipe and its insulation to prevent the pipe from becoming colder than its pressurized minimum of -20°F, in case of a shutdown during cold weather. An automatic emergency notification system is provided, as equipment malfunction calls will be initiated by the site's computer. In case of power failure, emergency power is supplied by a diesel generator to the instrumentation and air supply heat tapes.

2.5.2 Sensistors

Vertical strings of sensistors are installed, beneath and at the sides of all test pipes, for measurements of ground temperatures. These resistance temperature detectors are accurate to the nearest 0.1°F.

2.5.3 Heat Flux Transducers

Heat flux transducers encircle the test pipe sections, at judiciously selected locations, to measure differential and total heat flux.

2.5.4 Heave Measurements

The main purpose of the test facility is to observe vertical displacement of the chilled pipeline and the surrounding soil; as a consequence, heave rods are attached to the top of the test pipes, at locations adjacent to them and at several control locations on site. The heave rods, placed in plastic standpipes, are made of steel, and survey targets are attached to their projecting ends; the surveying equipment utilized will accurately record the three-dimensional position of the target, and this manually obtained information will be entered on the data tapes.

2.5.5 Other Instrumentation

Radial extensometers, one vertical and one horizontal at each location, are installed inside two of the pipes to measure change in ovalness. In addition, they are also placed at three locations within the interface test pipe, and one set is installed at the longitudinal center of the heat tube test pipe.

Strain gauges are installed within the interface test pipe only. Strain measurements will help in the evaluation of the stress changes consistent with pipe deformation.

The system air pressure is measured within the equipment building at the supply and return ends of the air circulation system, and the measurements are periodically entered on the data tape.

Soil and ice pressures on the pipe are obtained utilizing two types of instrumentation. One has a large sensing area, thus reducing the distorting effect of ice bridging, while the other is the standard 4 inch diameter pressure disc; both employ hydraulic sensors and electric transducers.

Porewater pressures are measured beneath several of the test pipes by electric transducers.

Snow depth on the test site will be directly measured and periodically entered on the data tapes.

The groundwater table is monitored regularly at six locations on site. This information is manually input to the data tapes.

III FROST HEAVE PREDICTIVE MODEL

3.1 General

The frost heave mechanism can be described in the following two processes: (Reference No. 6 and 7).

1. Mass Transfer - Continiuty of Water Flow

   During the process of freezing, by nature of the energy balance at the ice-water interface, a suction occurs, similar to the concept of the capillary model, which draws water toward the freezing front to form segregated ice lenses. The amount of water drawn to form ice lenses, under a fully saturated soil system, should be proportional to the permeability of an unfrozen soil and its hydraulic gradient (Darcy's Law).

2. Heat Transfer - Heat Extraction at the Freezing Point

   As the water is being drawn to form ice lenses, heat extraction must occur in order to freeze the in situ water in the soil and the water migrating to the frost front into ice. The amount of heat extraction is equal to the amount of heat flux into the frozen zone minus the incoming heat flux from the unfrozen zone.

3.2 Semi-Empirical Design Approach

As a result of extensive studies on the frost heave mechanism (Reference No. 9,10,11 and 12), a semi-empirical design approach has been developed. Rationale and validation of the semi-empirical frost heave model has been presented in a separate report (Reference No. 5). In the following subsections, a brief description on the rationale and methodology of the semi-empirical design approach will be made.

3.2.1 Rationale

The two processes, heat and mass transfer, required for frost heave to occur, are treated as follows:

1. The heat transfer aspect involves the consideration of heat transfer mechanisms in both the frozen and unfrozen zones of the soil domain, and the growth of the frost bulb; the geothermal model utilized has previously been verified (References No. 1 and No. 8). The thermal properties of the soils (frozen and unfrozen) such as thermal conductivity, specific heat and volumetric latent heat are defined. Geometry and temperature boundary conditions of thermal domain, including pipe diameter and operating temperatures, are specified.

2. The mass transfer aspect of the frost heave model, which evaluates the heave strain or ice segregation ratio, is determined by one-dimensional laboratory frost heave testing. The laboratory frost heave testing program, together with supportive equipment and instrumentation, is described and the testing results are summarized in graphical form in Appendix A.

In summary, the semi-empirical approach transforms the complicated frost heave problem into a conventional thermal problem and the heave strain, which implicitly accounts for mass transfer and is defined as heave per unit frost front penetration, constitutes another input parameter determined by laboratory testing techniques.

3.2.2 Methodology

The semi-empirical design approach may be summarized as follows:

1. Based upon the soil type, its grain size distribution and natural moisture content, the soil domain is divided into representative strata for which thermal soil properties (frozen and unfrozen) are defined.

2. The heave strain or ice segregation ratio of samples, representative of the strata defined for the thermal analysis, is obtained from laboratory frost heave tests (Appendix A); the selected samples are tested under their in situ overburden pressure. The heave strain or ice segregation ratio is defined as:

$$I_s = \frac{h_{max}}{X_{max}}$$

where h_{max}, X_{max} are frost heave and frost depth at steady-state, respectively.

Since ground freezing by a chilled pipeline is a slow transient thermal balance, and over the lifetime of a pipeline, the thermal state of the ground may not reach its ultimate state - the steady-state condition; as a consequence, the use of laboratory determined heave strain or ice segregation ratio after steady-state is reached should result in conservative (safe) designs.

3. Once the heave strain or ice segregation ratio is obtained for each representative soil layer, it is applied to the upper bound solution of the two-dimensional frost heave model to evaluate the frost depth and frost heave with time.

IV FROST HEAVE PREDICTION

4.1 General

The semi-empirical design approach of the frost heave predictive model transforms the complex frost heave phenomenon into a conventional thermal problem, with the ice segregation ratio defined as another input parameter in addition to those required for thermal analysis. Such an approach divides the performance predictions for the Fairbanks Frost Heave Test Facility into two isolated components: the variation of ground temperatures and the corresponding frost heave.

4.2 Input Parameters

4.2.1 Thermal Domain and Soil Properties

Typical stratigraphic cross sections of the test facility, presented in Figures 4.1 to 4.3, inclusive, depict the uniformity of the subsoils at the Gettinger site. This can be seen from Figure 2.2 showing the range of grain size distribution of the soils at the test site.

The thermal domain defined for the test sections is mainly based on soil layers of similar in situ water content. Figures 4.4 to 4.9 present soil layers under each test section.

Due to relatively uniform soil conditions at the test site, three laboratory frost heave tests were performed to evaluate the heave strain or ice segregation ratio of the soil. Figure 4.2 shows the sample locations at respective boreholes. Borehole locations within the test site are shown in Figure 2.1

Table I summarizes the laboratory frost heave test results, which are compared to the results obtained by E. Penner of the National Research Council of Canada.

The determination of heave strain is expected to have a variation of about 5%, the use of 10% as an overall heave strain for the test site soils was made. The result of 12.6% for Test TS(8) by Penner seems to have about twice as much clay content as those of the soil samples tested by EBA. This may explain partly the reason for higher heave strain. However, the difference among these test results are still within the accuracy level to be expected. A rather short duration of testing (2 days) is thought to be the prime reason for small heave strain as obtained for Test TS(9).

Based on sample locations with respect to the overall soil stratigraphy of the site, the use of 10% as the heave strain for the analysis is regarded as adequate and practical.

Table II to VII, inclusive, summarize the soil thermal properties for the test sections (Figure 4.4 to 4.9) analysed. The thermal properties were evaluated according to Kerstern's equations (Reference No. 13).

4.2.2 Meteorological Data

The meteorological data is required for the thermal analysis, as the ground surface heat transfer mechanism is considered. Table VIII summarizes the pertinent meteorological parameters which are:

a) Air temperature
b) Solar radiation
c) Wind velocity
d) Surface albedo, emissivity and greenhouse factor
e) Depth of snow cover and snow thermal conductivity

The meteorological data utilized is the 30 year average for Fairbanks. The air temperatures and snow depth data averaged over the past 3 years (1976-1978) were compared to the 30 year average and as can be observed from Figure 4.10 there is only a slight difference between the 3 and 30 years average.

4.2.3 Pipe Temperatures

As chilled air is circulated through the pipes, the pipe temperatures are a function of the chilled air temperature and the conductance between the air and the pipe wall. The air-pipe conductance is a function of pipe diameter, duct air temperature, pressure and velocity at which the duct air is circulated.

The air temperature was measured as $8^{\circ}F$ at inlet into the pipe sections and was measured as $12^{\circ}F$ at the outlet. Since the heat loss mainly occurs over the connecting pipe and the bare section, the following air temperatures are prescribed for the analyses:

$$T_{air} = 8^{\circ}F \text{ for insulated sections}$$

and

$$T_{air} = 10^{\circ}F \text{ for uninsulated sections}$$

The air-pipe conductance U (BTU/hr/ft^2/^{o}F) was determined according to the empirical relation as suggested by McAdams (Reference No. 14):

$$U = N_{NUD} \frac{k}{D}$$

Where

U = Air-pipe interface conductance (BTU/hr/ft^2/^{o}F)

N_{NUD} = $0.023\ (N_{RED})^{0.8} (N_{PR})^{0.4}$

D = pipe diameter (ft.)

N_{RED} = Reynolds number
= $V.D/v$

N_{PR} = Prandtl number
= $\mu.c/k$

V = velocity (ft/hr)

v = kimematic viscosity (ft^2/hr)
= μ/ρ

μ = dynamic viscosity (lbs/ft - hr)

ρ = density (lbs/ft^3)

k = thermal conductivity (BTU/hr/ft/^{o}F)

c = specific heat (BTU/lb/^{o}F)

For a 48" diameter pipe with air presssure being 670 psia, the relationship between the value of U versus flow velocity is shown in Figure 4.12 for aire temperature of 8 and 14^{o}F.

As the air flow rate of the test sections was measured as 910 cu.ft./min (with air pressure of 670 psia), the U value was evaluated as 1.42 BTU/hr/ft^2/^{o}F.

Thus the boundary condition at the air-pipe interface was described as

T_{air} = 8^{o}F for insulated section
10^{o}F for uninsulated section

and

$U = 1.42$ BTU/hr/ft^2/^{o}F

These input data should satisfy the convective boundary condition at the air-pipe interface for:

$$q = U\ (T_{air} - T_{pipe})$$

where

q = flux

T_{pipe} = pipe surface temperature

Both q and T_{pipe} are unknowns to be determined in the thermal analyses.

4.2.4 Finite Element Grid

A two-dimensional finite element model (Reference 8) utilizing triangular elements is used for the thermal analysis. The coarseness or fineness and the overall size of the mesh depend on variation in temperature gradients at any location, on the estimated zone of influence of the chilled pipe, and on the surface and boundary conditions. As a consequence, the mesh is made finer where temperature variations are of concern, especially near the chilled pipe, the ground surface and in the area where growth of the frost bulb is anticipated.

A typical finite element grid, utilized for the thermal analysis is presented as Figure 4.13.

V PREDICTION RESULTS

Based on the input parameters described in the previous section (IV), the model was applied to predict the ground temperatures and frost heaves at the test site. The predictions are presented in the following subsections.

5.1 Annual Undisturbed Ground Temperatures

One-dimensional simulation was made by the model to predict the seasonal ground temperature variations at areas not disturbed by the installation of the pipe sections.

Such thermal analyses will provide a calibration on the meteorological input parameters. The simulation assumed a constant bottom boundary temperature of 31°F at a depth of 100 feet.

Seasonal frost depth of the simulation is shown in Figure 5.1.

Predicted ground temperatures are compared with those measured by a thermistor string (ID No. 6300) installed on March 30, 1978 (Figures 5.2 to 5.6).

The satisfactory comparison between the predicted and measured values indicates the adequacy of the input parameters for the analyses.

5.2 Ground Temperatures Subsequent to Operation of Chilled Pipes

Based on the input parameters described in section IV, the thermal model was applied to predict ground temperatures at the test facility, subsequent to operation of the chilled pipes on October 13, 1979.

Test sections No.1, No.2, No.3, No.4, No.5 and No.8 were modelled. The ground temperature distribution obtained from the one-dimensional simulation of the undisturbed ground on October 13 was used as the initial condition for the two-dimensional analyses.

The following predictions are presented:

(a) pipe surface temperatures,
(b) soil temperatures at selected locations,
(c) contours of the 32°F isotherms and
(d) average heat flux around the pipe surface.

Figure 2.4 shows the configurations of the test sections.

5.2.1 Test Section No. 1 - Bare Pipe

The variation of pipe surface temperature versus time is shown in Figure 5.7. Soil temperatures at selected locations around the chilled pipe are shown in Figures 5.8 to 5.10. Contours of the 32°F isotherm are presented in Figure 5.11.

5.2.2 Test Section No. 2 - 2" Urethane Pipe Insulation

The temperature variations at both sides of the insulation are presented in Figure 5.12, which indicates an average temperature difference of about 18°F across the two inch insulation. Soil temperatures and contours of the 32°F isotherm are presented in Figure 5.13 and 5.14 respectively.

5.2.3 Test Section No. 3 - 2-3" Thick Styrofoam Boards with 6" Granular Bedding

The temperature difference across the 2-3" thick styrofoam boards is about 9°F (Figure 5.15). Ground temperatures at selected locations and contours of the 32°F isotherms are presented in Figures 5.16 and 5.17 respectively.

5.2.4 Test Section No. 4 - Bare Pipe with 3 Foot Granular Bedding

Soil temperatures at selected locations and contours of the 32°F isotherms are shown in Figures 5.18 to 5.20 inclusively.

5.2.5 Test Section No. 5 - 2" Urethane Pipe Insulation in Shallow Ditch with 3' Granular Berm

Figures 5.21 to 5.25 present the predicted temperatures at selected locations and contours of the 32°F isotherms.

5.2.6 Test Section No. 8 - 4" Urethane Insulation with 3' Granular Bedding

The variations of temperatures on both sides of the insulation are shown in Figure 5.26, which indicates an average temperature difference of about 24°F across the four inch insulation. Soil temperature at the pipe centreline 5.5 feet below the pipe is shown in Figure 5.27, and the 32°F isotherm contours are also shown in Figure 5.28.

5.3 Heat Flux

Due to temperature variation around the pipe surface (Figures 5.7, 5.12, 5.21), the heat flux around the pipe perimeter should also vary. The overall average pipe heat flux (total pipe flux divided by pipe surface area) resulting from the operation of a chilled pipeline is presented in Figures 5.29 to 5.31 for a bare pipe (Test Section No. 1), a pipe wrapped with 2 inches (Test Section No. 2) and 4 inches (Test Section No. 8) of urethane insulation, respectively.

The heat flux may be summarized as follows:

Pipe No.	Chilled Air Temperature (°F)	Average Pipe Heat Flux ($BTU/HR.FT^2$) Range	Average	Remarks
1	10	3.0-9.0	6.0	Bare pipe
2	8	1.1-1.9	1.5	Pipe wrapped with 2" urethane insulation.
8	8	0.7-1.2	0.95	Pipe wrapped with 4" urethane insulation.

The above summary illustrates the efficiency of insulation.

5.4 Frost Heave and Frost Depth

The result for frost heave and frost depth at the centerline of the pipe are presented in Figure 5.32 to 5.37. The following table summarizes the results:

Pipe No.	Chilled Air Temperature (^{o}F)	Frost Front Penetration* ($32^{o}F$ Isotherm) (Feet)	Heave* (Feet)
1	10	15.5	1.55
2	8	8.2	0.81
3	10	7.3	0.63
4	10	15.8	1.28
5	8	6.9	0.67
8	8	5.4	0.19
8	15	3.3	0

* After 5 years of operation.

VI DISCUSSIONS ON PREDICTION RESULTS

6.1 Temperatures

(1) The use of insulation is to raise the effective pipe surface temperatures to be closer to the ground temperatures. Figure 5.7 shows the surface temperature of a bare pipe. For two and four inches of insulation, the average effective surface temperature have been raised to 29°F and 31°F respectively, (Figures 5.12 and 5.26) from a chilled air temperature of 8°F.

(2) The effect of seasonal ground temperature variations on the pipe temperature is observed near the top of the pipe for both bare (Figure 5.7) and insulated (Figure 5.12 and 5.26) sections. However, it is not observed near the bottom of the pipes. It is therefore concluded that at the depth of the pipe bottom, which is about 7.5 feet below the ground surface, the effect of seasonal ground temperature variations on pipe surface temperature is insignificant.

(3) Test sections No. 2 and No. 5 were installed to investigate the effectiveness of the gravel berm in conducting heat during summer season so as to reduce the frost heave potential of the chilled pipeline. Comparing the frost bulbs of the two sections (Figures 5.14 and 5.25), the effectiveness of the gravel berm is observed.

(4) Wrapping insulation around the pipe is more efficient than the board insulation along the trench sides in reducing the size of the frost bulb around the pipe (Figures 5.25, 5.17 and 5.28).

6.2 Heat Flux

(1) For a 48" bare pipe circulating with chilled air at $10^{o}F$, the overall average heat flux around the pipe perimeter is about 6.0 BTU/hr/ft^2.

(2) When the pipe is wrapped with 2 inches of urethane insulation, the overall average heat flux becomes about 1.5 BTU/hr/ft^2.

(3) For 4 inches of insulation, the overall average heat flux is further reduced to about 0.9 BTU/hr/ft^2.

6.3 Frost Penetration and Frost Heave

The depth of frost penetration along the pipe centreline, together with the frost heave predictions are summarized in Figures 5.32 to 5.37, inclusive, and in table form in subsection 5.4.

An evaluation of these results reveals that:

(1) As discussed previously, the 3 foot gravel berm (Test Pipe No. 5) as opposed to the native soil berm (Test Pipe No. 2), results in less frost depth below pipe and thus less frost heave. This is mainly due to the effectiveness of the gravel berm in conducting heat during summer season so as to reduce the frost bulb beneath the chilled pipeline.

(2) As expected, the thicker the insulation, the less frost depth and thus less frost heave will be. Even though 0.2 feet of heave is predicted for Pipe No. 8 at the end of 5 years while circulating with $8^{o}F$ chilled air, it is interesting to observe that no heave is anticipated should the chilled air temperature be raised to $15^{o}F$ (Figure 5.37).

6.4 Conservatism of the Semi-Empirical Approach

The predicted values of frost heaves for various test sections are expected to be more than observed values. Such over-predictions are expected due to:

(1) Conservative factors built into the semi-empirical approach as described in another report (Reference 5). One-dimensional laboratory testing of a small finite length soil sample with free access of water at one end of the sample always provides greater water accessibility than the field condition for a chilled pipeline.

The heave strain or ice segregation ratio determined in the laboratory is at the steady-state condition: the ultimate condition of soil freezing. A soil element below the pipe, depending on its relative location with respect to the chilled pipe and time duration of pipeline operation may or may not reach its thermal steady-state equilibrium. It follows that the ice segregation ratio determined at the steady-state condition will result in over prediction of frost heave.

(2) Since an identical approach is being used for frost heave predictions at the Calgary and Fairbanks test sites, it is expected that similar agreement between predicted and measured values will be obtained.

(3) In all predictions of frost heave, the 32°F isotherm is used to indicate the boundary between frozen and unfrozen soils. It should be noted that, when soil temperatures are only slightly below 32°F (especially when the pipe is insulated) and the soil is, therefore, considered frozen, it may actually be unfrozen. This assumption may also account for some overprediction by the design approach.

VII CLOSURE

A performance prediction was made for the Fairbanks Test Facility, primarily in terms of soil temperatures and frost heave.

The methodology of the semi-empirical design approach for frost heave prediction has been demonstrated through the method of analysis and the input parameters.

It is anticipated that the accuracy of the prediction with respect to the performance of various test sections will be similar to that of the Calgary Test Facility which has been in operation since March, 1974.

It is hoped that the performance data obtained from both test sites not only will further confirm the applicability of the semi-empirical approach for pipeline frost heave design, but also will further improve the method.

Respectfully submitted,

EBA Engineering Consultants Ltd.

PROFESSIONAL ENGINEER ALBERTA C. T. HWANG

C.T. Hwang, Ph.D, P.Eng.
Principal Consultant

PROFESSIONAL ENGINEER ALBERTA CHEVALLIER

J-M Chevallier, P.Eng.
Project Engineer

CTH/hek

REFERENCES

1. EBA Engineering Consultants Ltd., 1979. "Performance Analysis of Calgary Frost Heave Test Facility". A report submitted to Foothills Pipe Lines (Yukon) Ltd.

2. R.M. Hardy and Associates Ltd. and R.A. Kreig and Associates, 1978. "Survey for Frost Heave Test Site". A report submitted to Northwest Alaskan Pipeline Co.

3. Shannon & Wilson Inc., 1978. "Subsurface Investigations Potential Frost Heave Test Sites". A report submitted to Northwest Alaskan Pipeline Company.

4. Northwest Alaskan Pipeline Co., 1978. "Frost Heave Program Description". A report submitted to the Executive Policy Board, Technical Subcommittee-Permafrost.

5. EBA Engineering Consultants Ltd., 1980. "Development of an Empirical Frost Heave Design Procedure". A report submitted to Northwest Alaskan Pipeline Co.

6. EBA Engineering Consultants Ltd., 1976. "Interim Report on Frost Heave Study, Two-Dimensional Model". A report submitted to Foothills Pipe Lines Ltd.

7. EBA Engineering Consultants Ltd., 1976. "Freezing of Saturated Soils, One-Dimensional Model". A report submitted to Foothills Pipe Lines Ltd.

8. Hwang, C.T., 1976. "Predictions and Observations on the Behaviour of a Warm Gas Pipeline on Permafrost". Canadian Geotechnical Journal, 13 (4), pp. 452-480.

9. Kaplar, C.W., 1974. "Freezing Test for Evaluating Relative Frost Susceptibility of Various Soils". U.S. Army CRREL, Hanover, New Hampshire.

10. Penner, E. and Walton, T., 1978. "Effects of Temperature and Pressure on Frost Heave". Proceedings, International Symposium of Ground Freezing, Ruhr, Germany.

11. Hwang, C.T. and Yip, F.C., 1977. "Advances in Frost Heave Prediction and Mitigative Methods for Pipeline Application". Proceedings, ASME Winter Annual Meeting, Atlanta, Georgia.

References (continued)

12. Hwang, C.T., 1977. "Frost Heave Design of a Chilled gas Pipeline". Proceedings, 30th Canadian Geotechnical Conference, Saskatoon Saskatchewan, Canada.

13. Kerstern, M.S. 1949. "Laboratory Research for the Determination of Thermal Properties of Soils", Final Report, Eng. Exp. Stn. Univ. Minn. Minneapolis, Minn.

14. McAdams, W.H., "Review and Summary of Developments in Heat Transfer by Conduction and Convection", Trans. A.I.Ch.E., Vol. 36, 1940, p.1.

TABLE I

SUMMARY OF HEAVE STRAIN FROM LABORATORY TESTS

Test No	Clay Contents (%)	Consolidation Pressure kPa	Test Pressure kPa	Warm Side Temperature ($0^{o}C$)	Cold Side Temperature ($0^{o}C$)	Test Duration (days)	Water Intake (ml)	Heave (mm)	Penetration of $0^{o}C$ Isotherm (mm)	Heave Strain (Tested)	Heave Strain Used for Prediction
FH15	6	51	51	1.04 to 1.17	-1.01 to -1.08	77	13.8	5.11	61.5	8%	
FH16	9(Est.)	56	56	1.17 to 1.36	-1.05 to -1.10	77	15.5	4.48	51.5	9%	10%
FH18	9	57	57	1.26 to 1.34	-0.60 to -0.67	64	23.3	3.78	38.4	10%	
TS(8)*	19	393.3	73.6	4.0**	-1.0 to -1.1	24	-	7.2	56.9	12.6%	
TS(9)*	9	393.3	73.5	4.0**	-1.0 to -1.1	2	-	0.52	58.2	0.9%	

* Test results by E. Penner "Frost Heave Study of Soils from Frost Heave Test Facility at Fairbanks, Alaska" (1979).

** Control chamber temperature.

TABLE II

SOIL PROPERTIES - TEST SECTION NO. I

Soil Type	Depth Below Ground Surface (FEET)	Moisture Content (%)		Heave Strain* or Ice Segregation Ratio (%)	Bulk Density Lbs/FT^3		Thermal Conductivity BTU/HR.FT.$^{\circ}$F		Specific Heat BTU/LB/$^{\circ}$F		Latent Heat BTU/FT^3
		Unfrozen	Frozen+		Unfrozen	Frozen	Unfrozen	Frozen	Unfrozen	Frozen	
Backfill	-	21.7	21.7	-	108.9	108.9	0.67	0.86	.32	.25	2300
Silt	0-4	20.0	20.0	-**	124.8	124.8	0.88	1.12	.31	.24	2400
Silt	4-14	31.0	38.0	10	118.9	112.7	0.77	1.23	.37	.27	3900
Silt	14-80	43.0	51.3	10	110.0	104.7	0.63	1.24	.42	.29	4700

* From laboratory one-dimensional frost heave tests.

** Heave strain not considered within seasonal frost depth.

+ Unfrozen water content 4.5%.

TABLE III

SOIL PROPERTIES - TEST SECTION NO. 2

Soil Type	Depth Below Ground Surface (FEET)	Moisture Content(%) Unfrozen	Moisture Content(%) Frozen +	Heave Strain* or Ice Segregation Ratio (%)	Bulk Density Lbs/FT^3 Unfrozen	Bulk Density Lbs/FT^3 Frozen	Thermal Conductivity BTU/HR.FT.^{o}F Unfrozen	Thermal Conductivity BTU/HR.FT.^{o}F Frozen	Specific Heat BTU/LB/^{o}F Unfrozen	Specific Heat BTU/LB/^{o}F Frozen	Latent Heat BTU/FT^3
Backfill	-	26	26	-	78.9	78.9	0.38	0.60	0.35	0.25	2000
Silt	0-4	20	20	-**	124.8	124.8	0.88	1.12	0.31	0.24	2400
Silt	4-9	31	38.0	10	118.9	112.7	0.77	1.23	0.37	0.27	3900
Silt	9-13	34	41.4	10	115.0	109.2	0.71	1.22	0.38	0.28	4100
Silt	13-80	40	47.9	10	112.0	106.5	0.65	1.22	0.41	0.29	4500
Insulation (Urethane)	-	-	-	-	2.2	2.2	0.012	0.012	0.29	0.29	0

* From laboratory one-dimensional frost heave tests.

** Heave strain not considered within seasonal frost depth.

\+ Unfrozen water content 4.5%.

TABLE IV

SOIL PROPERTIES - TEST SECTION NO. 3

Soil Type	Depth Below Ground Surface (FEET)	Moisture Content (%)		Heave Strain* or Ice Segregation Ratio (%)	Bulk Density Lbs/FT^3		Thermal Conductivity BTU/HR.FT.^{o}F		Specific Heat BTU/LB/^{o}F		Latent Heat BTU/FT^3
		Unfrozen	Frozen+		Unfrozen	Frozen	Unfrozen	Frozen	Unfrozen	Frozen	
Backfill	-	26.0	26.0	-	78.9	78.9	0.38	0.60	0.35	0.25	2000
Gravel	-	7.0	7.0	-	133.8	133.8	1.47	1.52	0.23	0.19	1300
Silt	0-6	25.5	25.5	-**	124.5	124.5	0.87	1.22	0.34	0.25	3100
Silt	6-26	37.0	44.6	10	114.4	108.7	0.69	1.21	0.40	0.28	4300
Silt	26-80	40.0	47.9	10	112.0	106.5	0.65	1.22	0.41	0.29	4500
Insulation (Styrofoam)	-	-	-	-	2.20	2.20	0.017	0.017	0.29	0.29	0

* From laboratory one-dimensional frost heave tests.

** Heave strain not considered within seasonal front depth.

\+ Unfrozen water content 4.5%.

TABLE V

SOIL PROPERTIES - TEST SECTION NO. 4

Soil Type	Depth Below Ground Surface (FEET)	Moisture Content(%) Unfrozen	Moisture Content(%) Frozen+	Heave Strain* or Ice Segregation Ratio (%)	Bulk Density Lbs/FT^3 Unfrozen	Bulk Density Lbs/FT^3 Frozen	Thermal Conductivity BTU/HR.FT.^{o}F Unfrozen	Thermal Conductivity BTU/HR.FT.^{o}F Frozen	Specific Heat BTU/LB/^{o}F Unfrozen	Specific Heat BTU/LB/^{o}F Frozen	Latent Heat BTU/FT^3
Backfill	-	24.5	24.5	-	117.4	117.4	0.76	1.08	.33	.25	2800
Gravel	-	7.1	7.1	-	133.1	133.1	1.4	1.46	.23	.19	1300
Silt	0-6	24.0	24.0	-**	126.0	126.0	0.9	1.21	.33	.25	2900
Silt	6-12	29.0	35.8	10	121.0	114.6	0.8	1.20	.36	.27	3700
Silt	12-80	40.0	47.9	10	112.0	106.5	0.6	1.22	.41	.29	4500

* From laboratory one-dimensional frost heave tests.

** Heave strain not considered within seasonal frost depth.

\+ Unfrozen water content 4.5%.

TABLE VI

SOIL PROPERTIES - TEST SECTION NO. 5

Soil Type	Depth Below Ground Surface (FEET)	Moisture Content (%) Unfrozen	Moisture Content (%) Frozen+	Heave Strain* or Ice Segregation Ratio (%)	Bulk Density Lbs/FT^3 Unfrozen	Bulk Density Lbs/FT^3 Frozen	Thermal Conductivity BTU/HR.FT.$^{\circ}$F Unfrozen	Thermal Conductivity BTU/HR.FT.$^{\circ}$F Frozen	Specific Heat BTU/LB/$^{\circ}$F Unfrozen	Specific Heat BTU/LB/$^{\circ}$F Frozen	Latent Heat BTU/FT^3
Backfill	-	24.0	24.0	-	83.2	83.2	0.41	0.61	0.34	0.25	1900
Gravel	-	5.0	5.0	-	126.5	126.5	1.18	1.00	0.21	0.19	800
Silt	0-4	20.0	20.0	-**	124.8	124.8	0.88	1.12	0.31	0.24	2400
Silt	4-8	35.0	42.4	10	114.8	109.0	0.70	1.20	0.39	0.28	4200
Silt	8-80	40.0	47.9	10	112.0	106.5	0.65	1.22	0.41	0.29	4500
Insulation (Urethane)	-	-	-	-	2.20	2.20	0.012	0.012	0.29	0.29	0

* From laboratory one-dimensional frost heave tests.

** Heave strain not considered within seasonal frost depth.

\+ Unfrozen water content 4.5%.

TABLE VII

SOIL PROPERTIES - TEST SECTION NO. 8

Soil Type	Depth Below Ground Surface (FEET)	Moisture Content(%) Unfrozen	Moisture Content(%) Frozen+	Heave Strain* or Ice Segregation Ratio (%)	Bulk Density Lbs/FT^3 Unfrozen	Bulk Density Lbs/FT^3 Frozen	Thermal Conductivity BTU/HR.FT.^{o}F Unfrozen	Thermal Conductivity BTU/HR.FT.^{o}F Frozen	Specific Heat BTU/LB/^{o}F Unfrozen	Specific Heat BTU/LB/^{o}F Frozen	Latent Heat BTU/FT^3
Backfill	-	22.5	22.5	-	99.1	99.1	0.55	0.76	.32	.25	2200
Gravel	-	6.9	6.9	-	133.7	133.7	1.45	1.50	.22	.19	1200
Silt	0-4	20.0	20.0	-**	124.8	124.8	0.88	1.12	.31	.24	2400
Silt	4-8	35.0	42.4	10	114.8	109.0	0.70	1.20	.38	.28	4170
Silt	8-80	40.0	47.9	10	112.0	106.5	0.65	1.22	.41	.29	4500
Insulation	-	-	-	-	2.2	2.2	0.012	0.012	.29	.29	0

* From laboratory one-dimensional frost heave tests.

** Heave strain not considered within seasonal frost depth.

+ Unfrozen water content 4.5%

TABLE VIII

METEOROLOGICAL INPUT DATA
FAIRBANKS FROST HEAVE TEST FACILITY

Date	Ambient Temperature (°F)	Average Wind Velocity (MPH)	Snow Depth (FT)	Average Solar Radiation (BTU/HR/FT²)
Oct. 13	27.4	5.33	-	13.70
Oct. 15	26.2	5.30	-	12.60
Nov. 15	3.9	3.80	.58	4.31
Dec. 15	-7.7	2.80	1.02	0.92
Jan. 15	-11.1	2.80	1.52	2.46
Feb. 1	-7.0	3.20	1.75	6.78
Feb. 15	-2.9	3.60	1.75	11.10
Mar. 15	8.9	4.70	1.67	32.80
Apr. 1	19.2	5.50	1.58	45.30
Apr. 15	29.4	6.30	0.83	57.80
May 5	41.2	6.90	-	67.30
May 15	47.1	7.20	-	72.10
Jun. 15	58.4	6.50	-	78.70
July 15	59.7	6.10	-	68.20
Aug. 15	54.3	5.70	-	49.10
Sept. 15	43.6	5.80	-	28.50

Properties of Snow Cover:	Thermal Conductivity	0.12 BTU/HR/FT/°F
	Surface Emissivity	0.92
	Surface Absorbtivity	0.40
Properties of Bare Ground:	Surface Emissivity	0.90
	Surface Absorbtivity	0.85

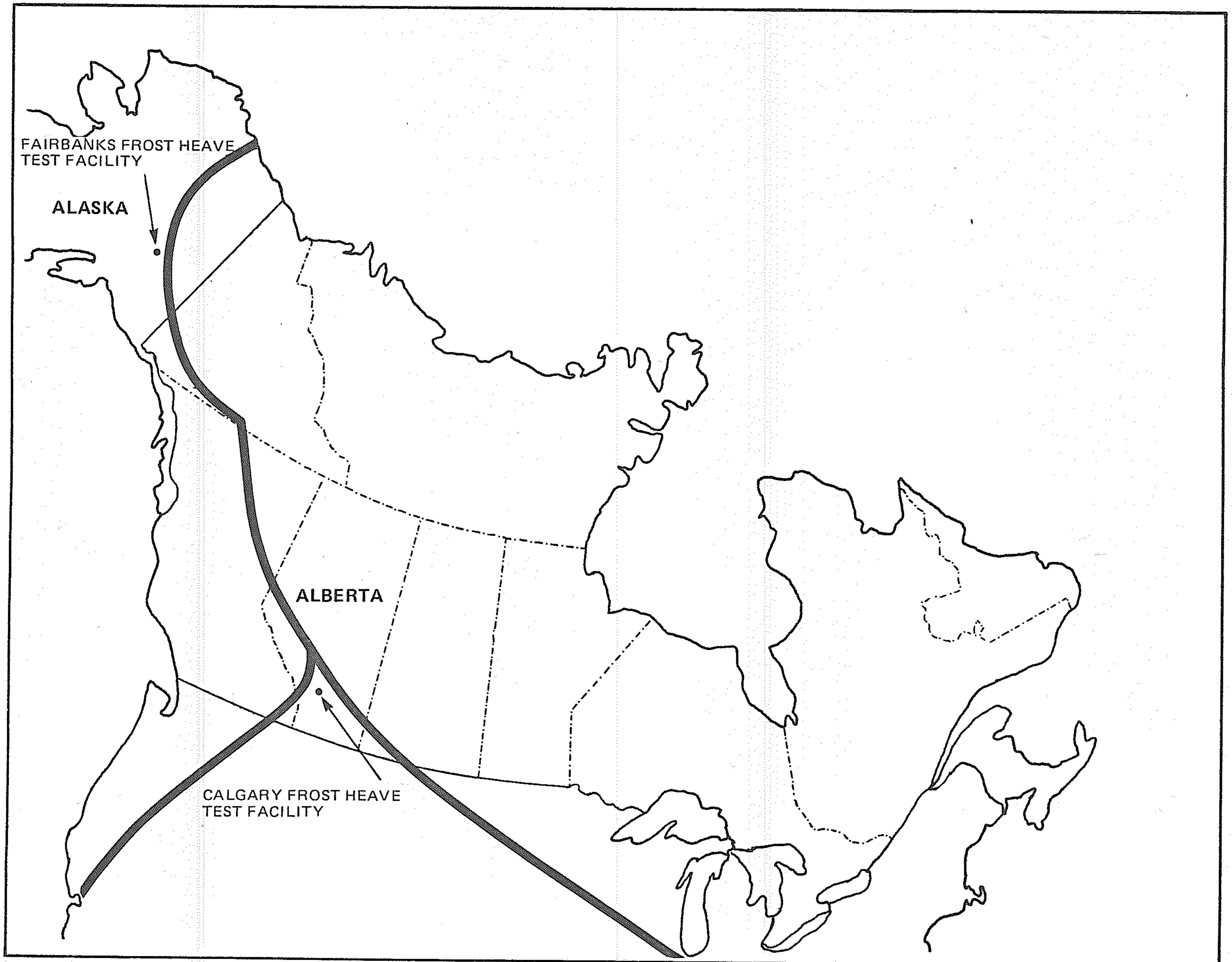


FIGURE 1.1 PIPELINE ROUTE

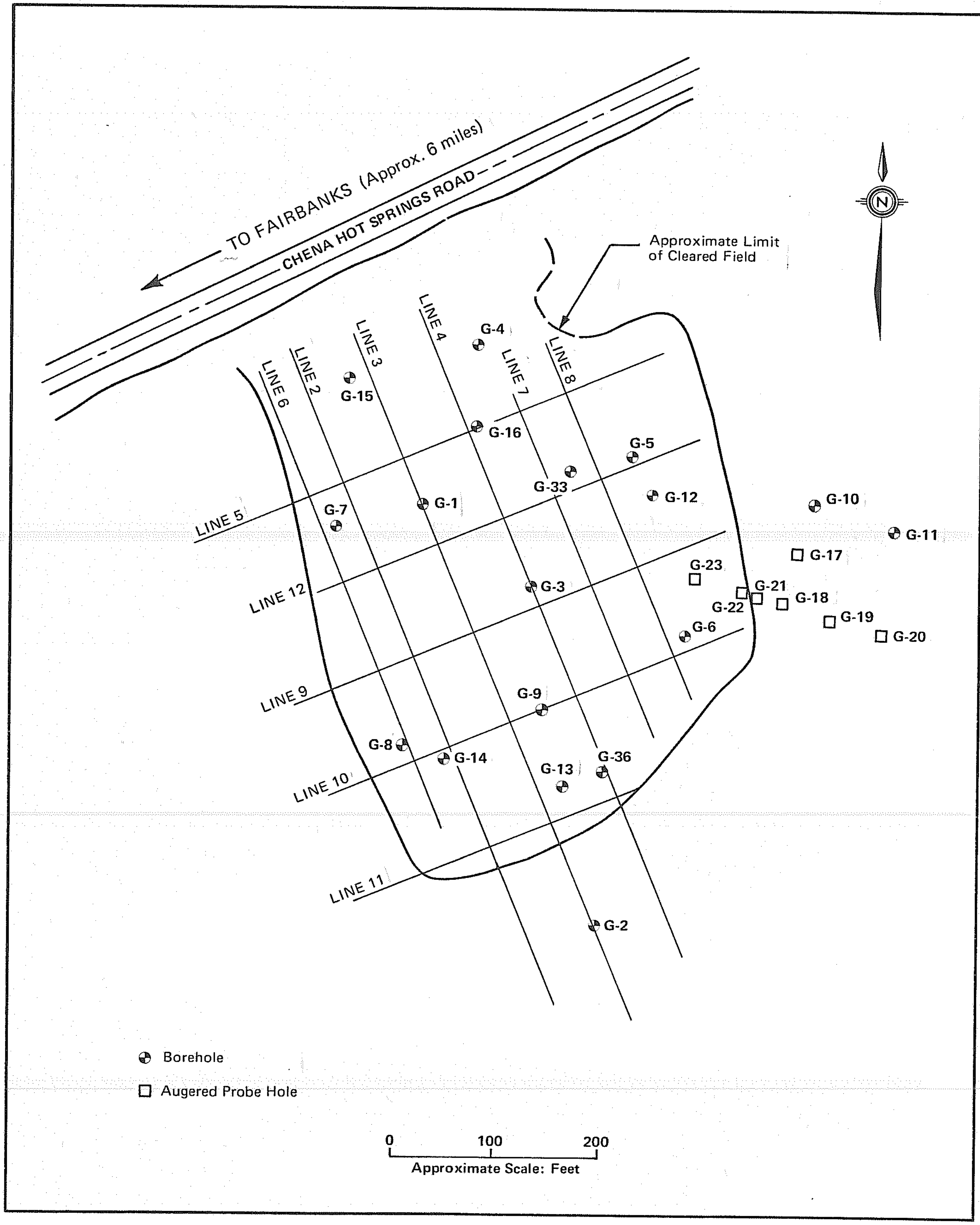


FIGURE 2.1

LOCATION OF TEST FACILITY
GETTINGER SITE
FAIRBANKS, ALASKA

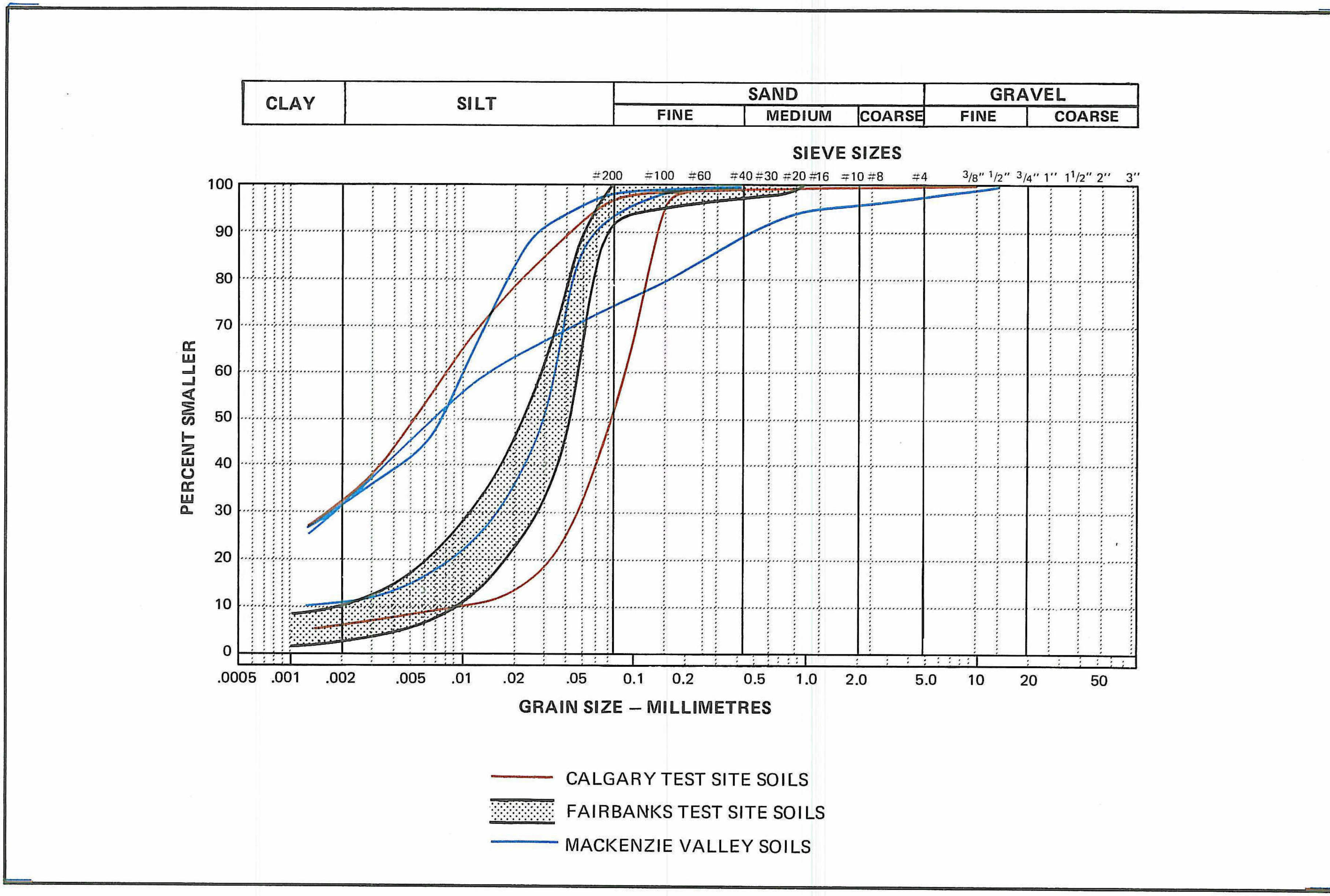


FIGURE 2.2 RANGE OF SOILS – GRAIN SIZE DISTRIBUTION

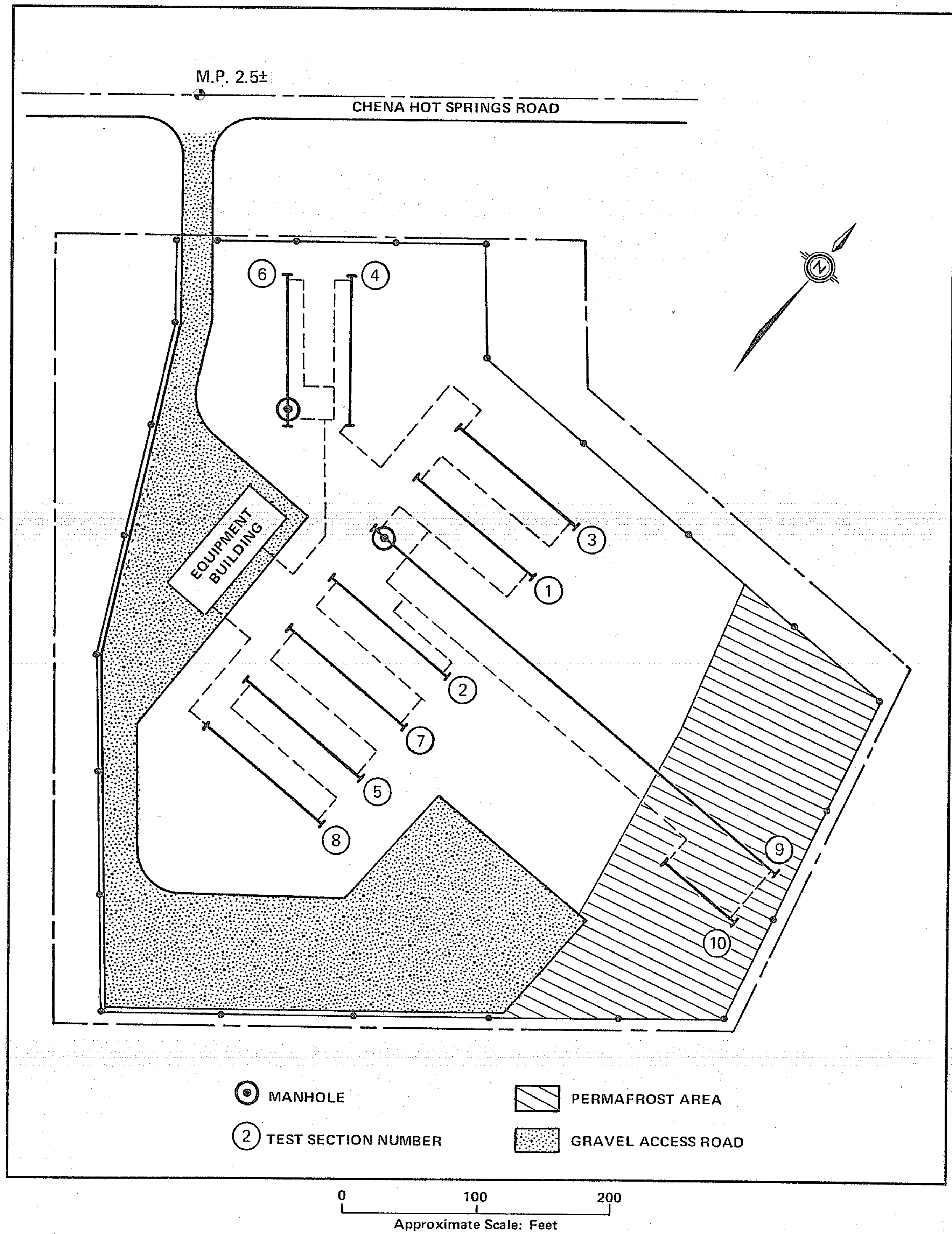


FIGURE 2.3 LAYOUT OF THE FAIRBANKS FROST HEAVE TEST FACILITY

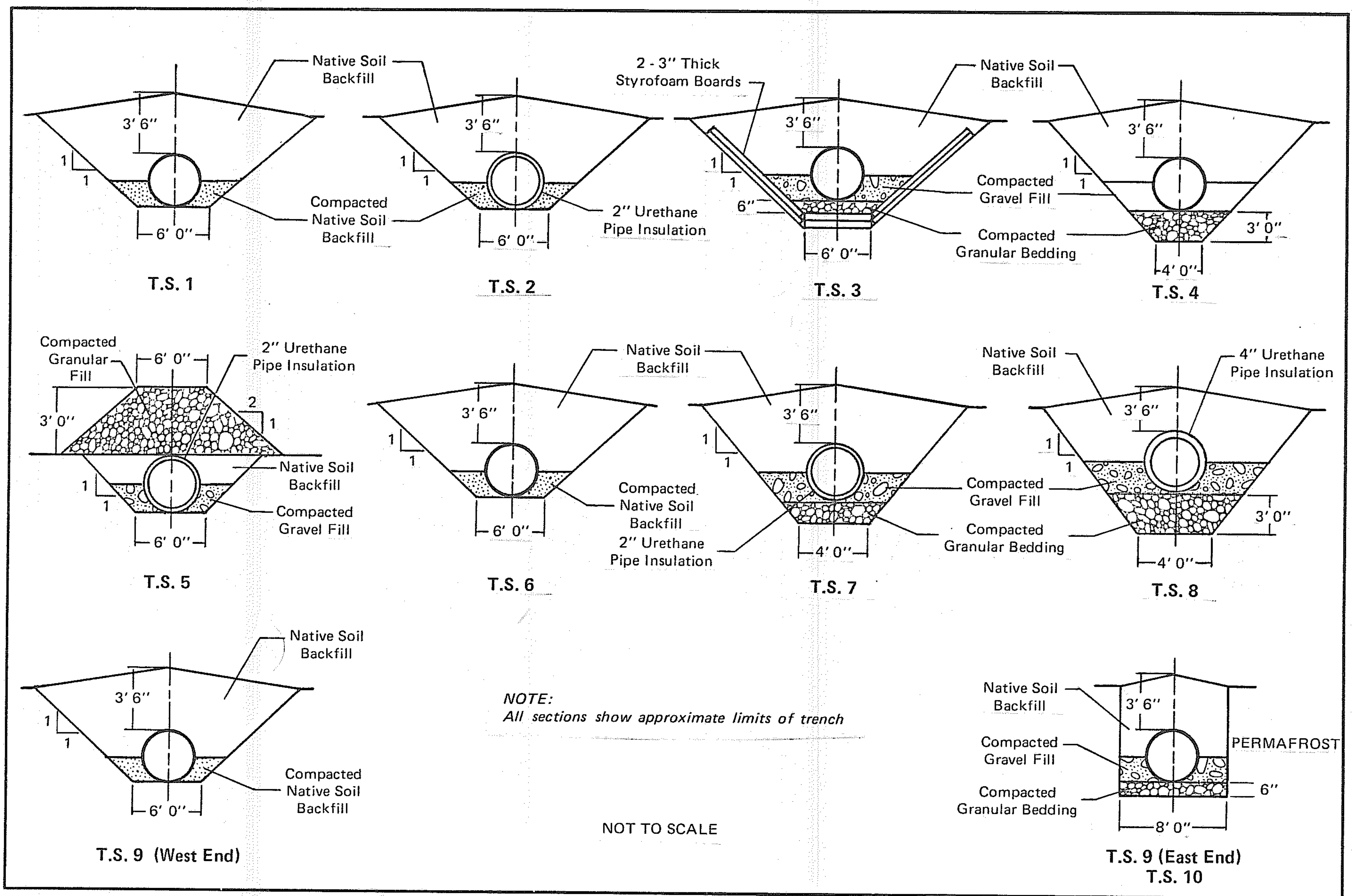


FIGURE 2.4 CONFIGURATIONS OF TEST SECTIONS FAIRBANKS FROST HEAVE TEST FACILITY

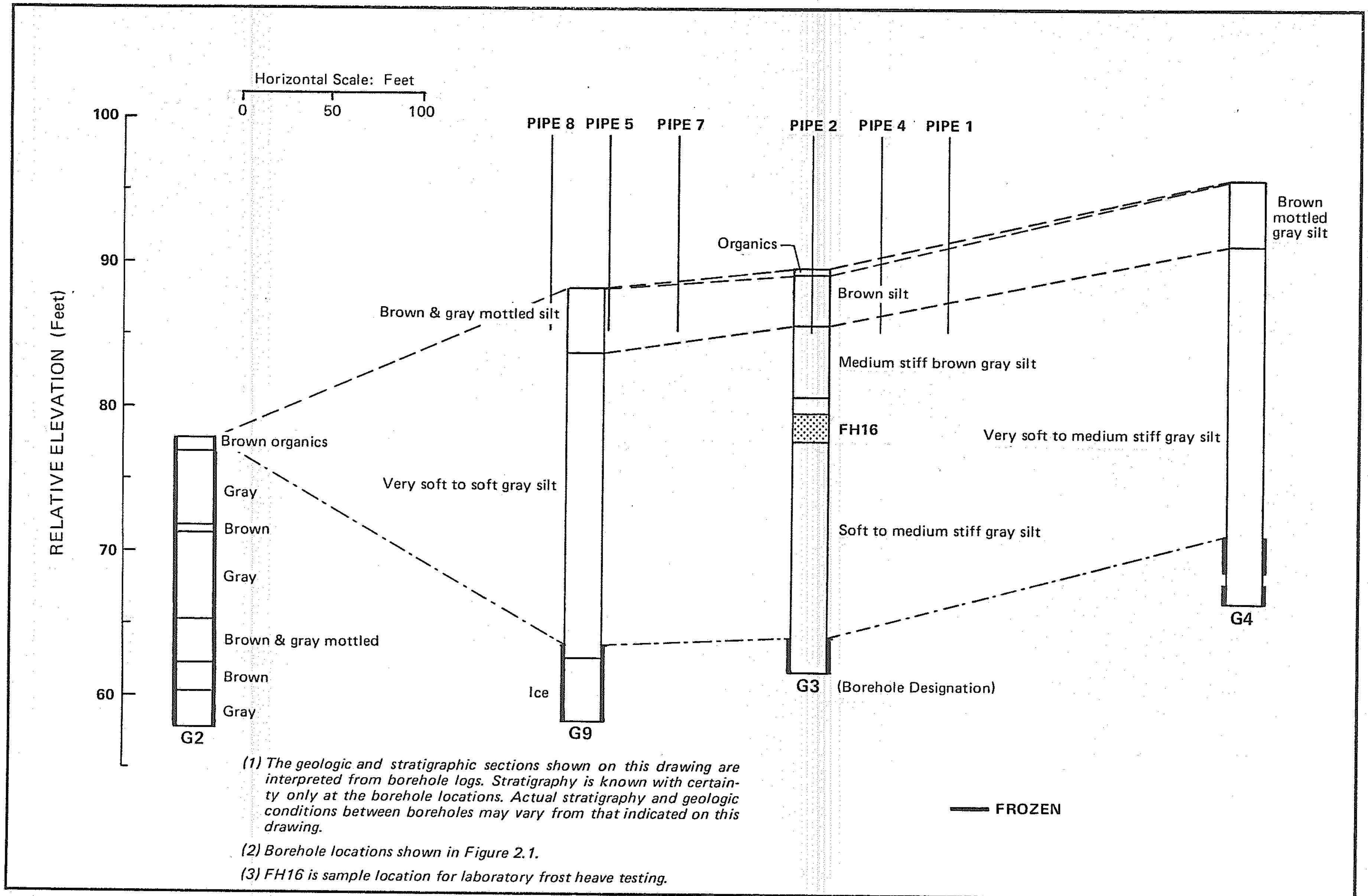


FIGURE 4.1 STRATIGRAPHIC CROSS SECTION

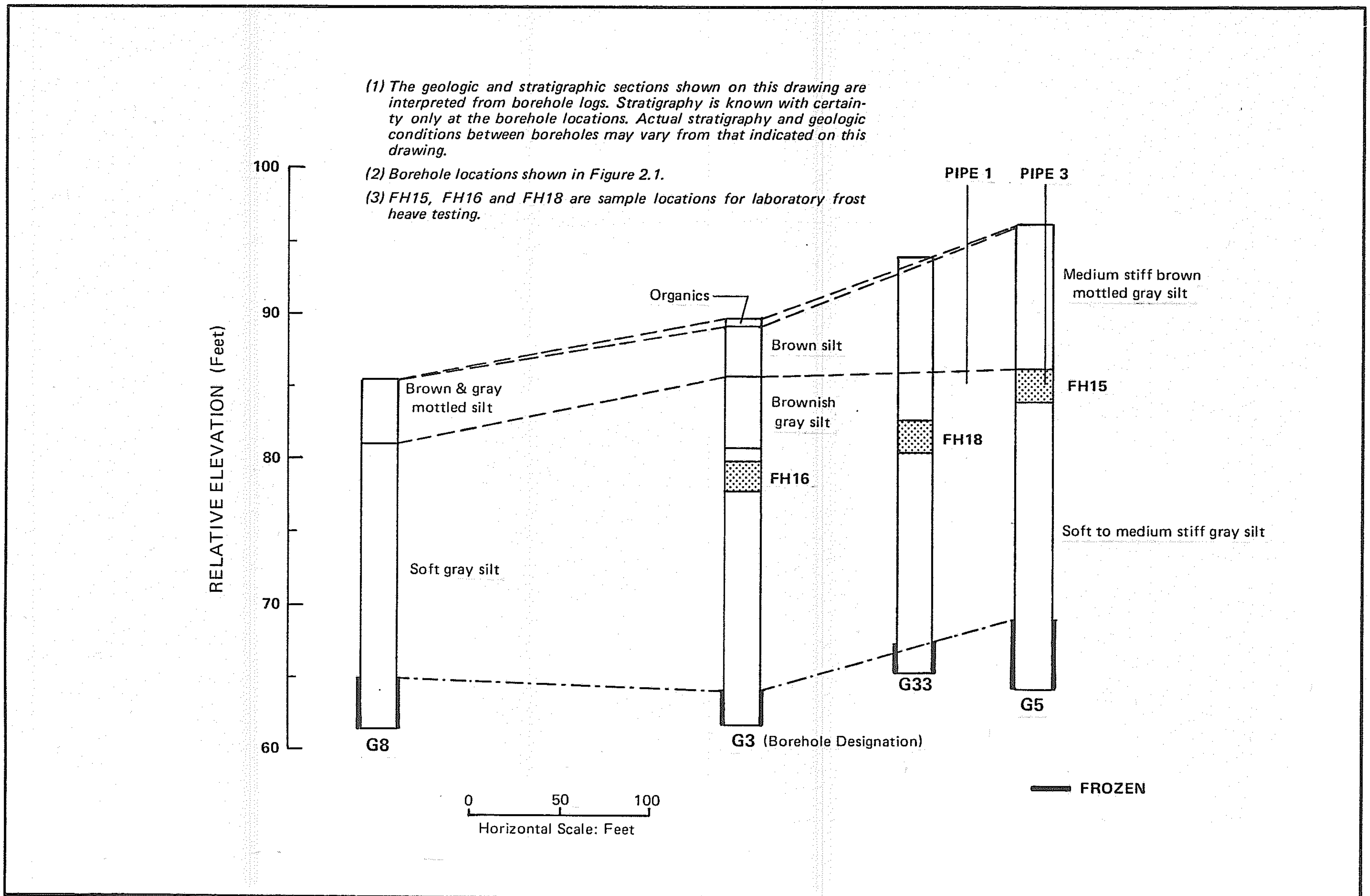
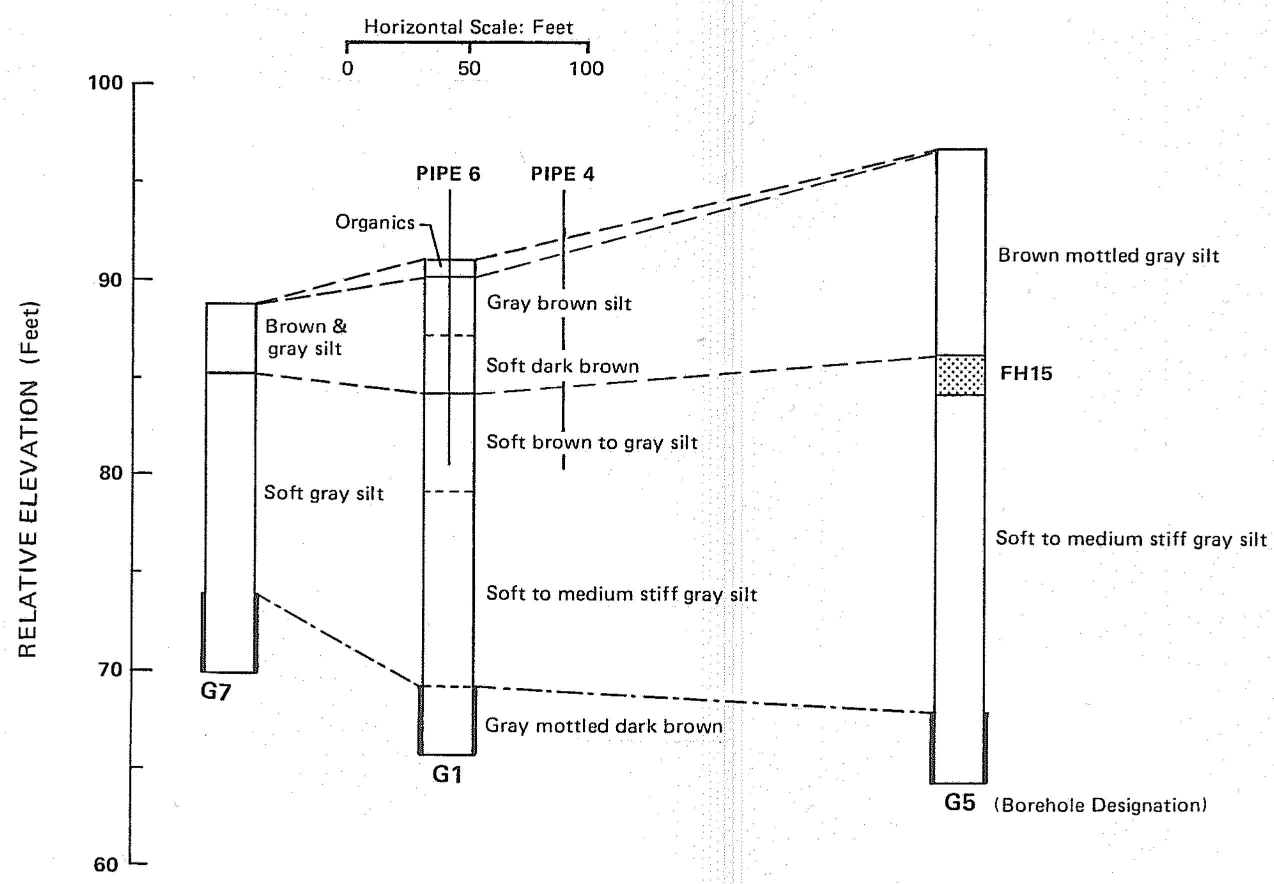


FIGURE 4.2 STRATIGRAPHIC CROSS SECTION



(1) *The geologic and stratigraphic sections shown on this drawing are interpreted from borehole logs. Stratigraphy is known with certainty only at the borehole locations. Actual stratigraphy and geologic conditions between boreholes may vary from that indicated on this drawing.*

(2) *Borehole locations shown in Figure 2.1.*

(3) *FH15 is sample location for laboratory frost heave testing.*

FROZEN

FIGURE 4.3 STRATIGRAPHIC CROSS SECTION

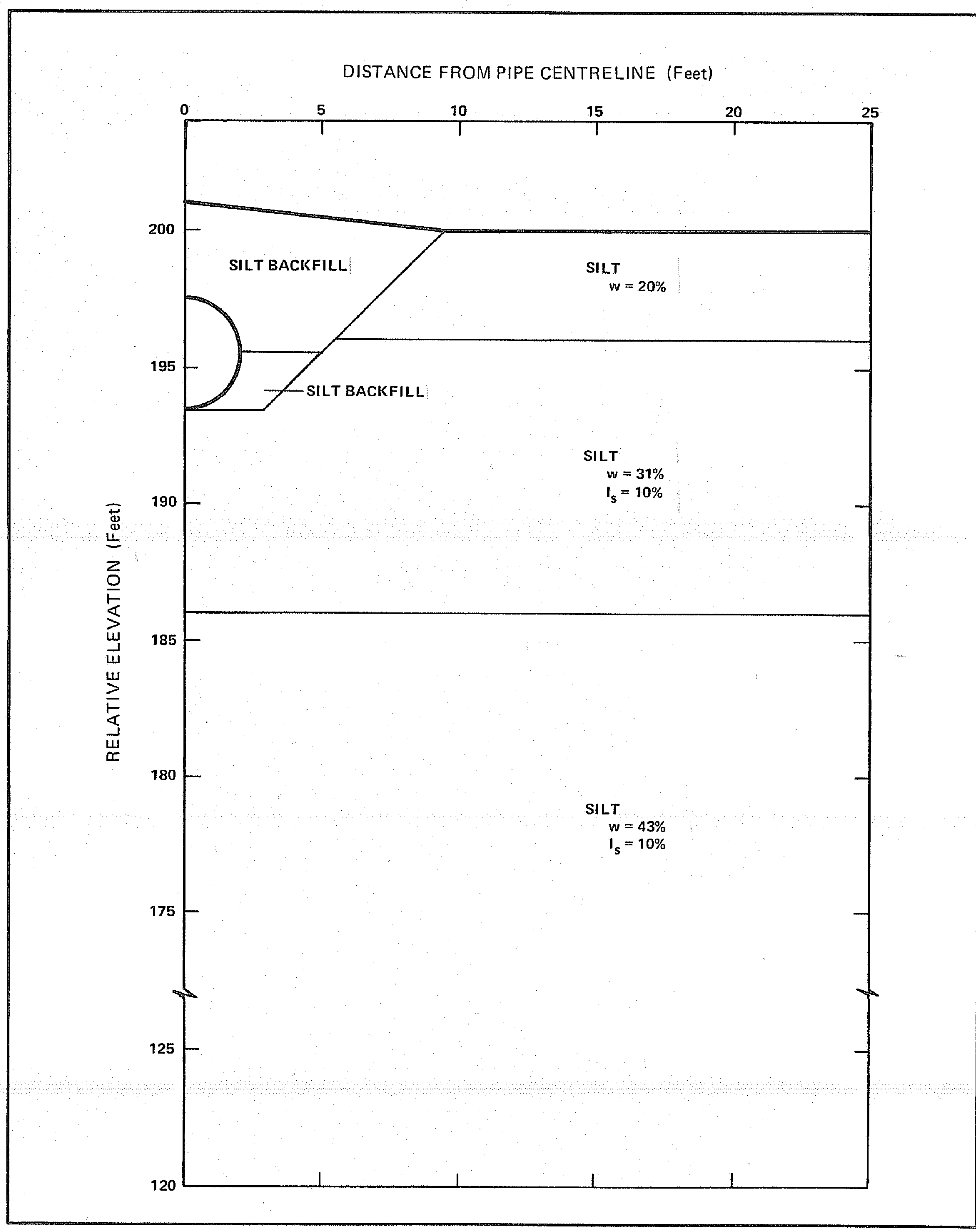


FIGURE 4.4 REGIONS DEFINED FOR THERMAL ANALYSIS PIPE No. 1

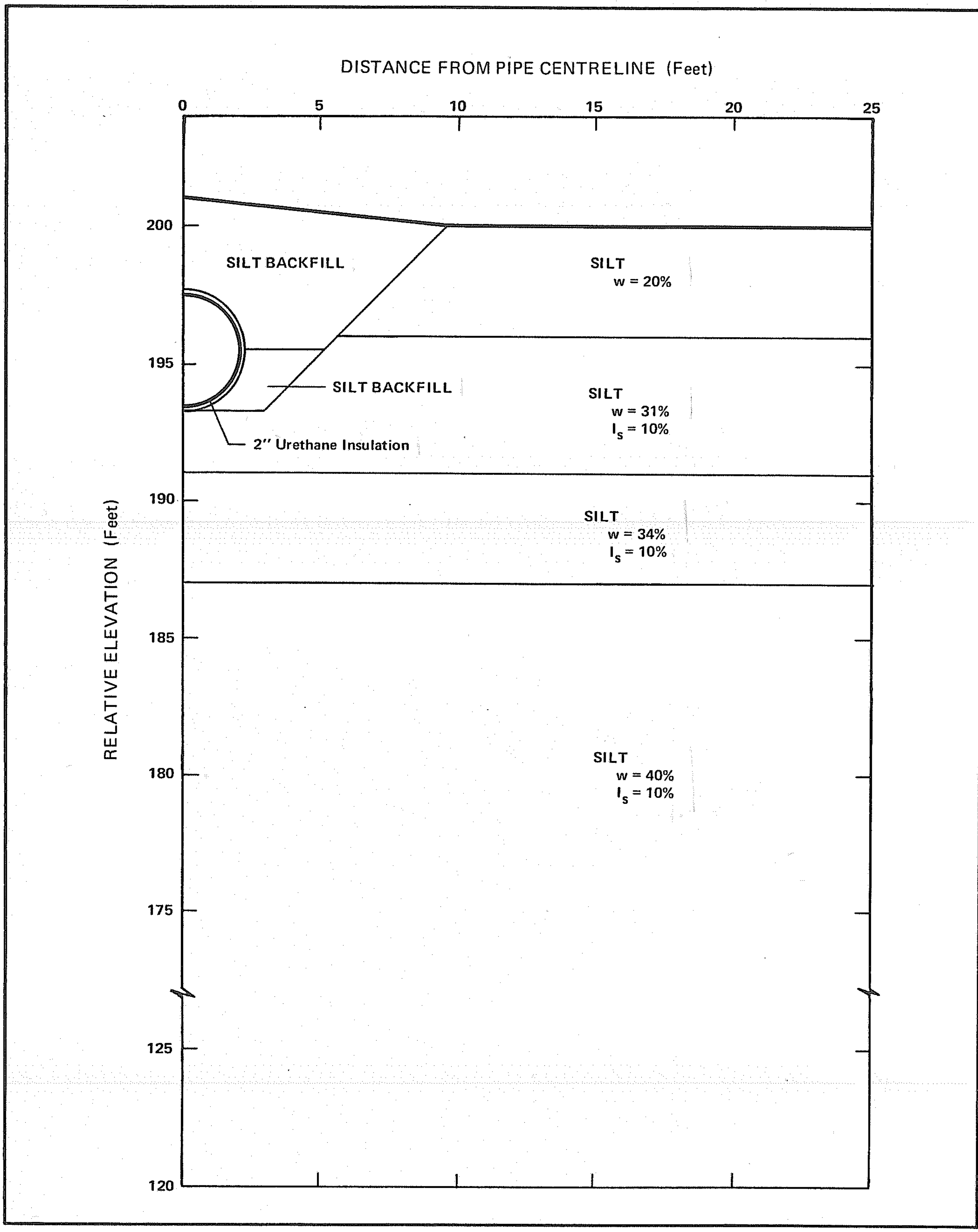


FIGURE 4.5 REGIONS DEFINED FOR THERMAL ANALYSIS
PIPE No. 2

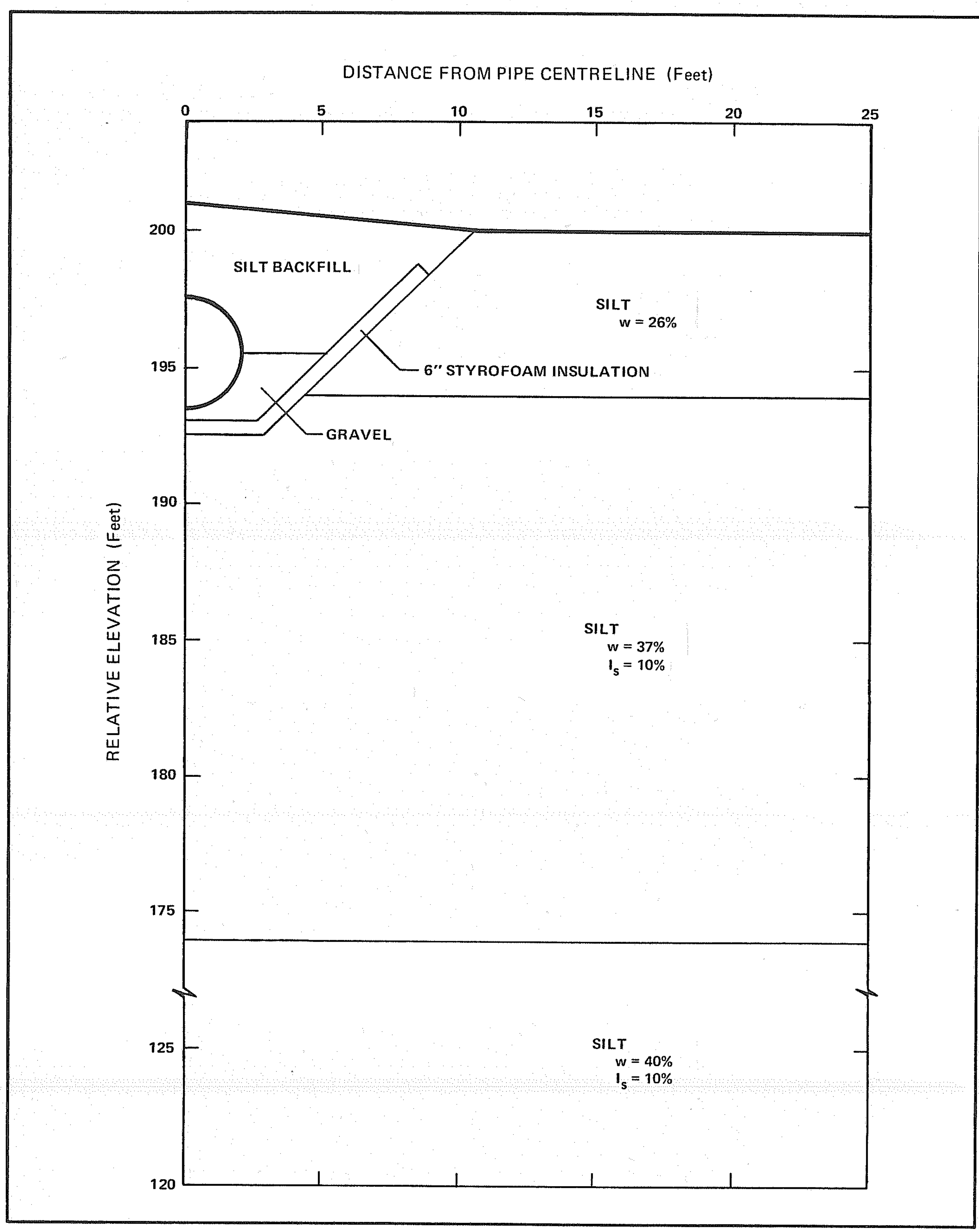


FIGURE 4.6 REGIONS DEFINED FOR THERMAL ANALYSIS PIPE No. 3

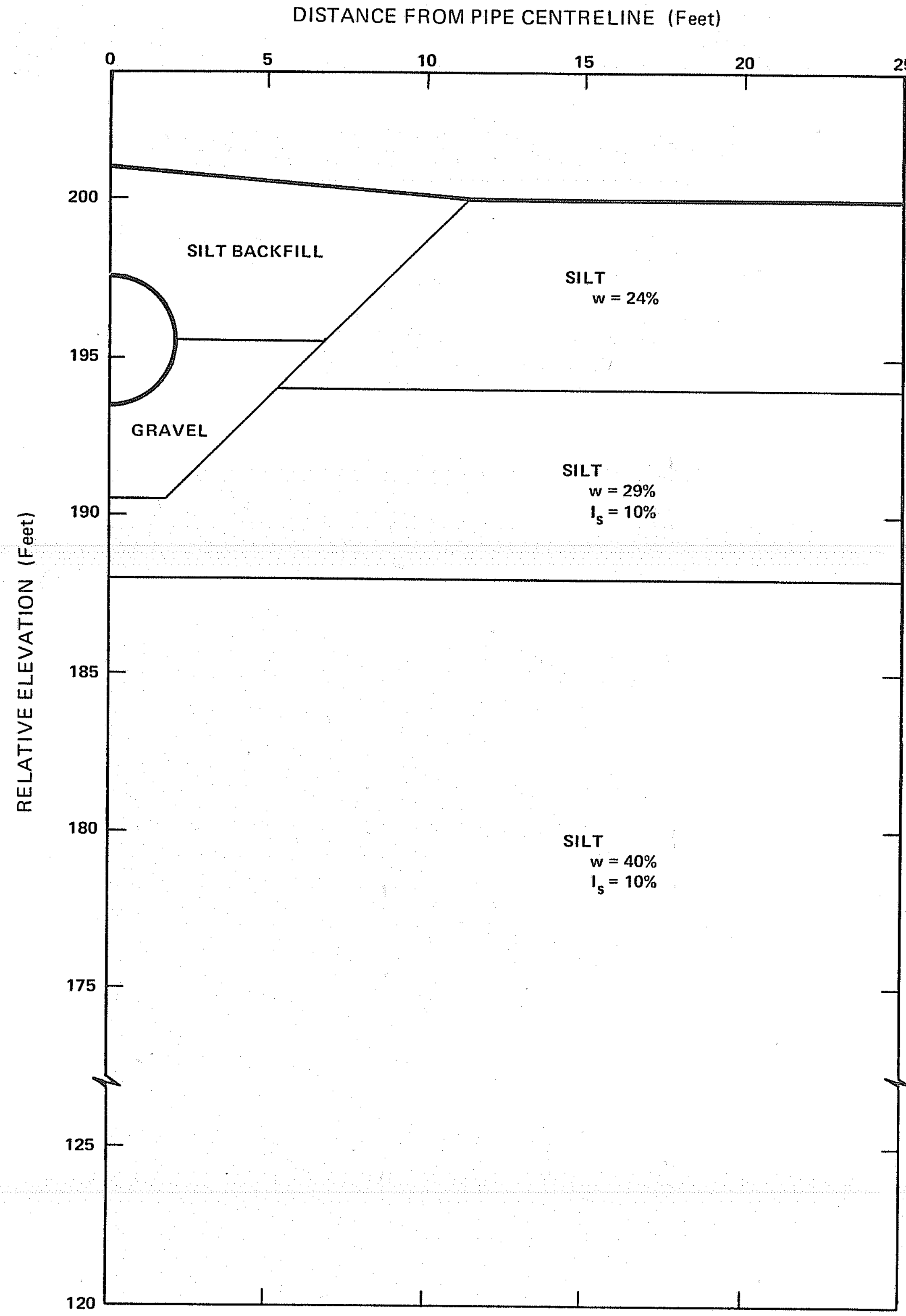


FIGURE 4.7 REGIONS DEFINED FOR THERMAL ANALYSIS
PIPE No. 4

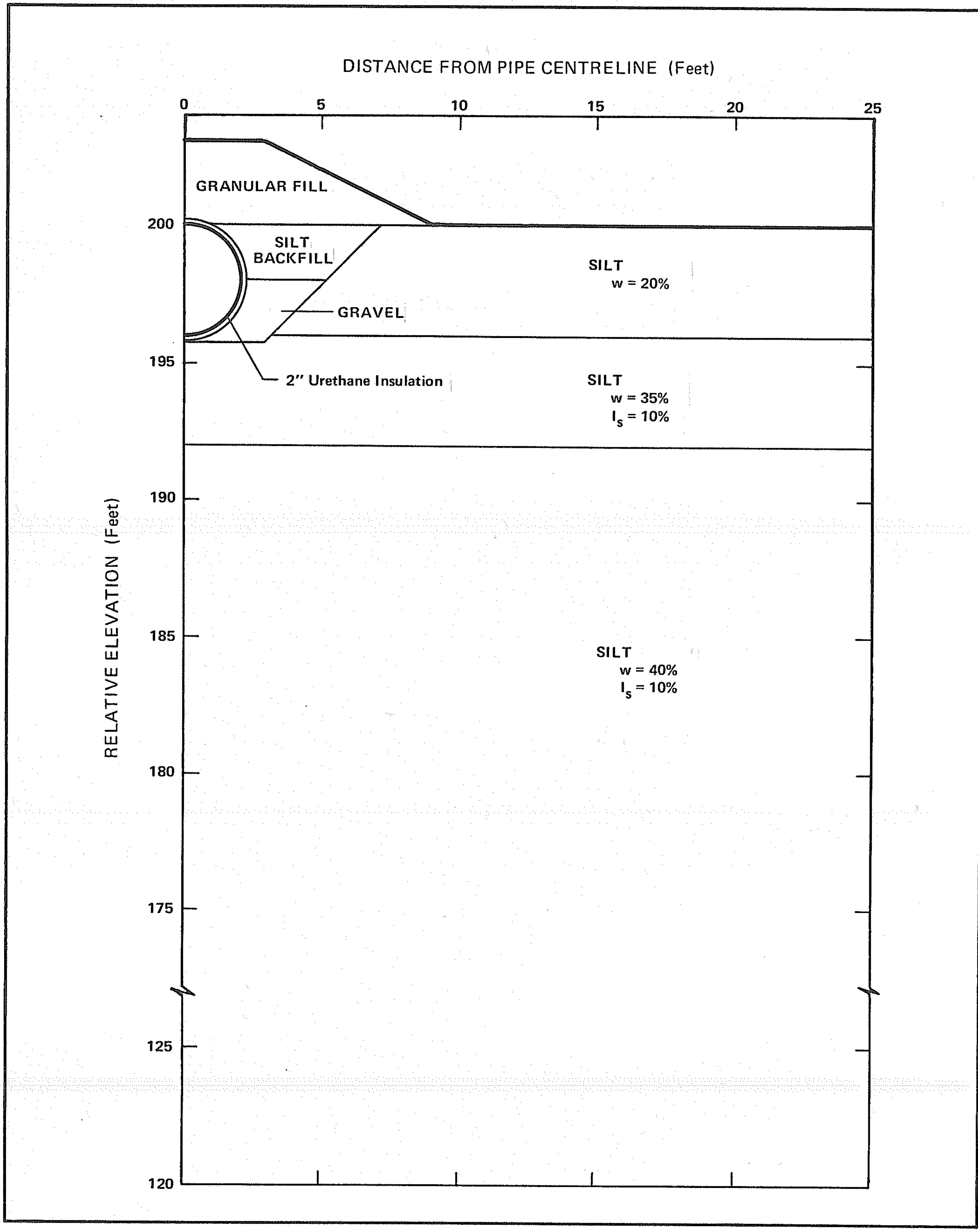


FIGURE 4.8 REGIONS DEFINED FOR THERMAL ANALYSIS PIPE No. 5

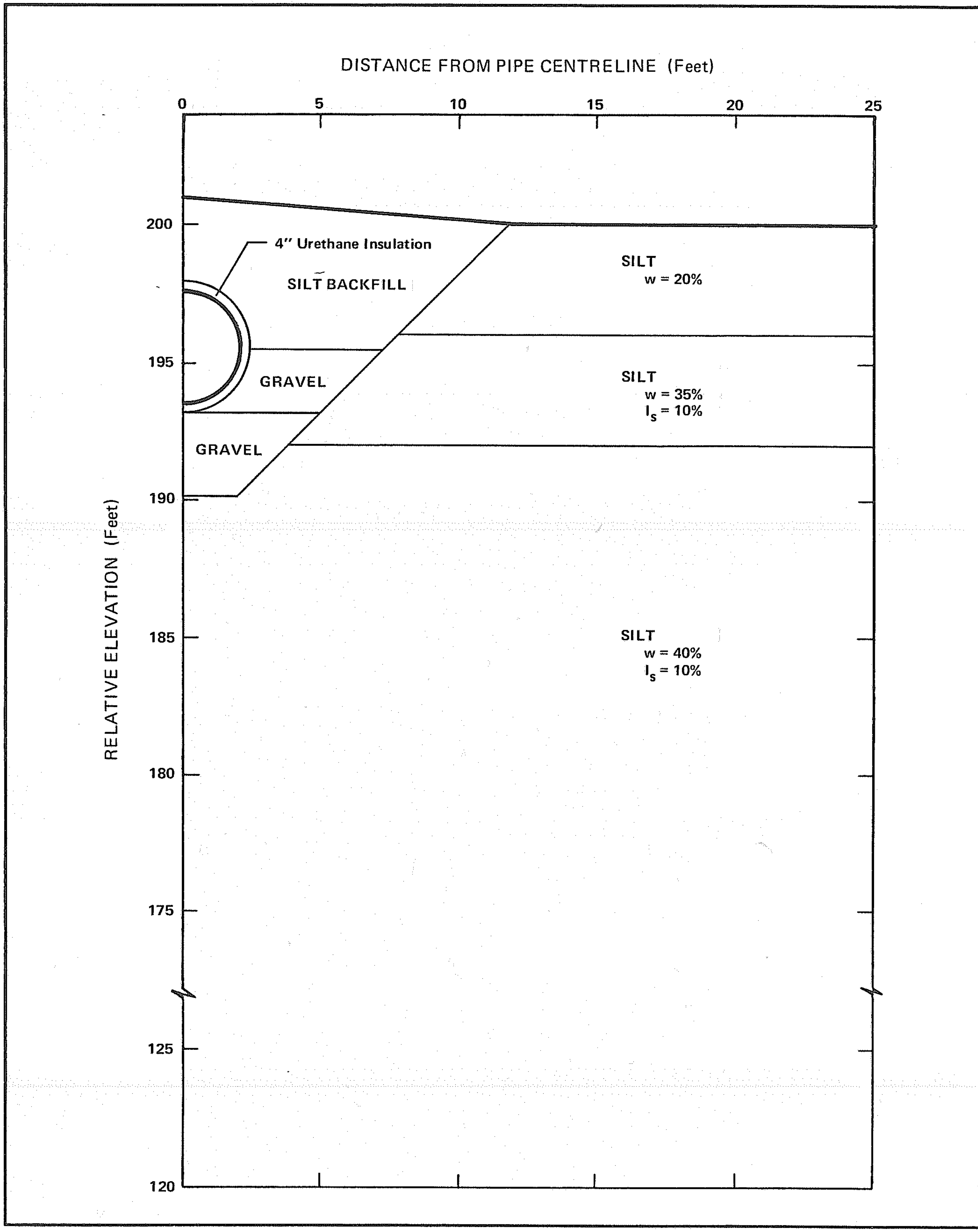


FIGURE 4.9 REGIONS DEFINED FOR THERMAL ANALYSIS
PIPE No. 8

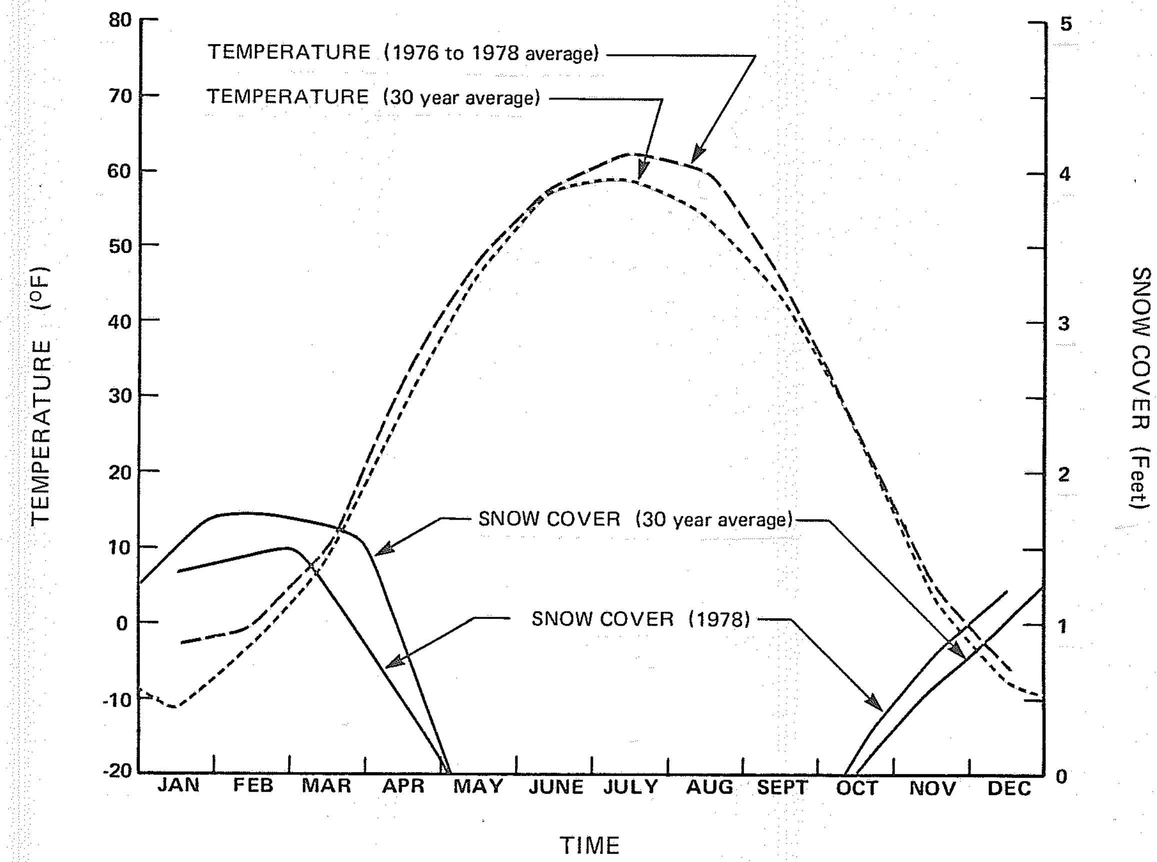


FIGURE 4.10 AMBIENT AIR TEMPERATURE AND SNOW COVER
3 AND 30 YEAR AVERAGES

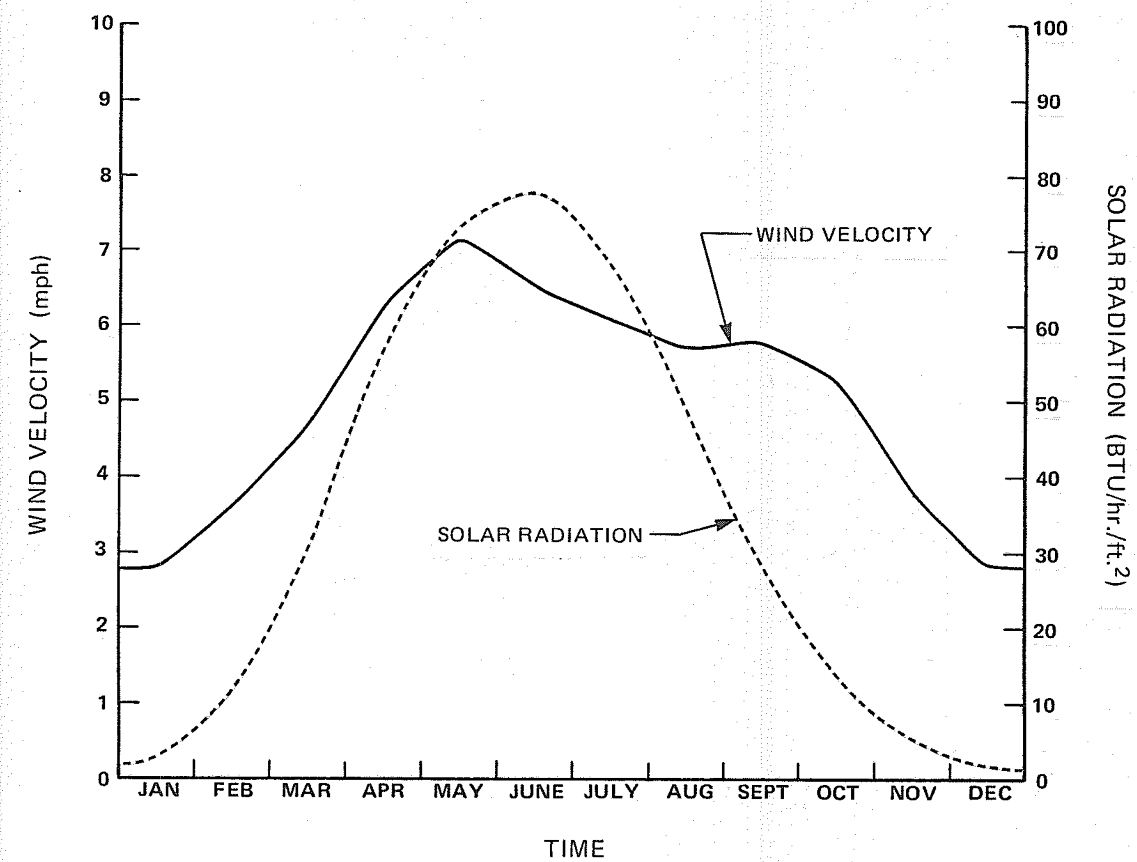


FIGURE 4.11 SOLAR RADIATION AND WIND VELOCITY

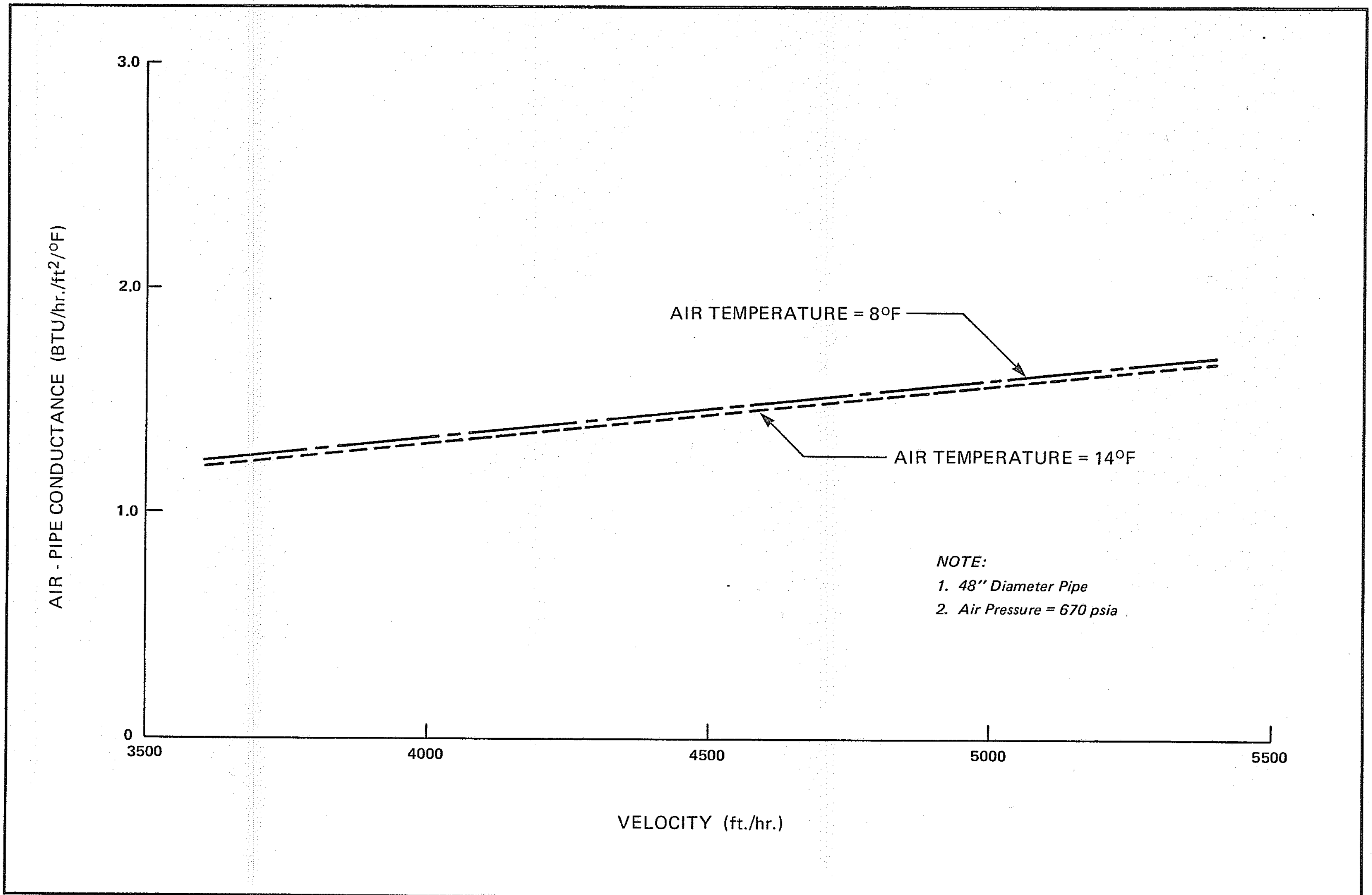


FIGURE 4.12 AIR-PIPE INTERFACE CONDUCTANCE

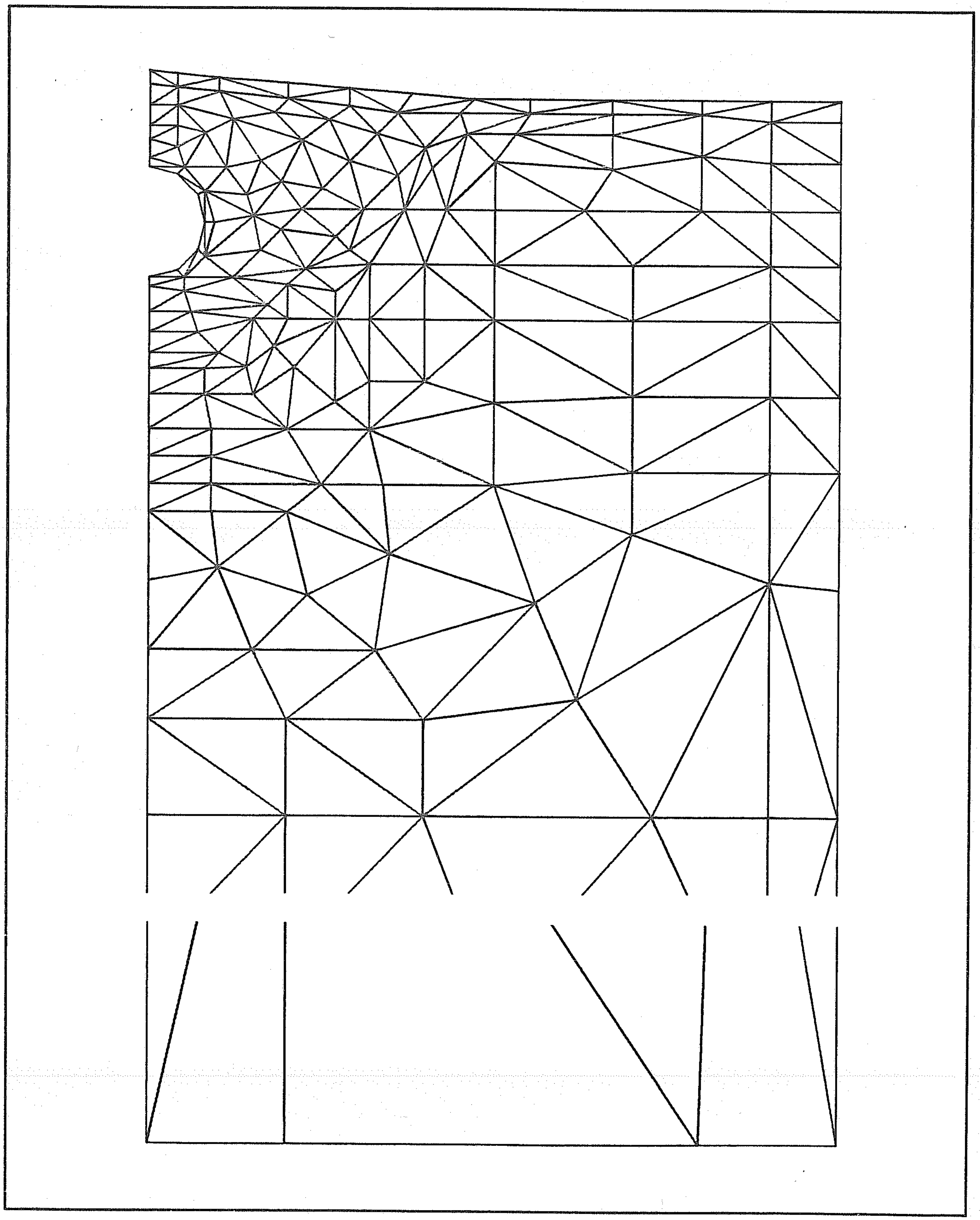


FIGURE 4.13 TYPICAL FINITE ELEMENT GRID

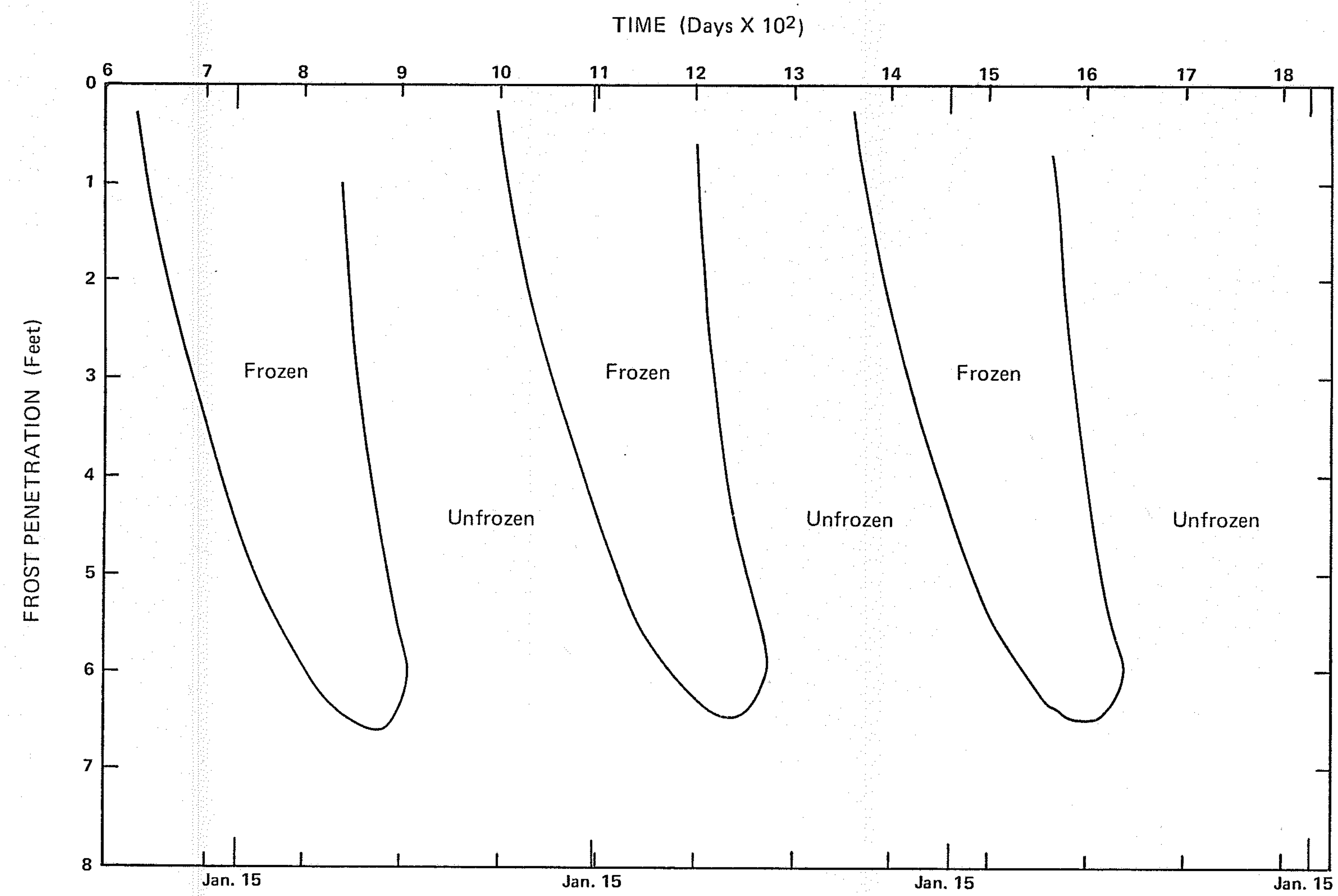


FIGURE 5.1 **ANNUAL VARIATION OF 32°F ISOTHERM FOR UNDISTURBED GROUND**

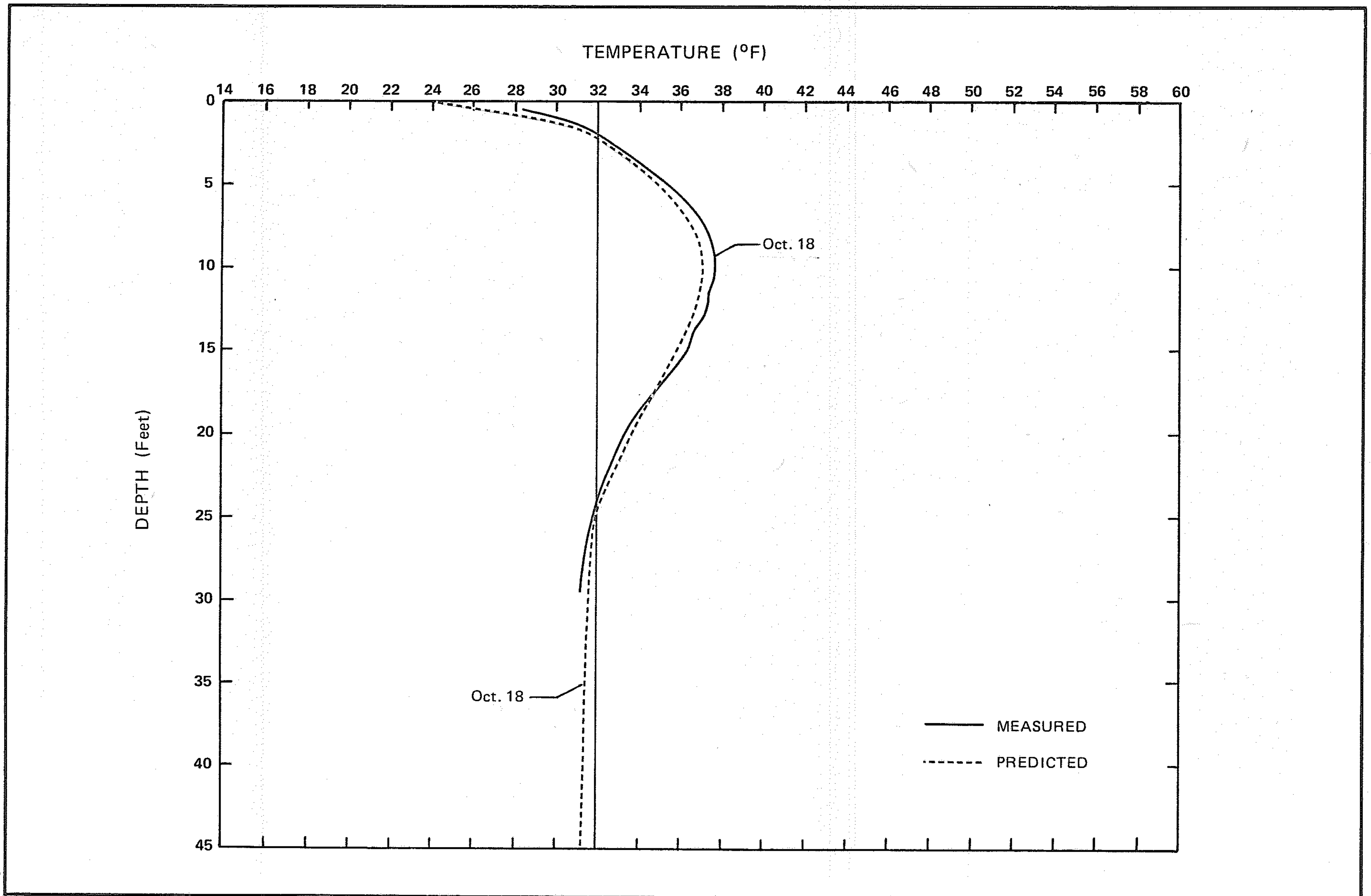


FIGURE 5.2 PREDICTED vs. MEASURED UNDISTURBED GROUND TEMPERATURES (October)

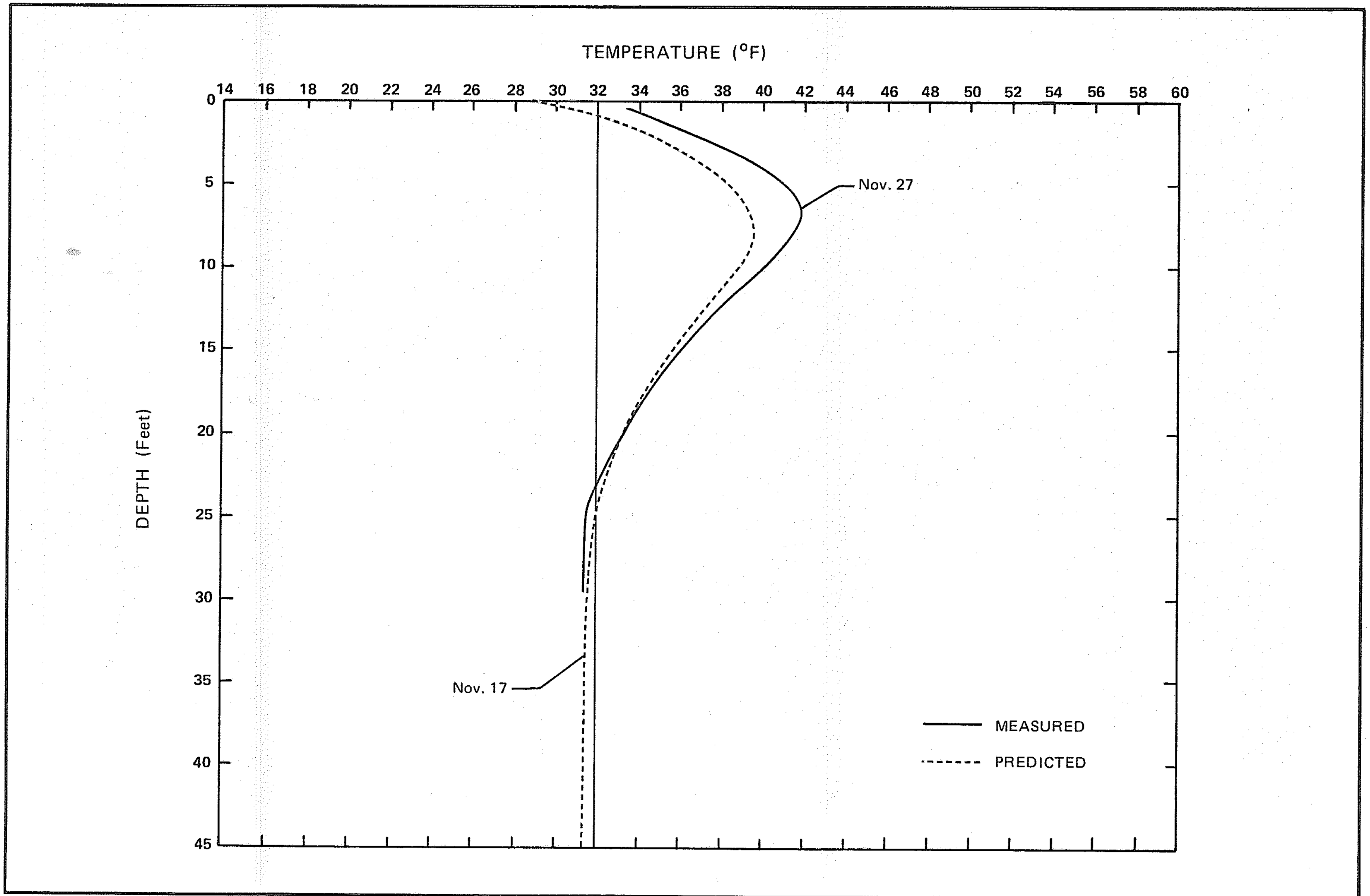


FIGURE 5.3 PREDICTED vs. MEASURED UNDISTURBED GROUND TEMPERATURES (November)

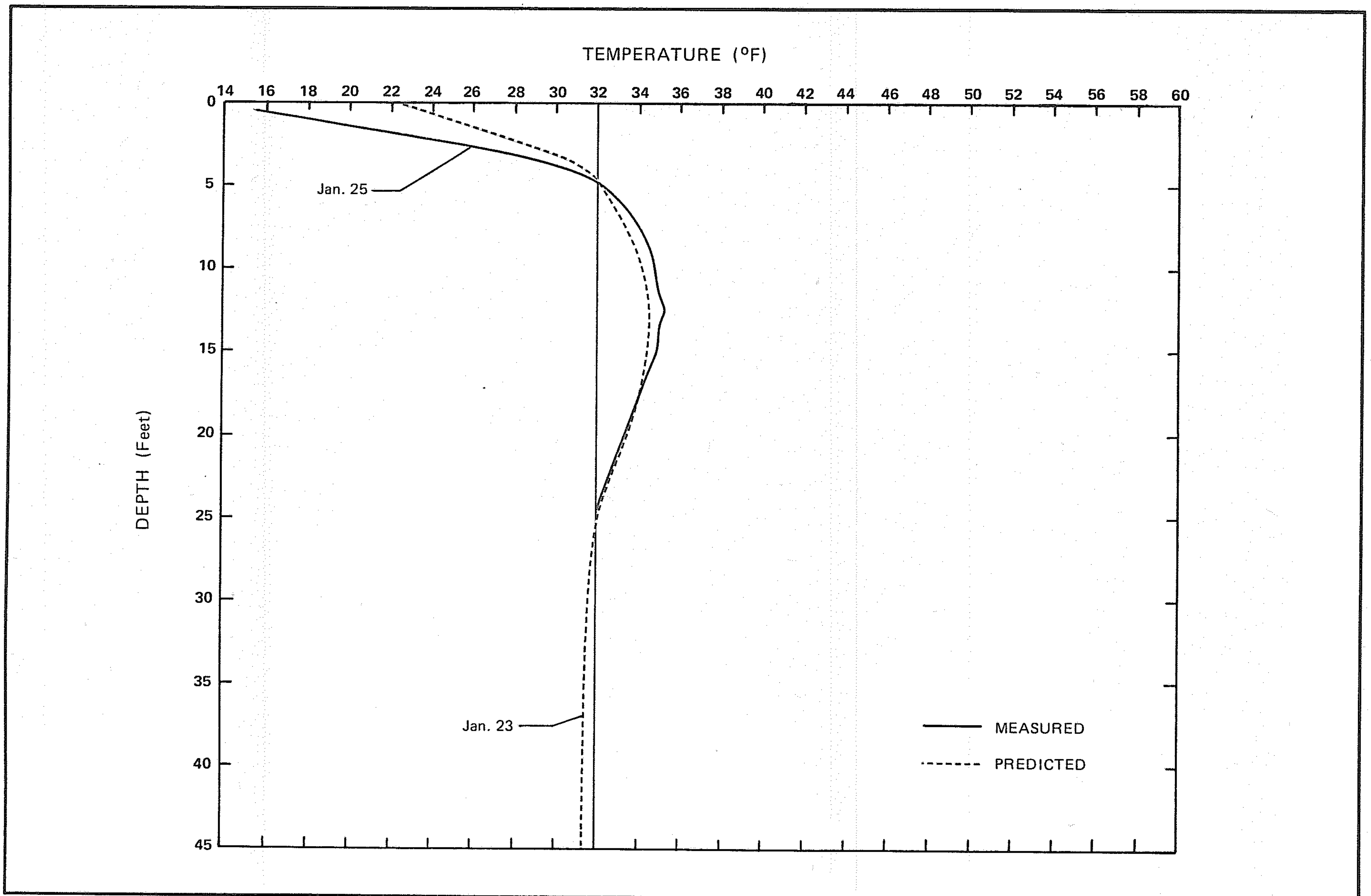


FIGURE 5.4 PREDICTED vs. MEASURED UNDISTURBED GROUND TEMPERATURES (January)

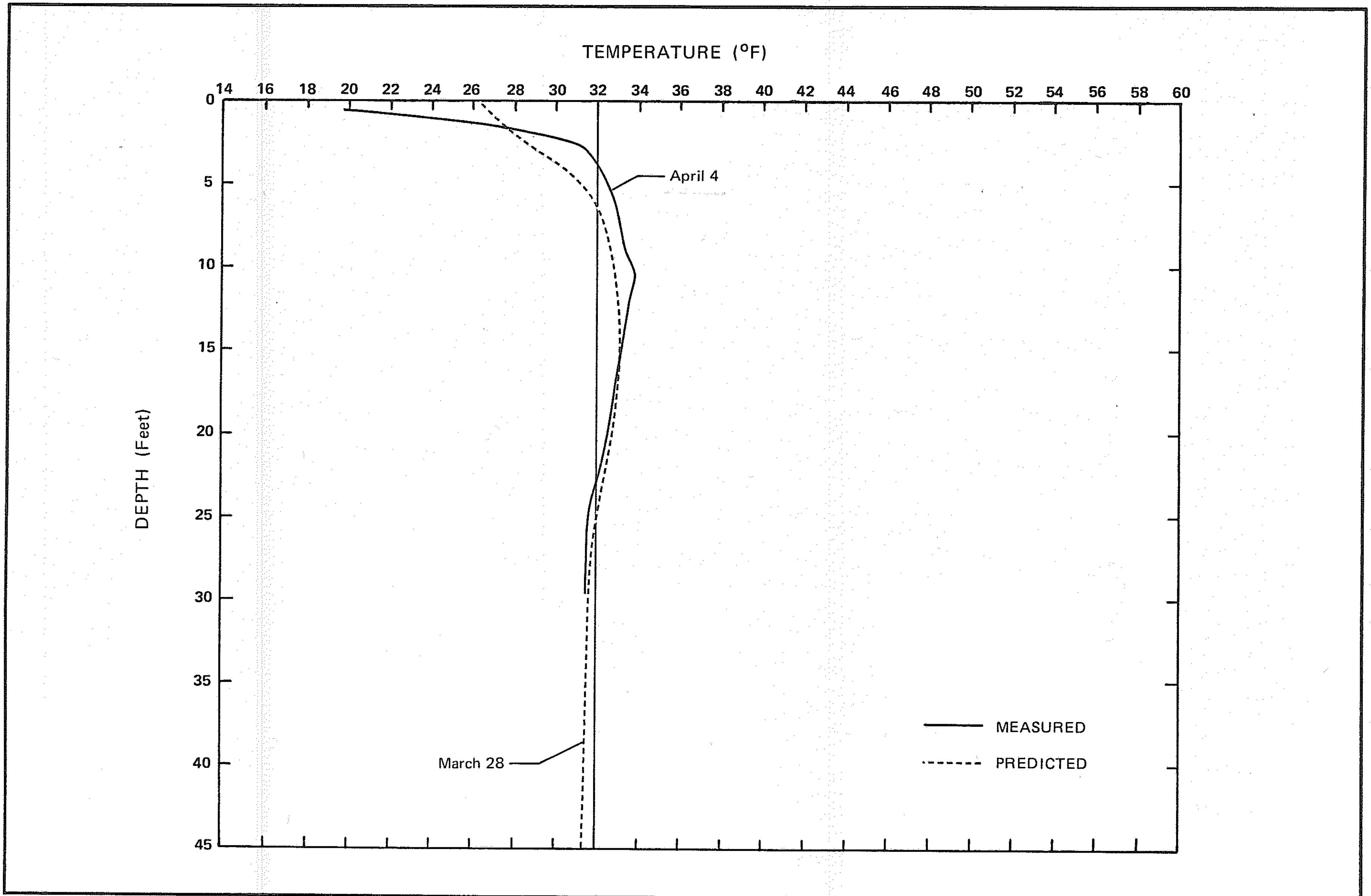


FIGURE 5.5

PREDICTED vs. MEASURED
UNDISTURBED GROUND TEMPERATURES
(March)

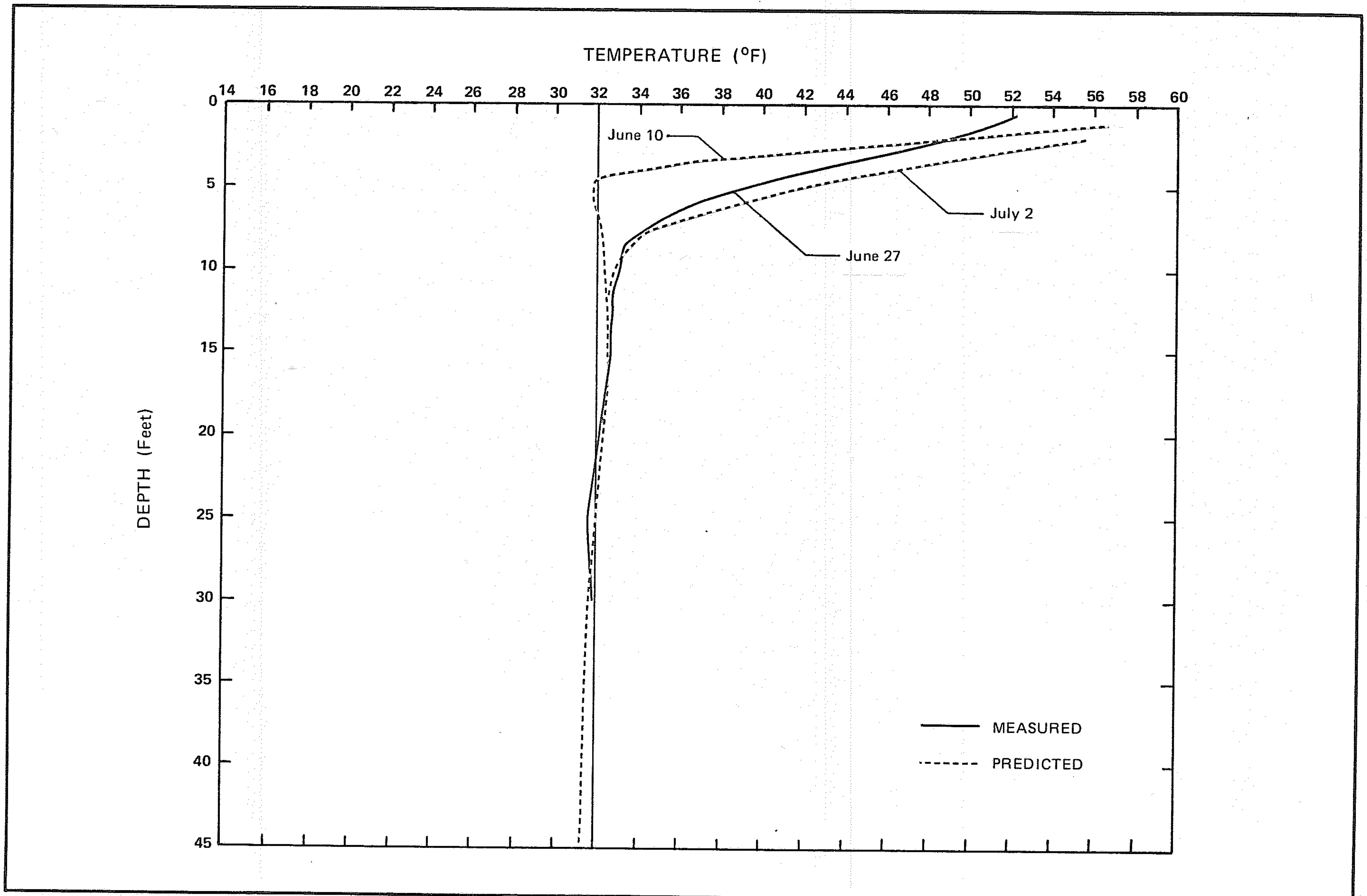


FIGURE 5.6

PREDICTED vs MEASURED
UNDISTURBED GROUND TEMPERATURES
(June)

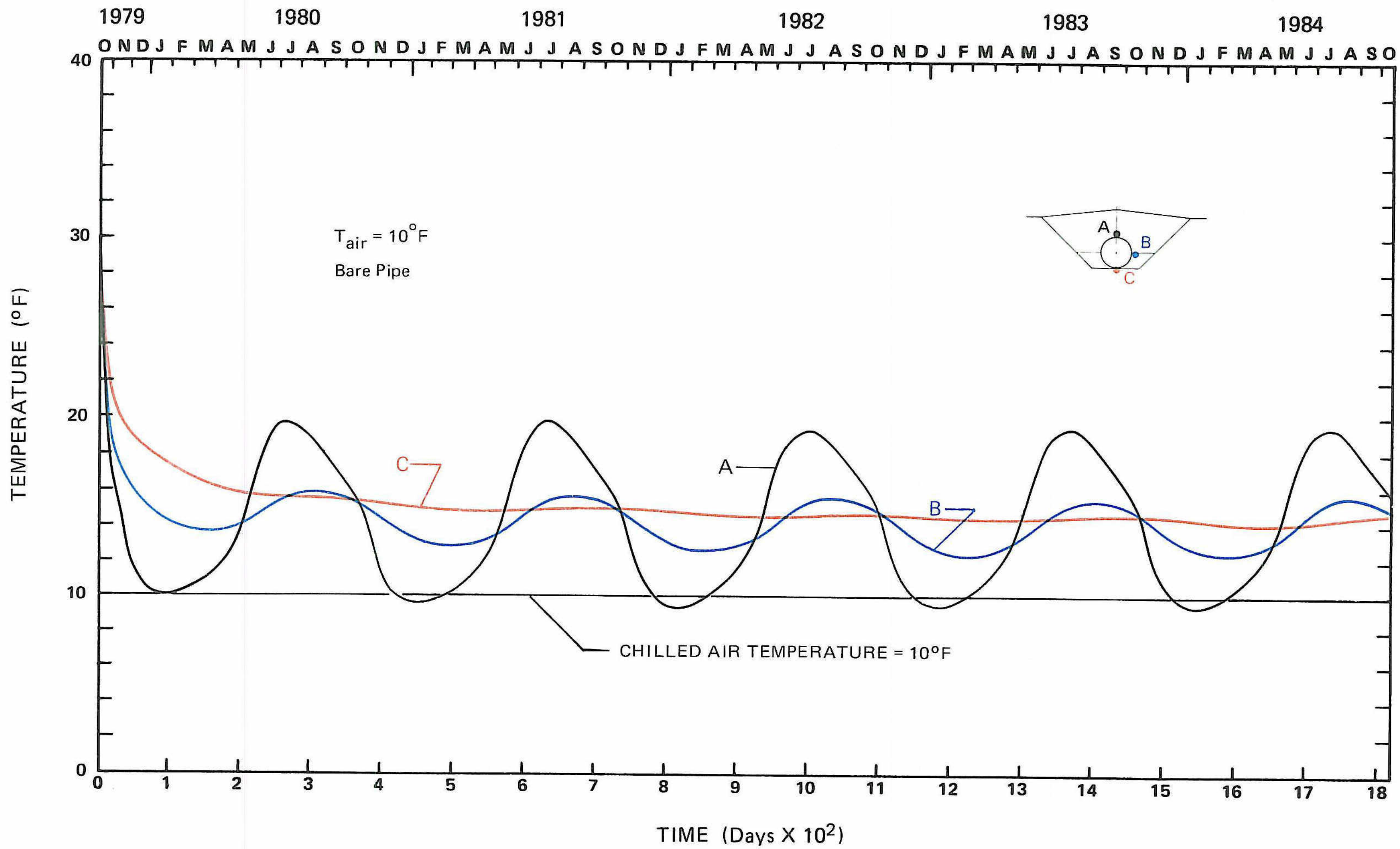


FIGURE 5.7

PREDICTED TEMPERATURES AT
PIPE SURFACE vs. TIME
PIPE No. 1

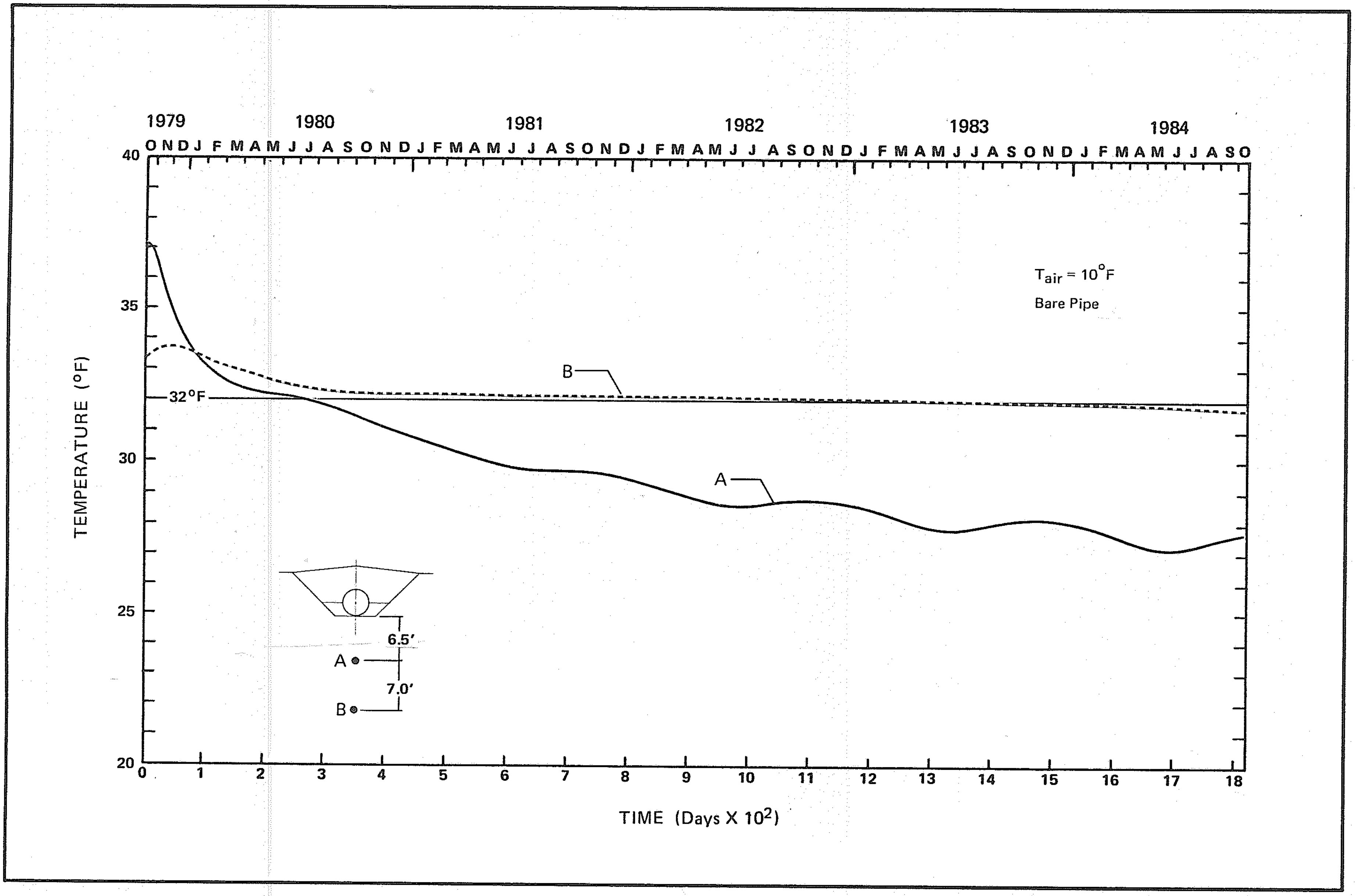


FIGURE 5.8 PREDICTED SOIL TEMPERATURES AT POINTS A & B vs. TIME PIPE No. 1

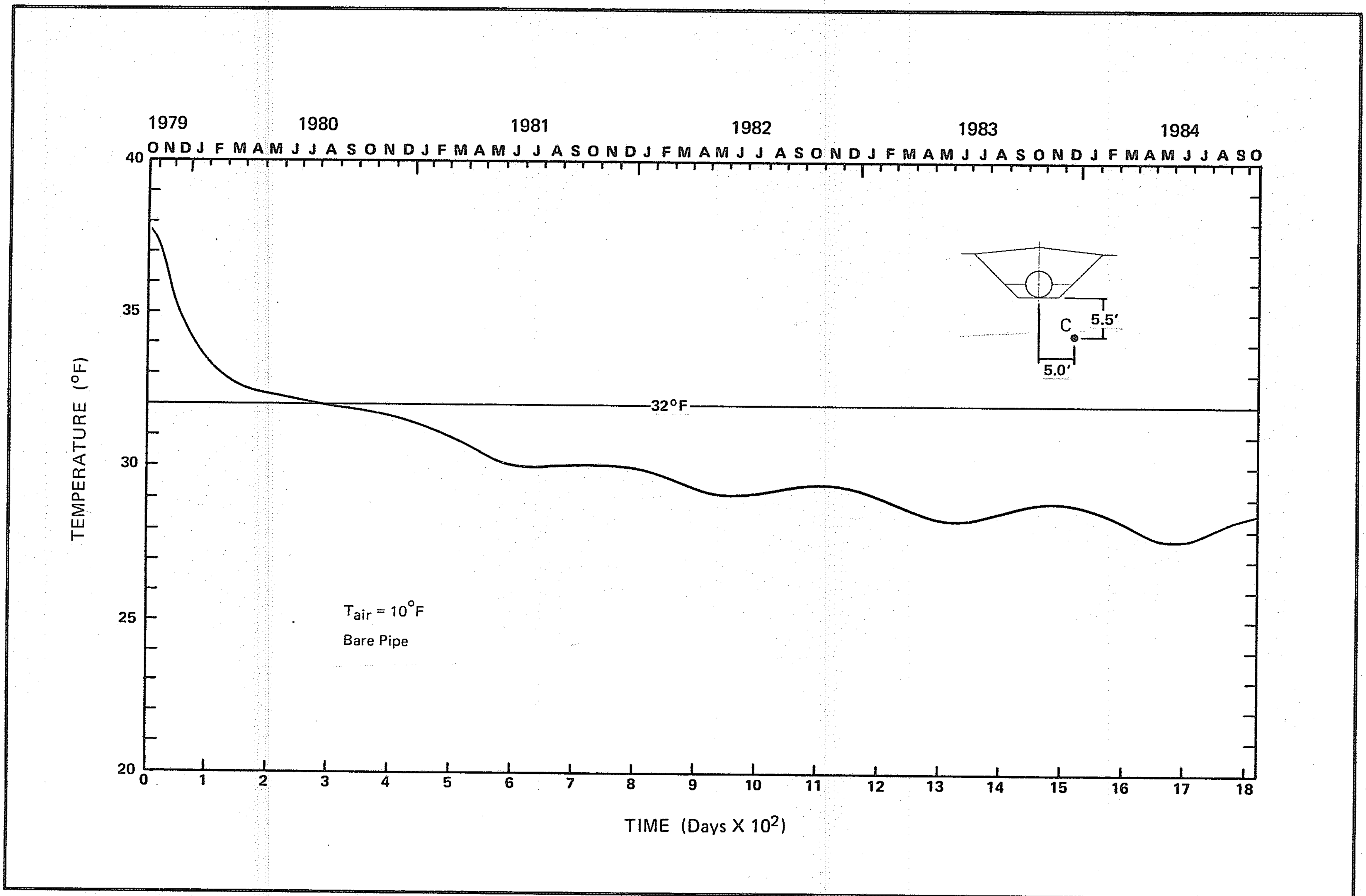


FIGURE 5.9 PREDICTED SOIL TEMPERATURES AT POINT C vs. TIME PIPE No. 1

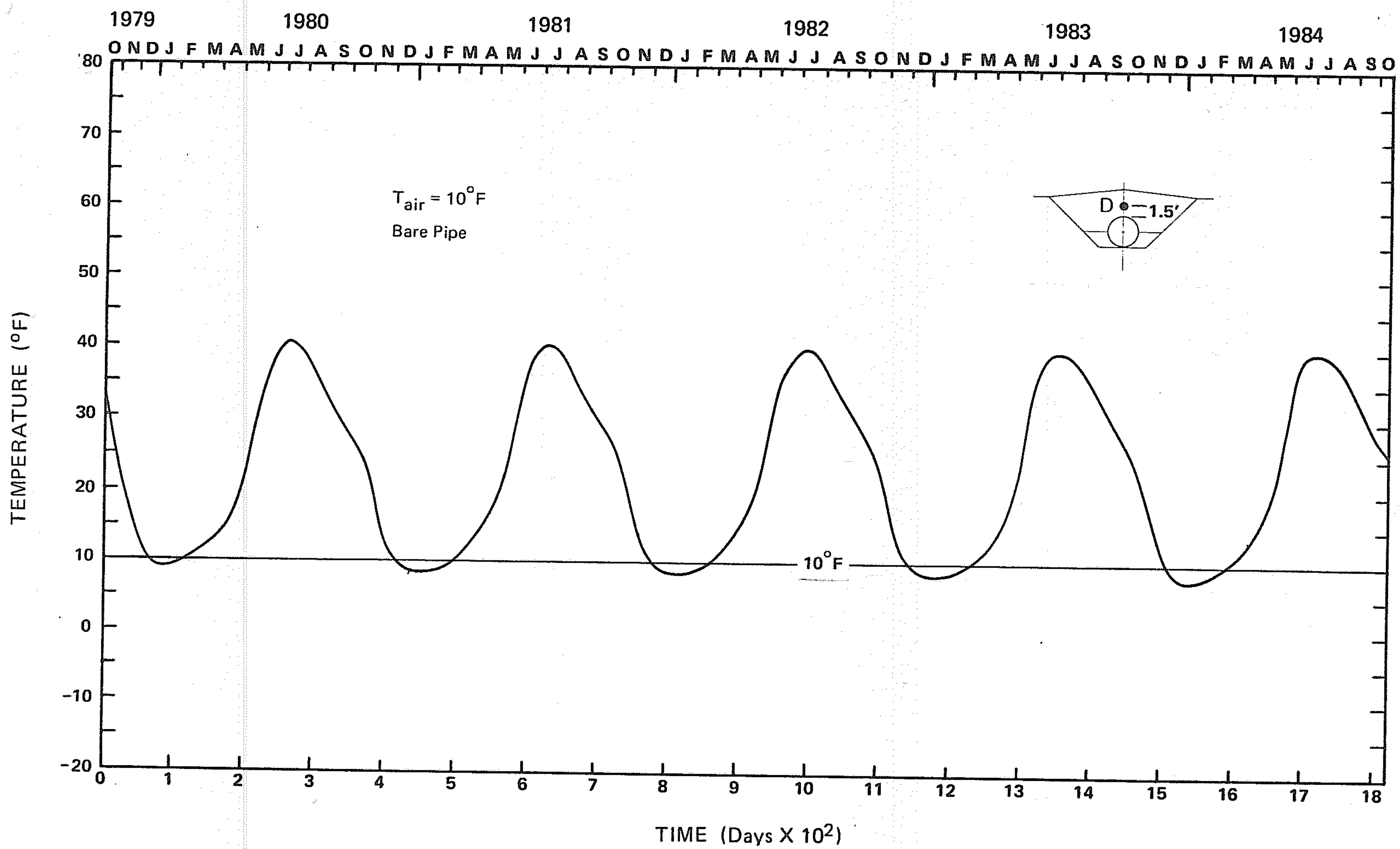


FIGURE 5.10

PREDICTED SOIL TEMPERATURE AT POINT D vs. TIME PIPE No. 1

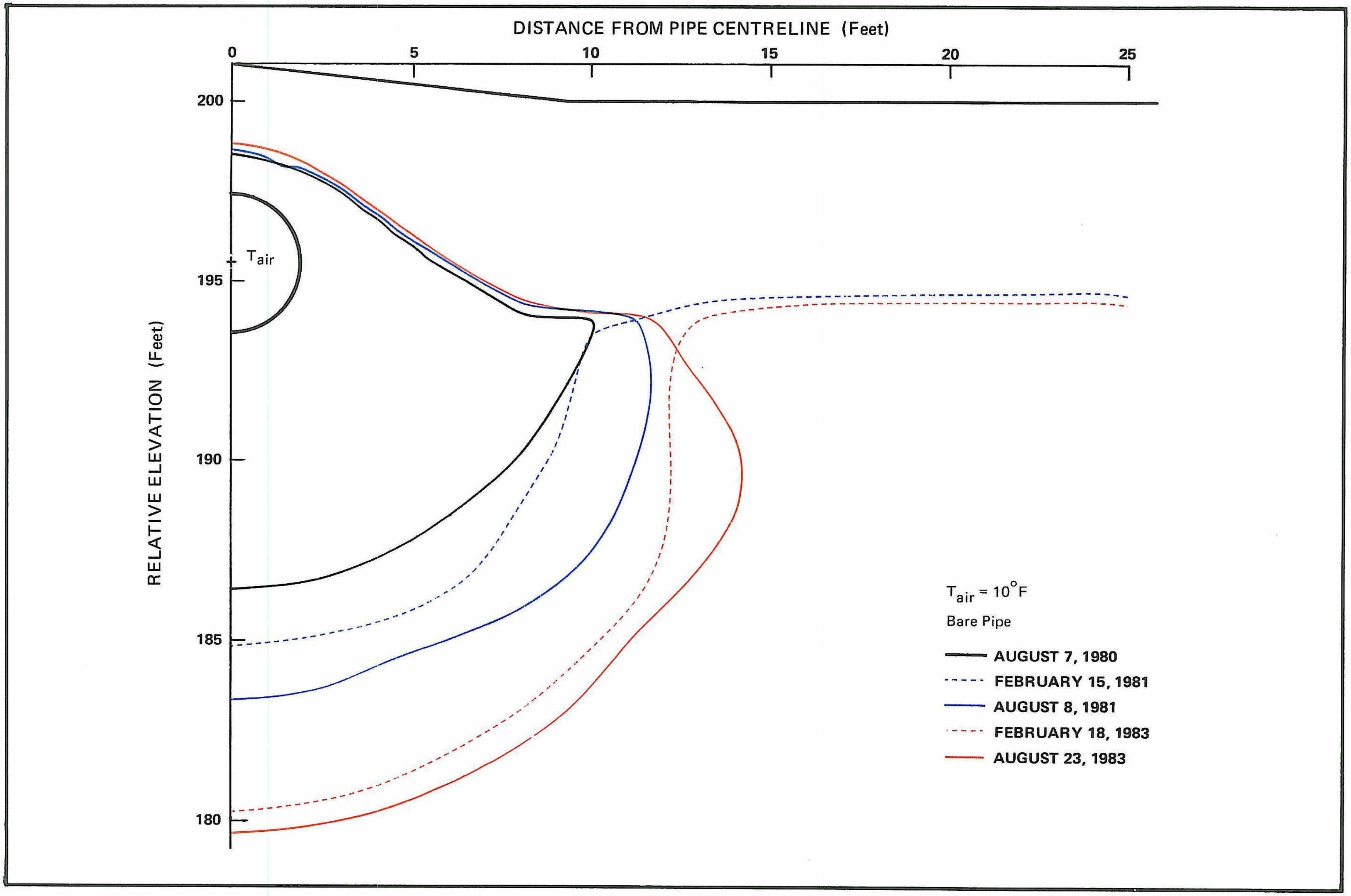


FIGURE 5.11

32°F CONTOURS AT SELECTED TIMES
PIPE No. 1

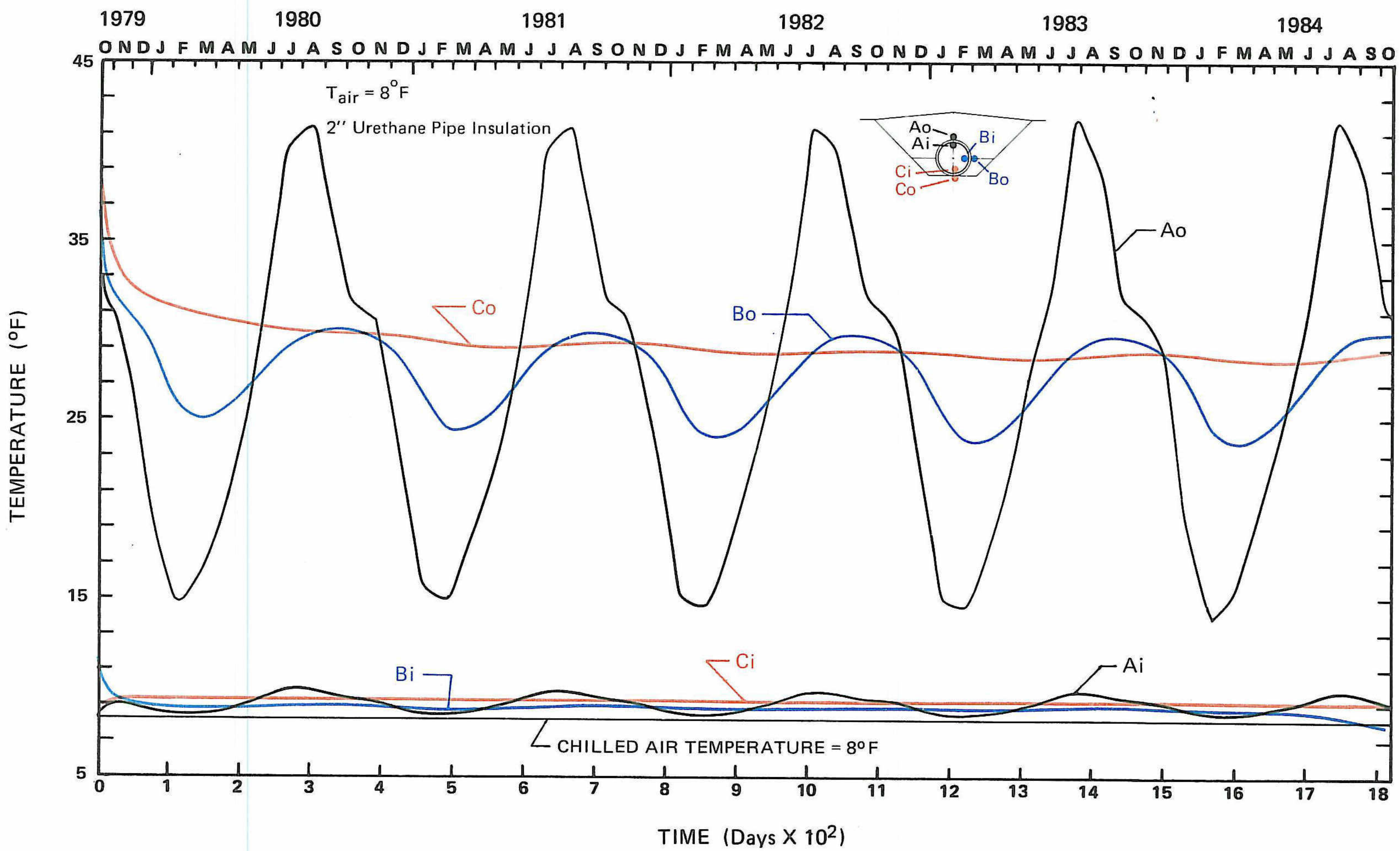


FIGURE 5.12

PREDICTED TEMPERATURES AT
PIPE & INSULATION SURFACES vs. TIME
PIPE No. 2

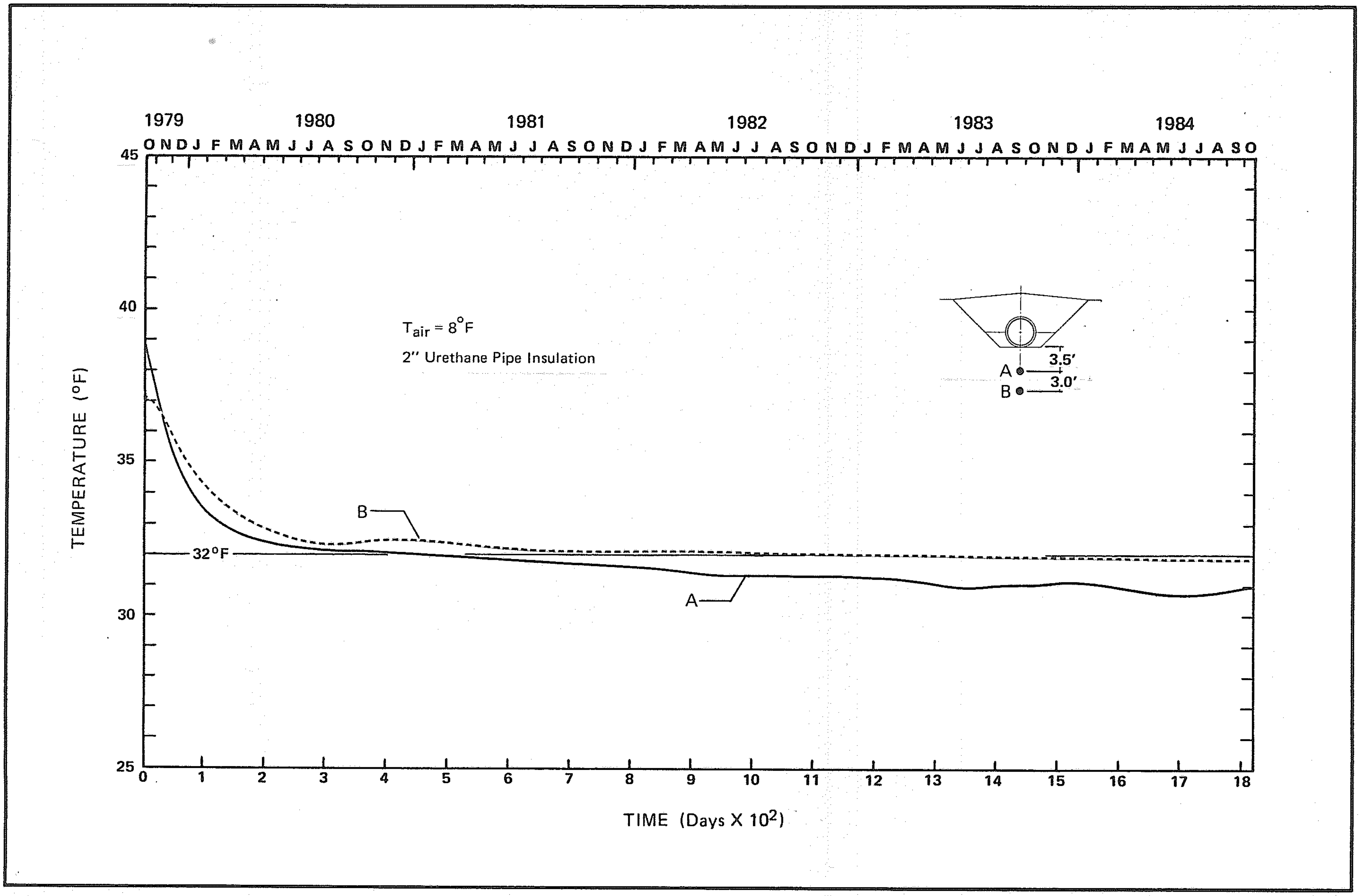


FIGURE 5.13 PREDICTED SOIL TEMPERATURES AT POINTS A & B vs. TIME PIPE No. 2

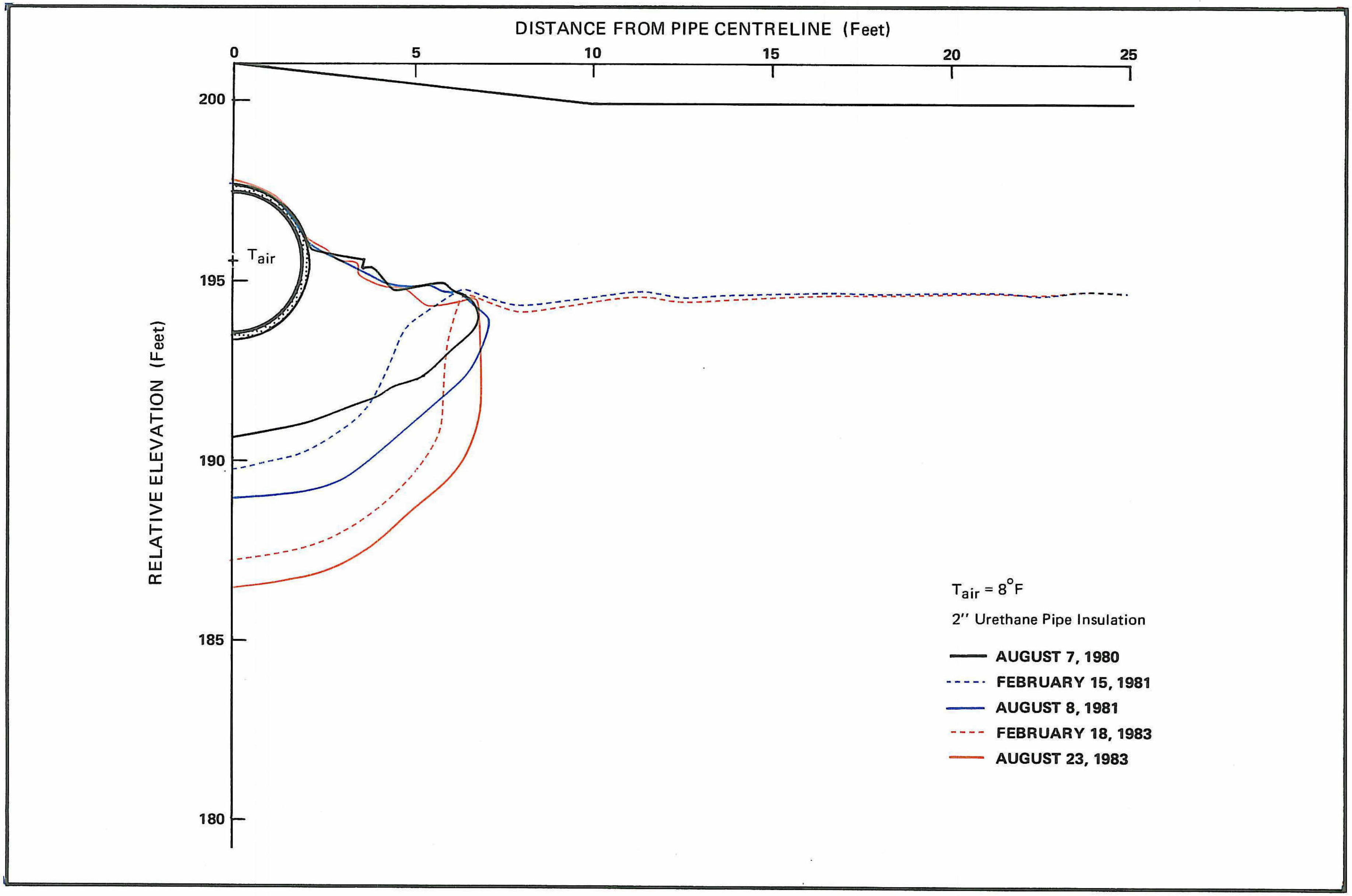


FIGURE 5.14 32°F CONTOURS AT SELECTED TIMES PIPE No. 2

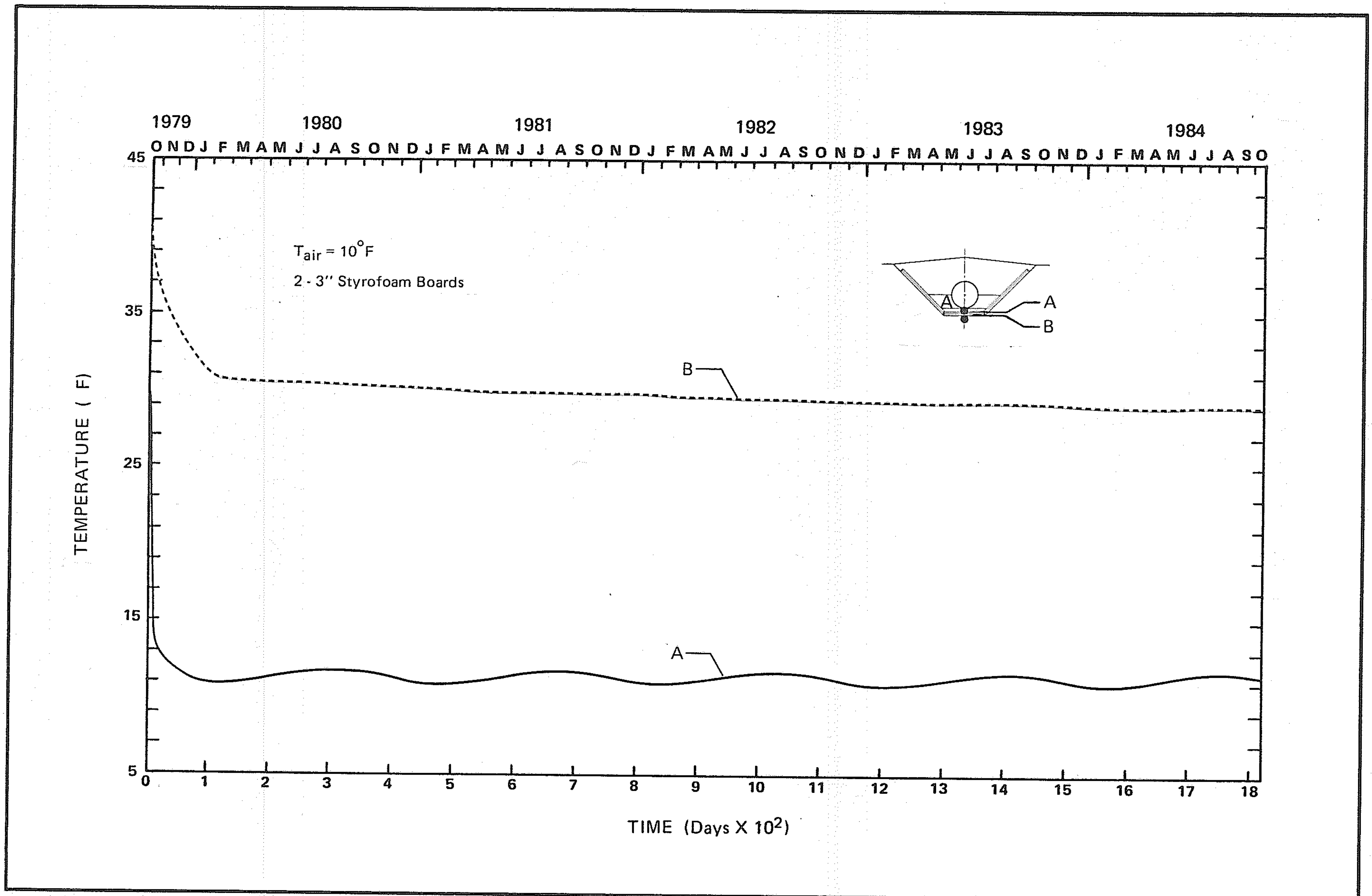


FIGURE 5.15 PREDICTED SOIL TEMPERATURES AT POINTS A & B vs. TIME PIPE No. 3

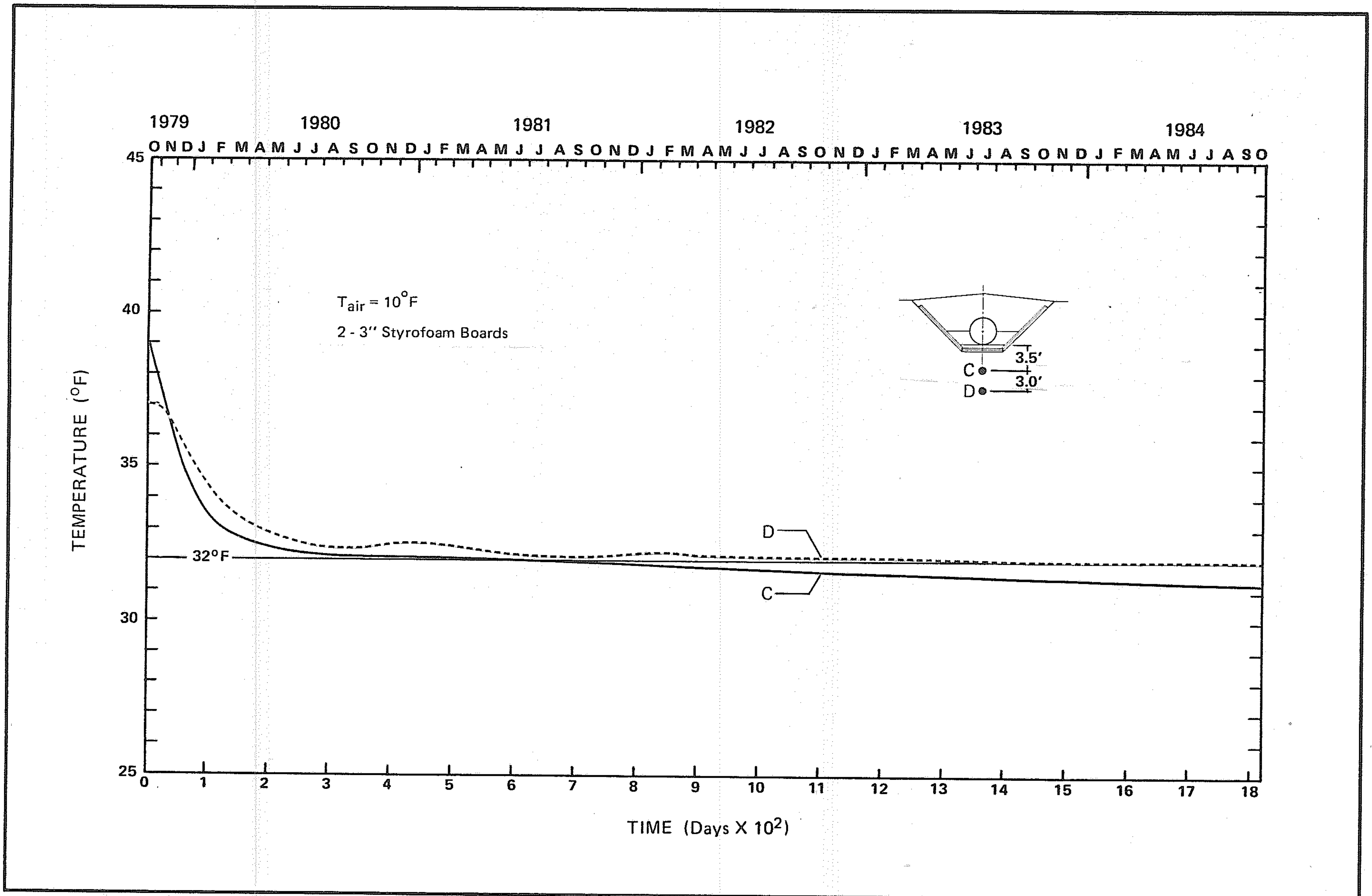


FIGURE 5.16 PREDICTED SOIL TEMPERATURES AT POINTS C & D vs. TIME PIPE No. 3

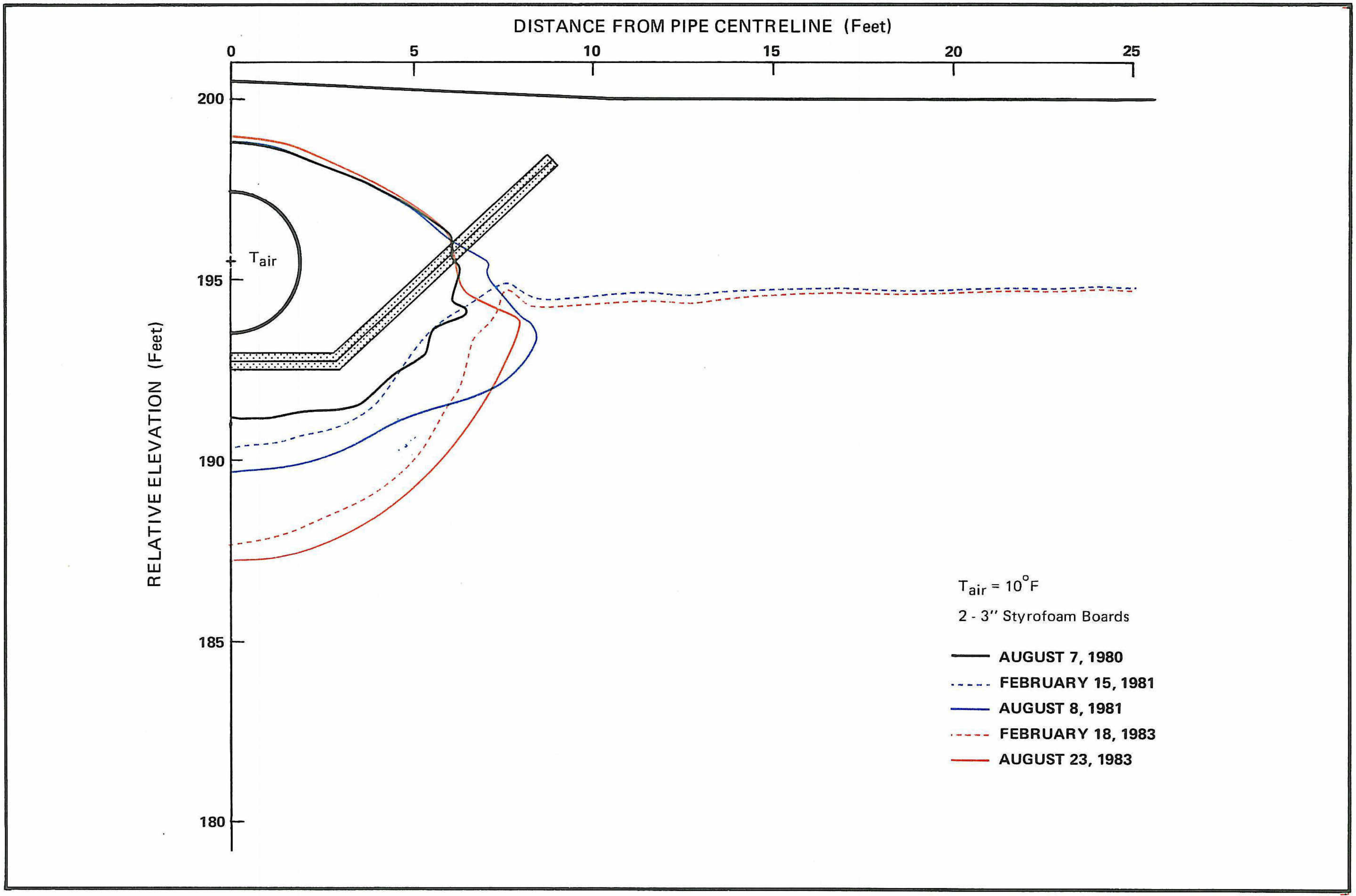


FIGURE 5.17 32°F CONTOURS AT SELECTED TIMES
PIPE No. 3

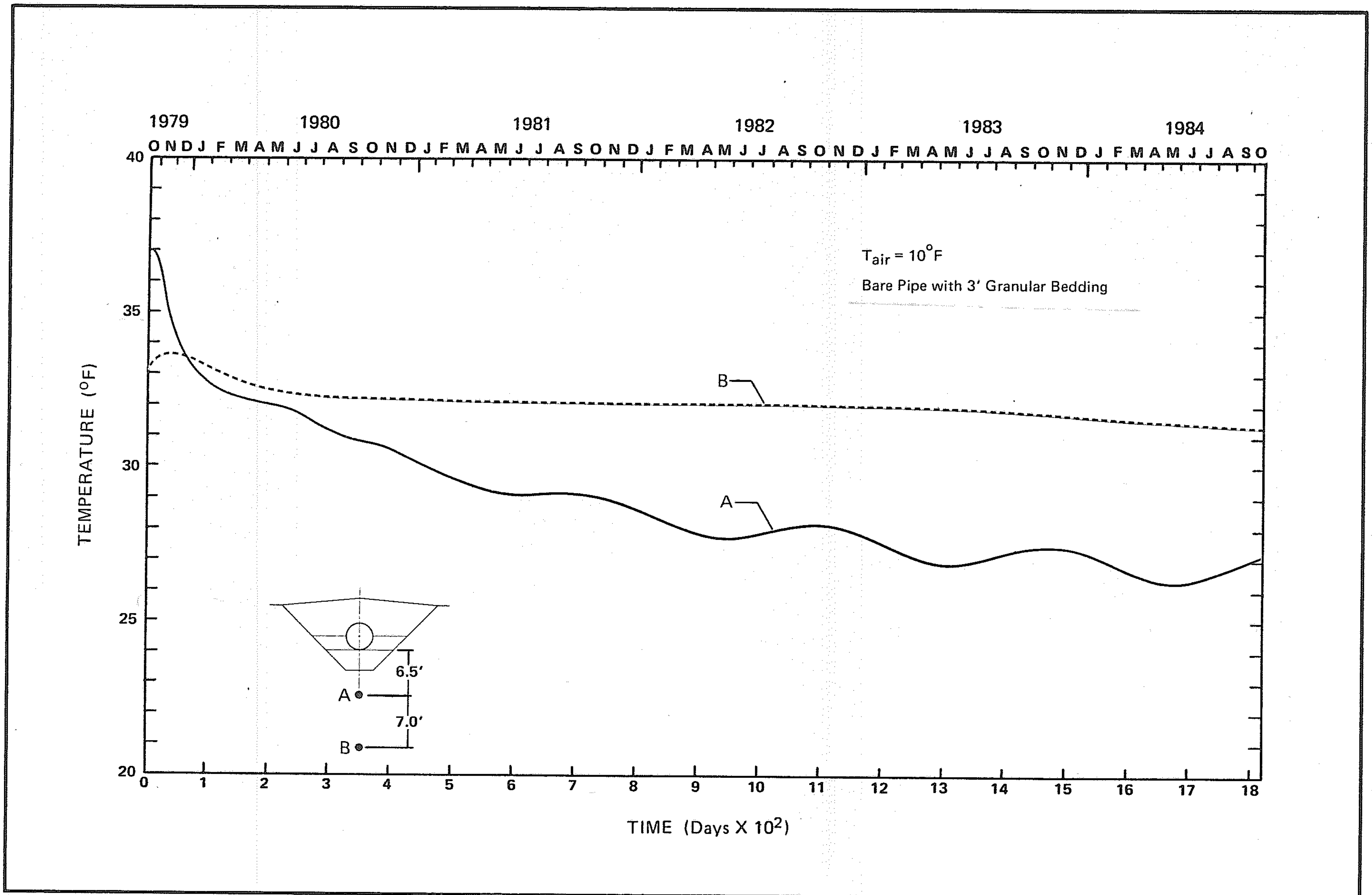


FIGURE 5.18 PREDICTED SOIL TEMPERATURES AT POINTS A & B vs. TIME PIPE No. 4

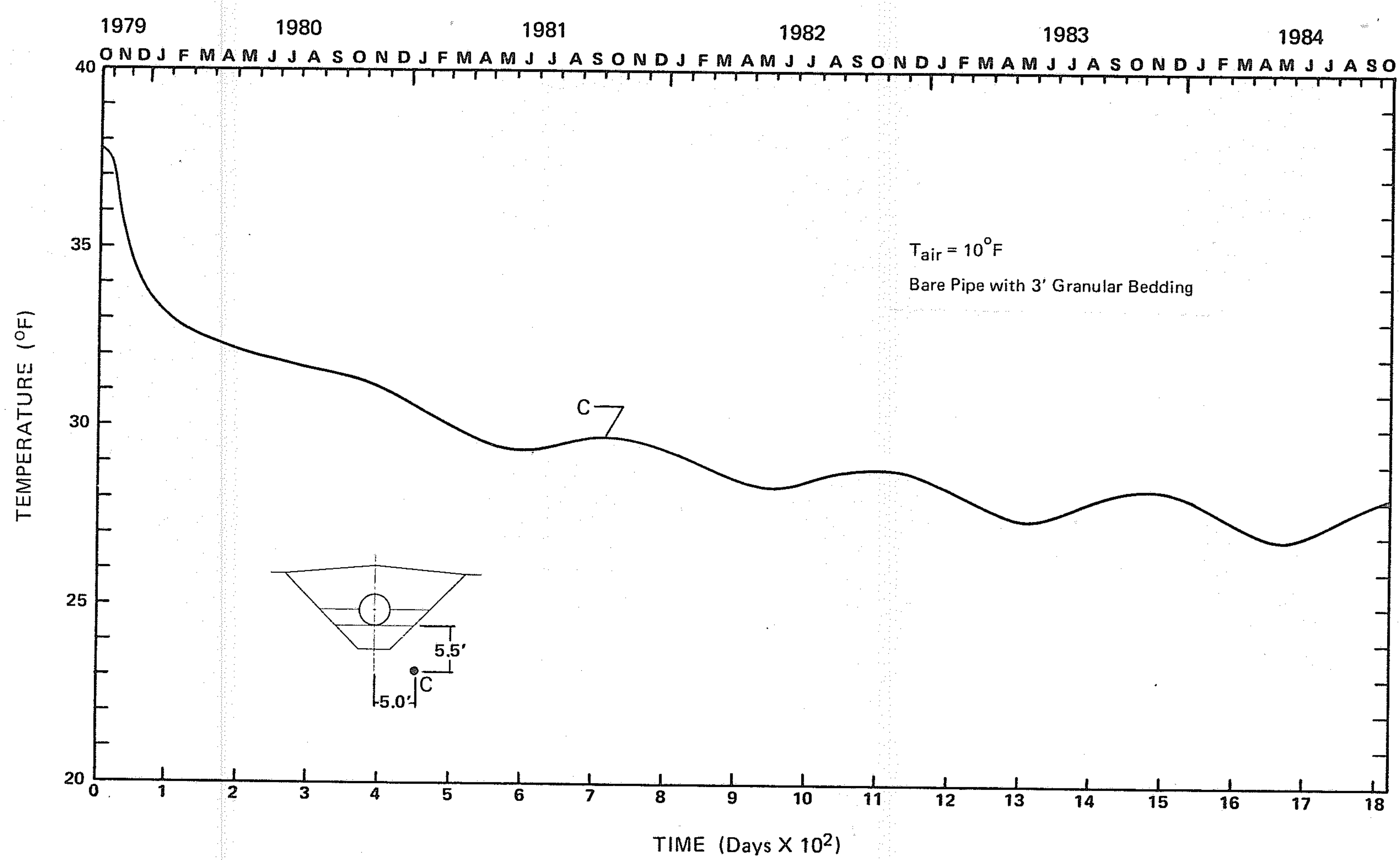


FIGURE 5.19 PREDICTED SOIL TEMPERATURES AT POINT C vs. TIME PIPE No. 4

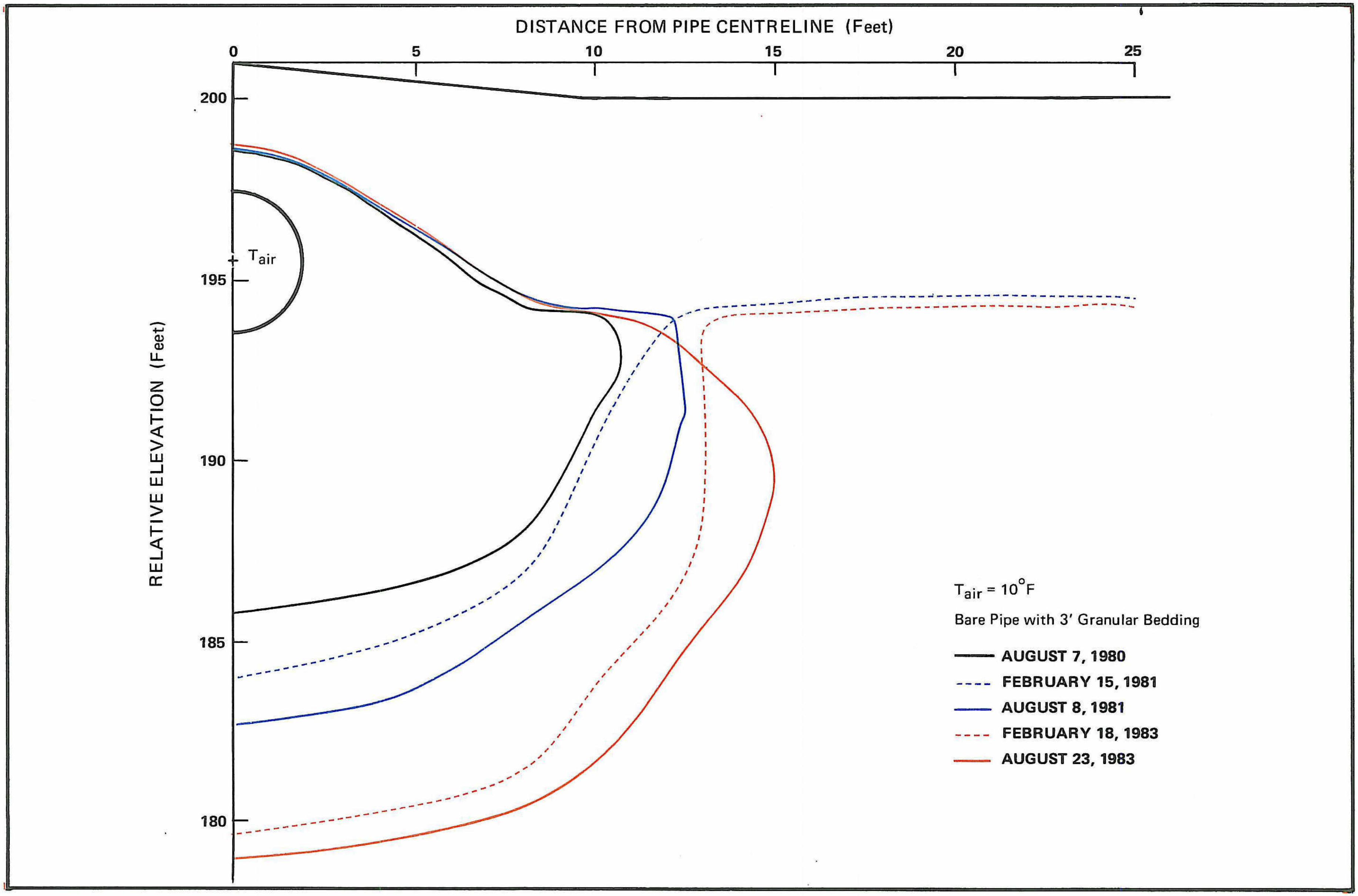


FIGURE 5.20 32°F CONTOURS AT SELECTED TIMES PIPE No. 4

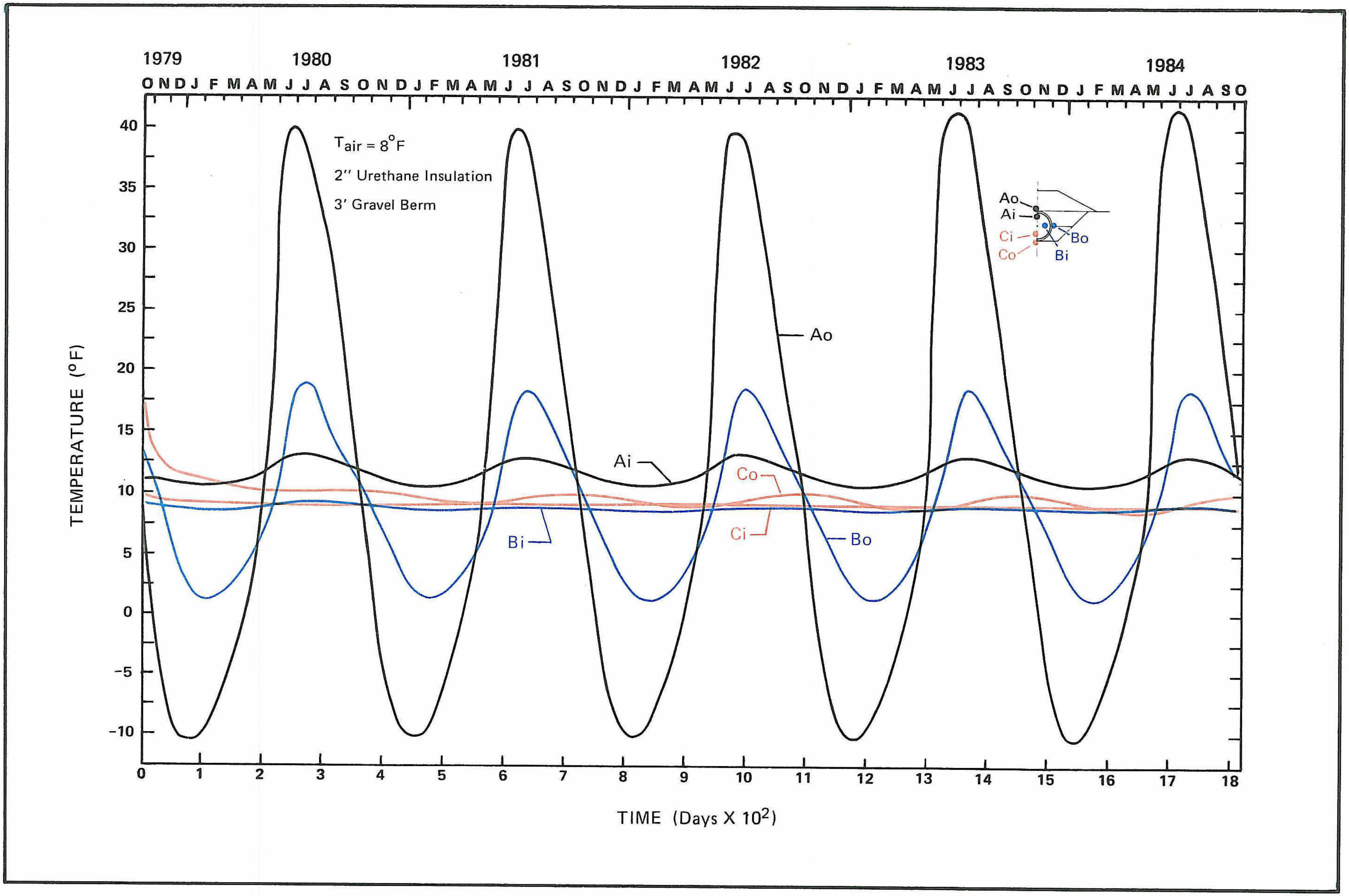


FIGURE 5.21 PREDICTED TEMPERATURES AT PIPE & INSULATION SURFACES vs. TIME PIPE No. 5

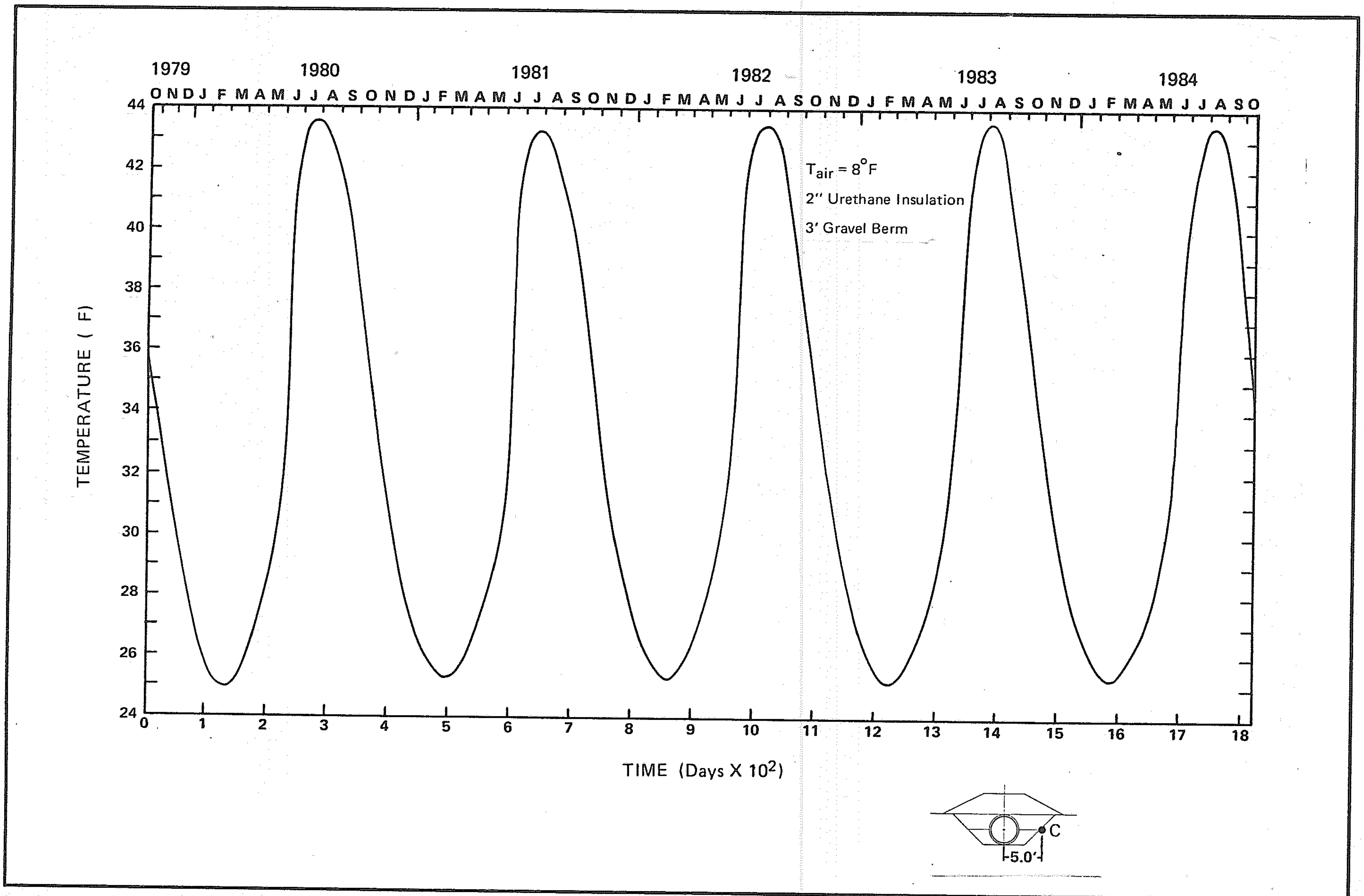


FIGURE 5.22 PREDICTED SOIL TEMPERATURES AT POINT C vs. TIME PIPE No. 5

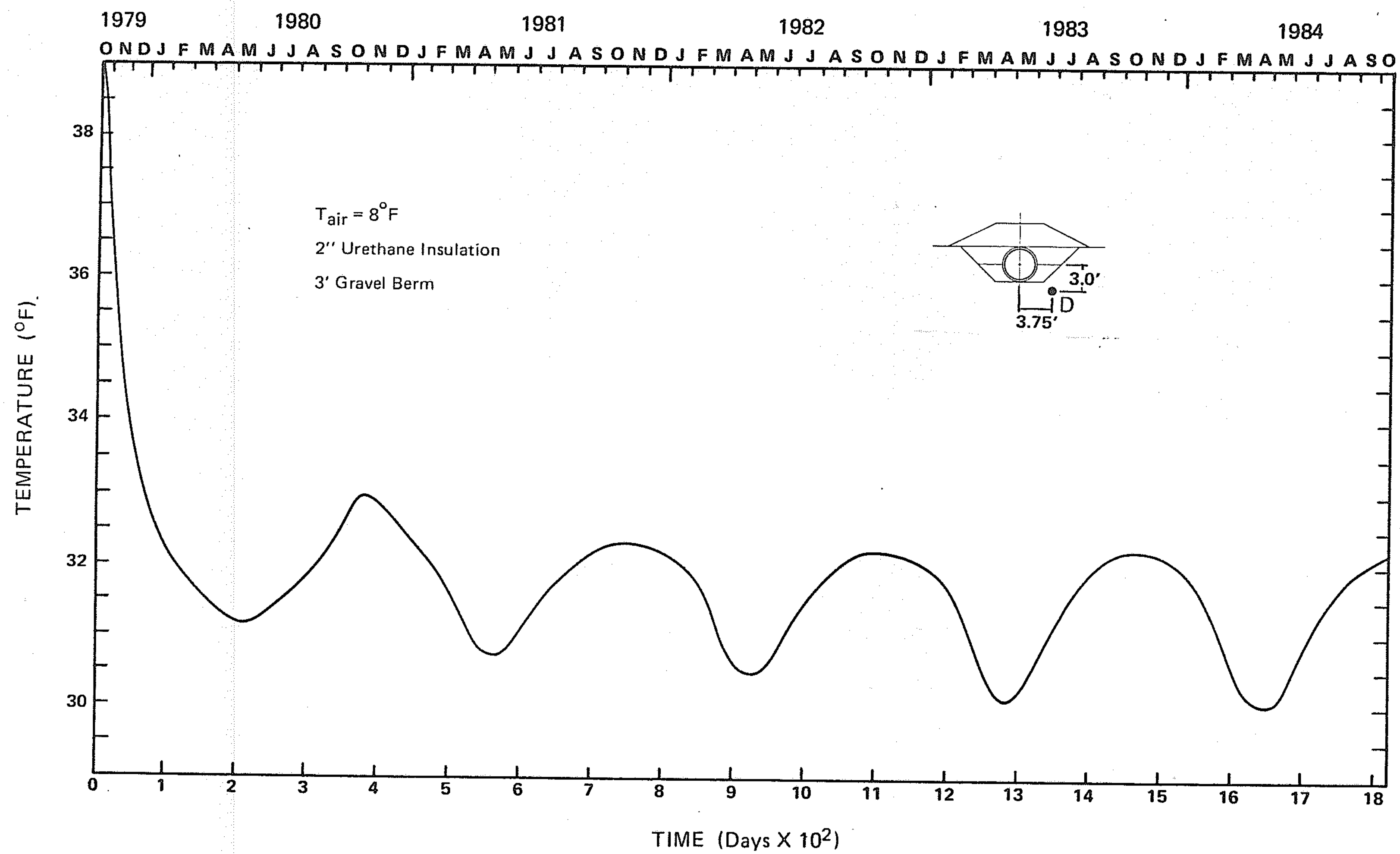


FIGURE 5.23 PREDICTED SOIL TEMPERATURES AT POINT D vs. TIME PIPE No. 5

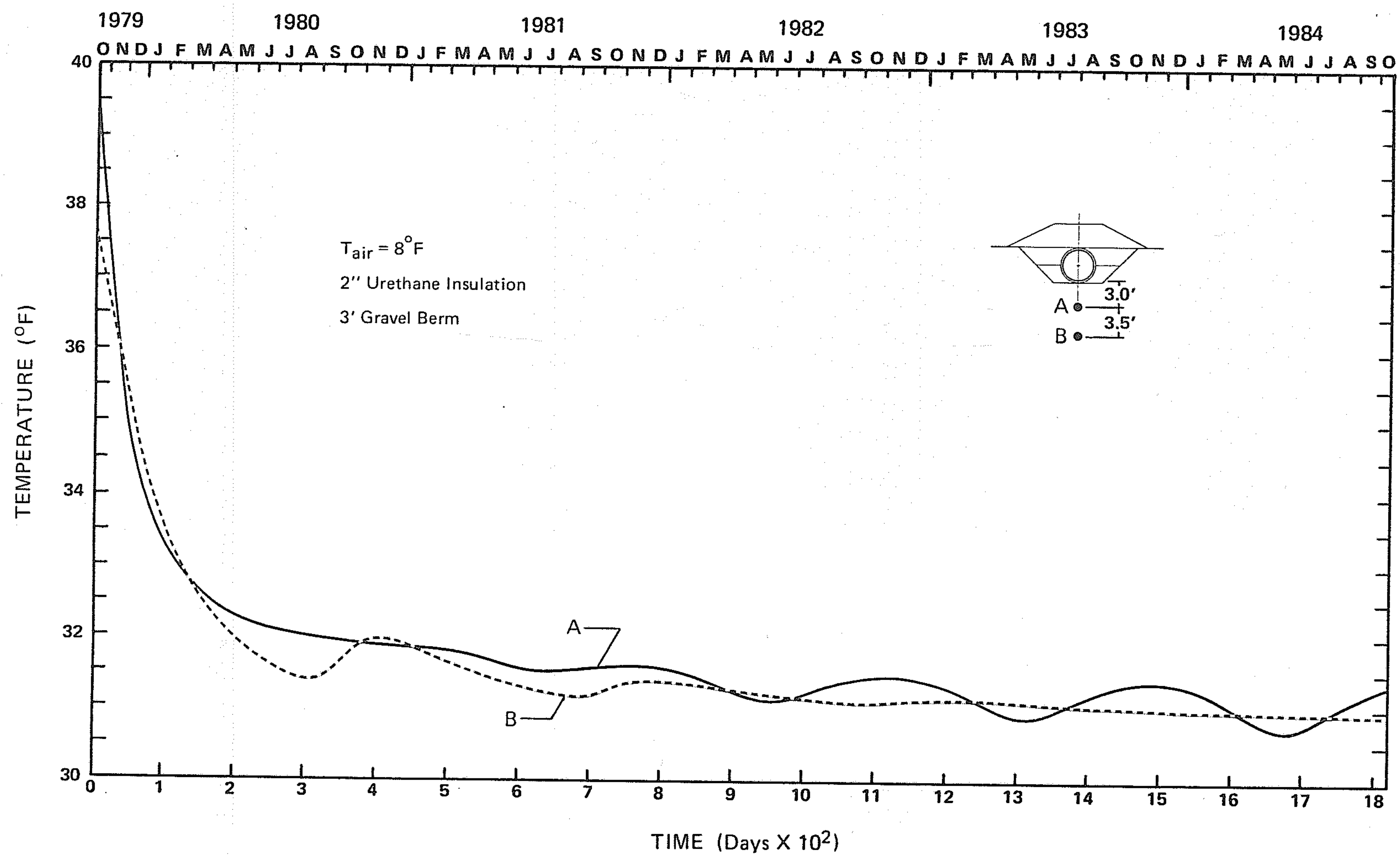


FIGURE 5.24 PREDICTED SOIL TEMPERATURES AT POINTS A & B vs. TIME PIPE No. 5

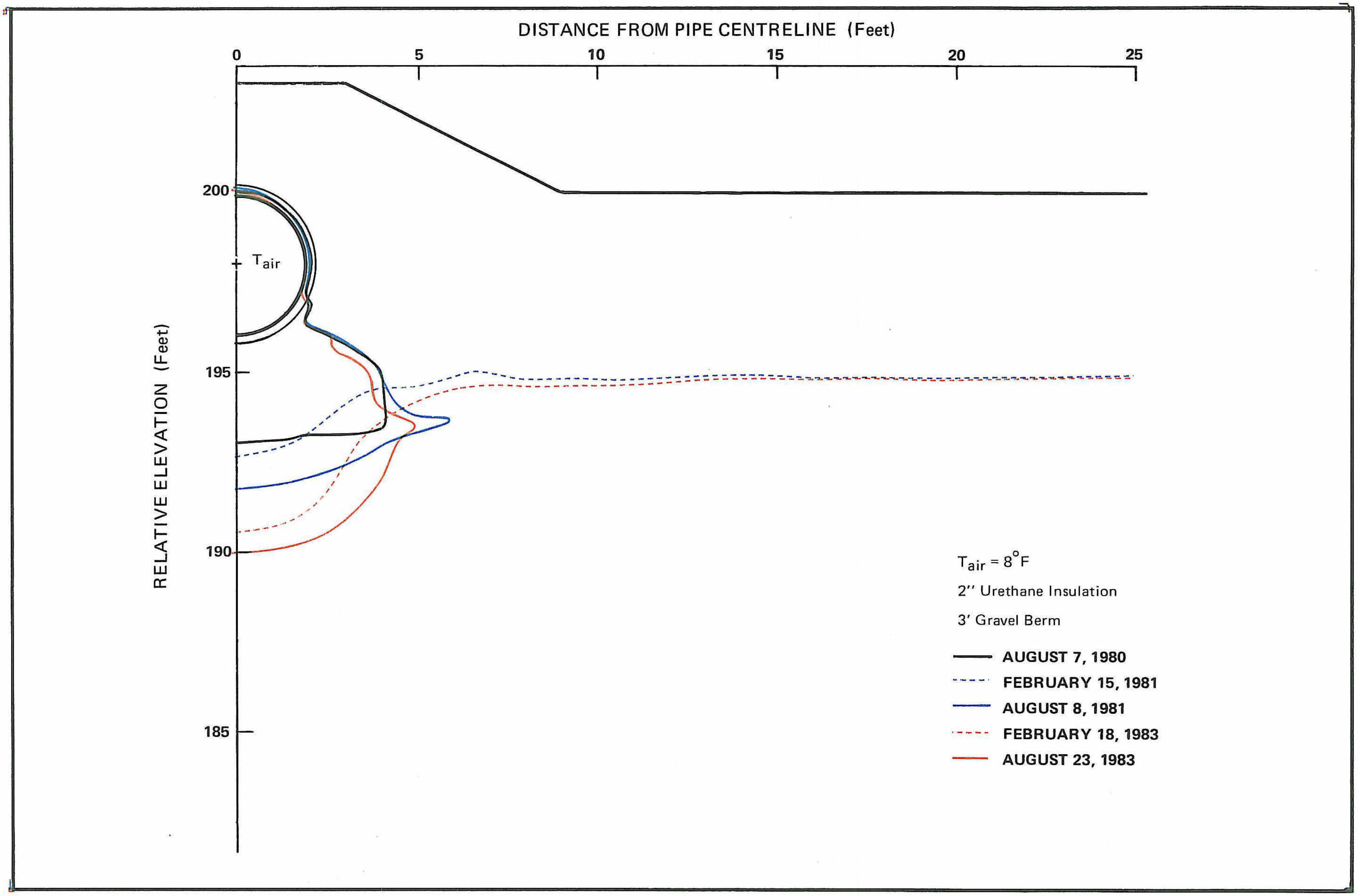


FIGURE 5.25 32°F CONTOURS AT SELECTED TIMES PIPE No. 5

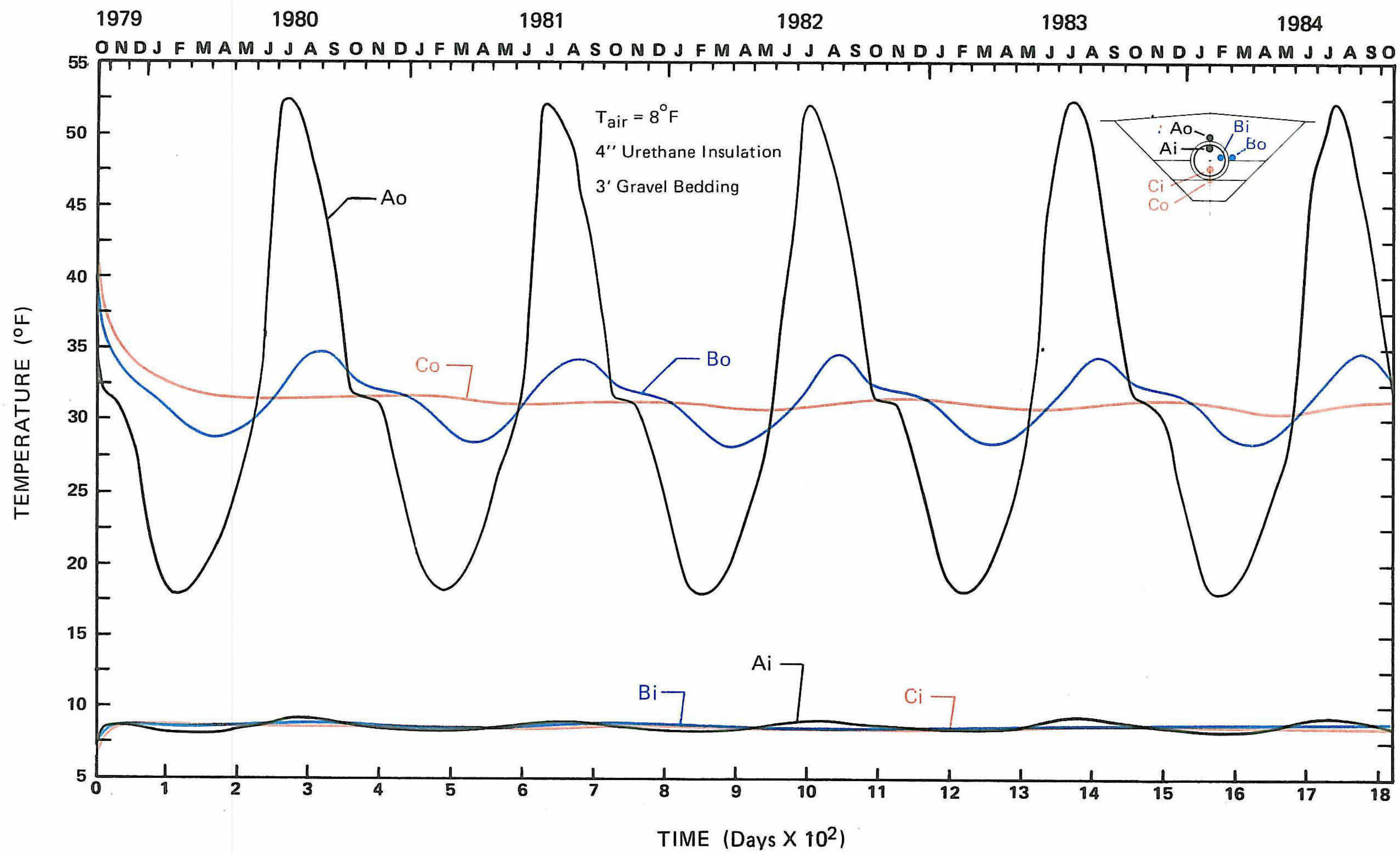


FIGURE 5.26 PREDICTED TEMPERATURES AT PIPE & INSULATION SURFACES vs. TIME PIPE No. 8

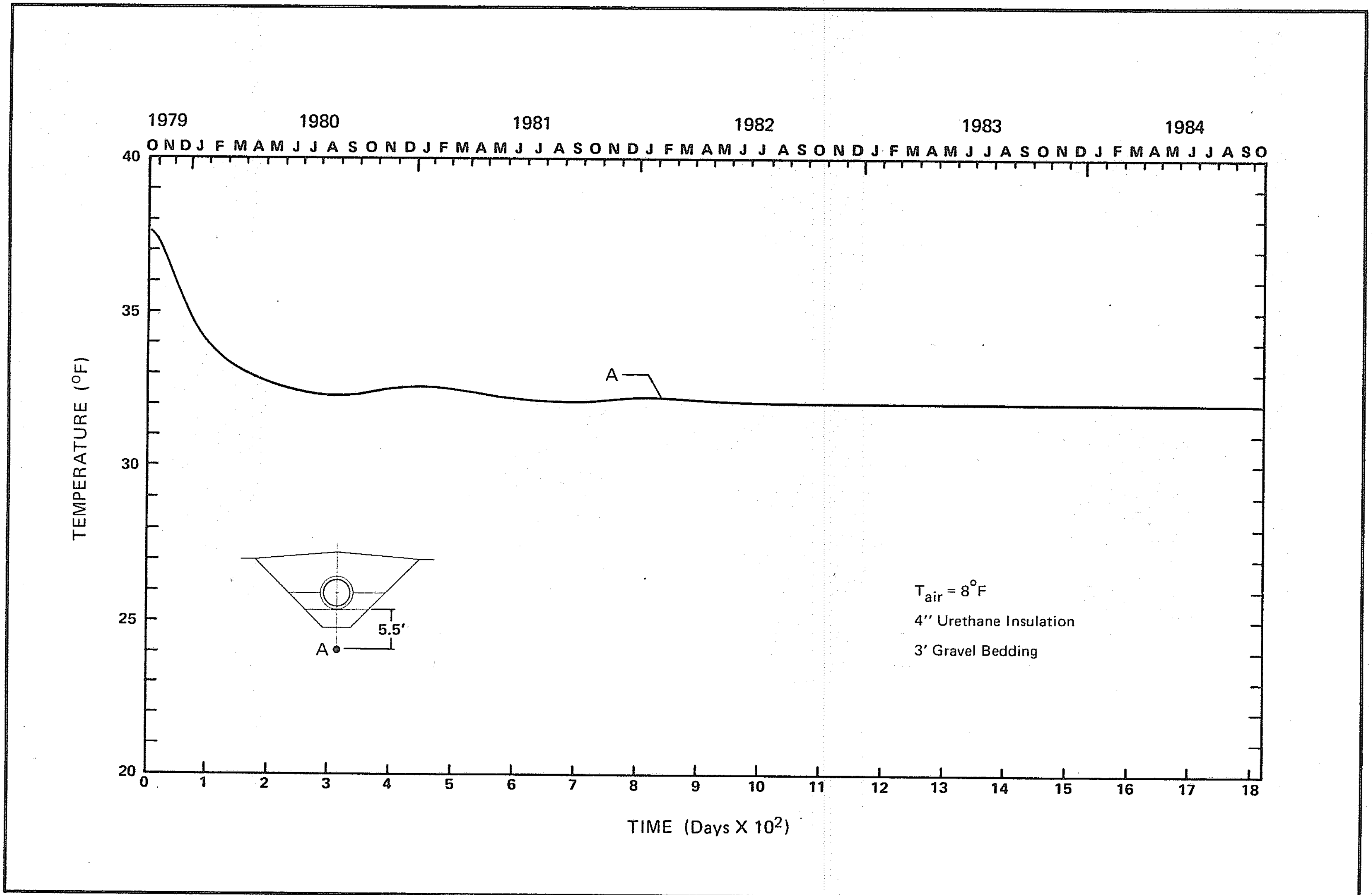


FIGURE 5.27 PREDICTED SOIL TEMPERATURES AT POINT A vs. TIME PIPE No. 8

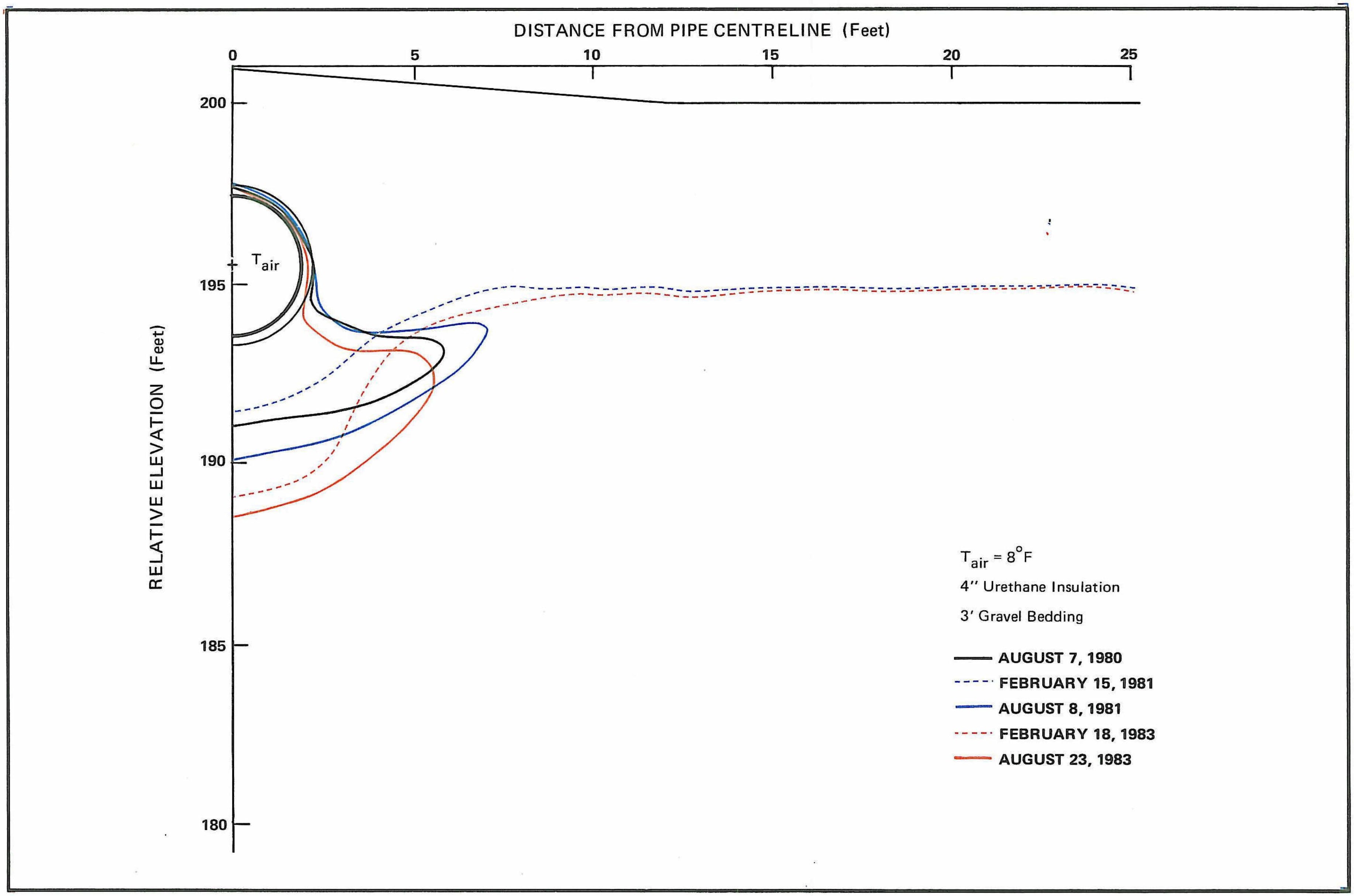


FIGURE 5.28 32°F CONTOURS AT SELECTED TIMES
PIPE No. 8

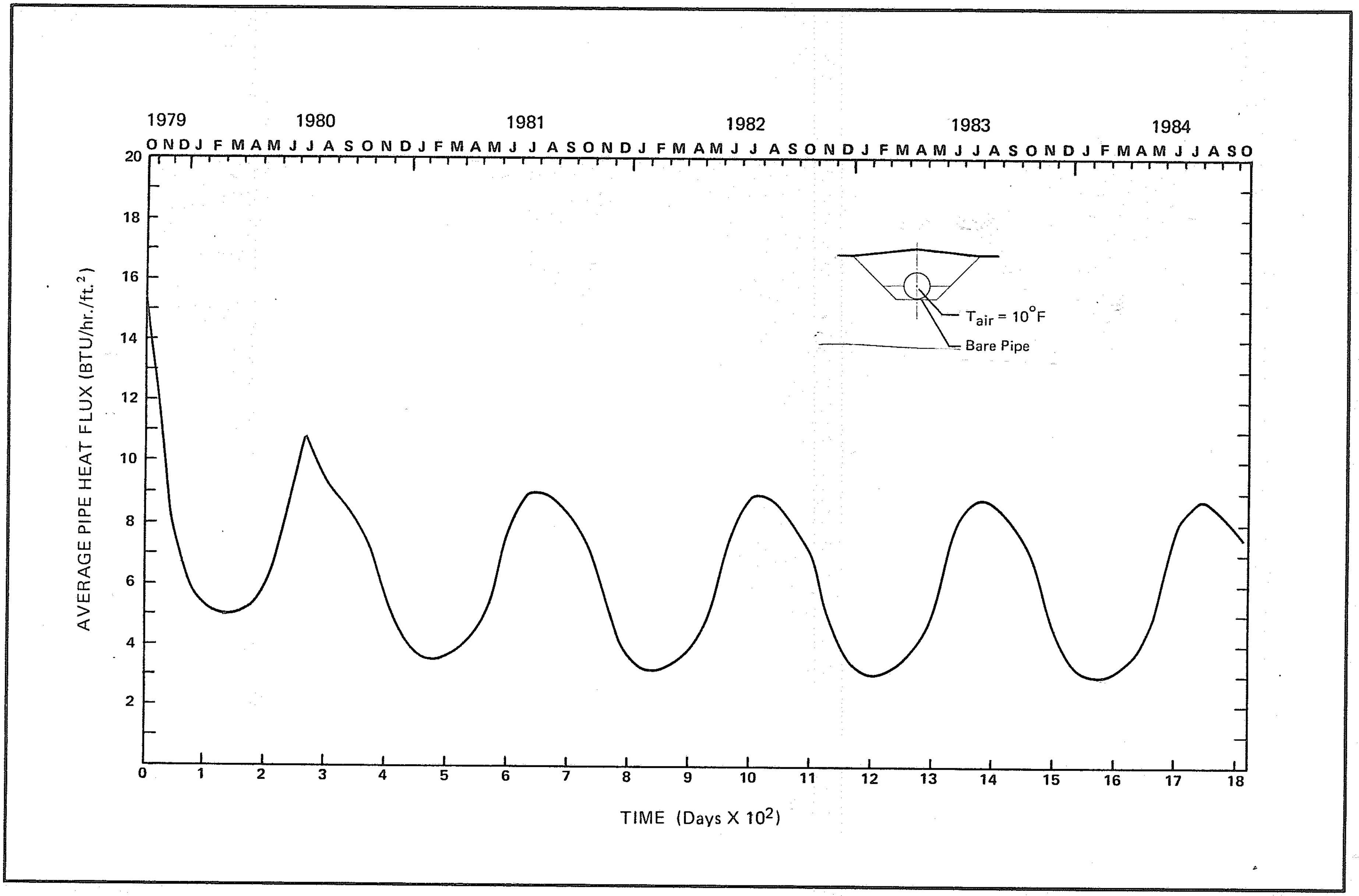


FIGURE 5.29 AVERAGE HEAT FLUX AROUND PIPE VERSUS TIME
TEST SECTION No. 1

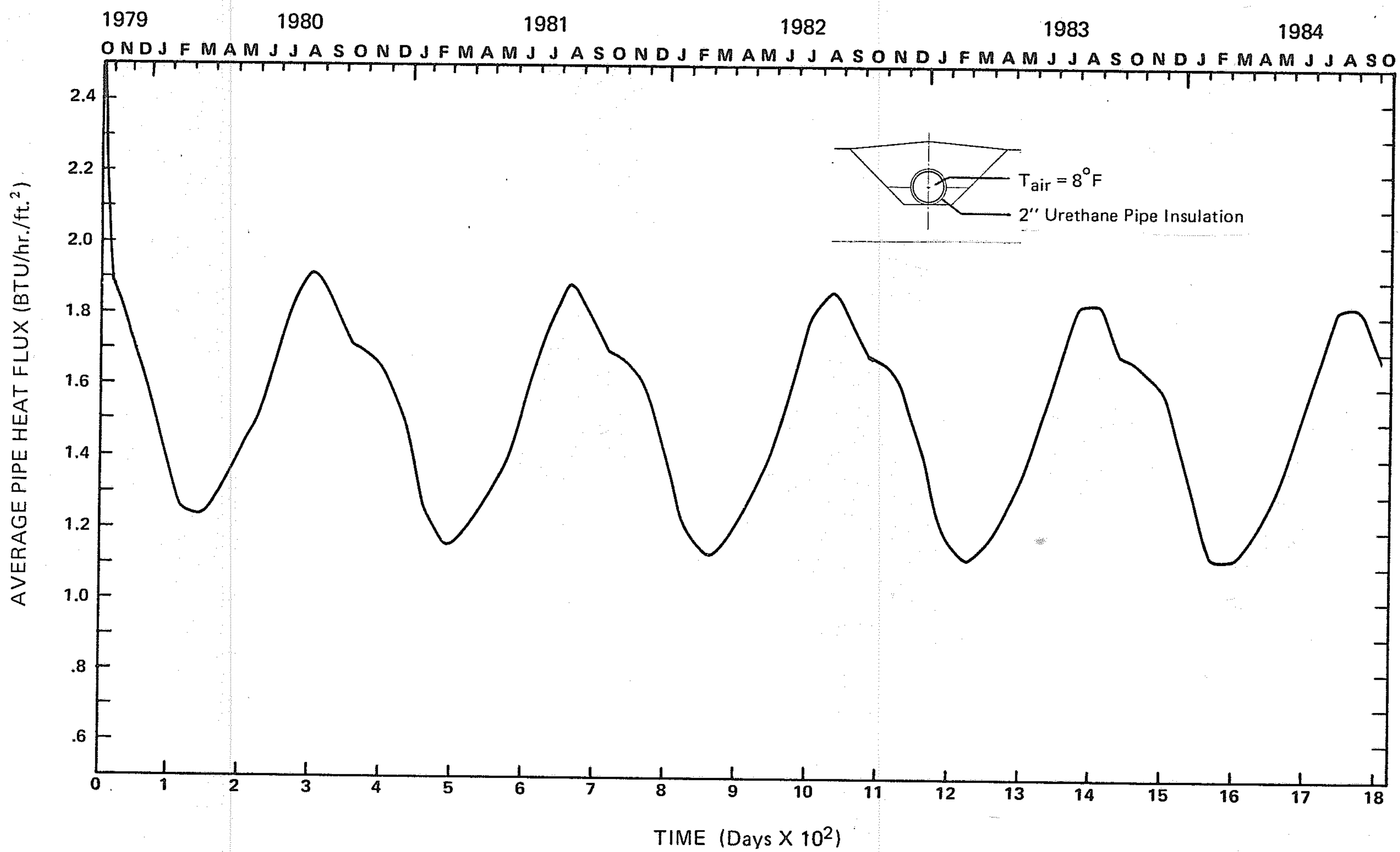


FIGURE 5.30 AVERAGE HEAT FLUX AROUND PIPE VERSUS TIME
TEST SECTION No. 2

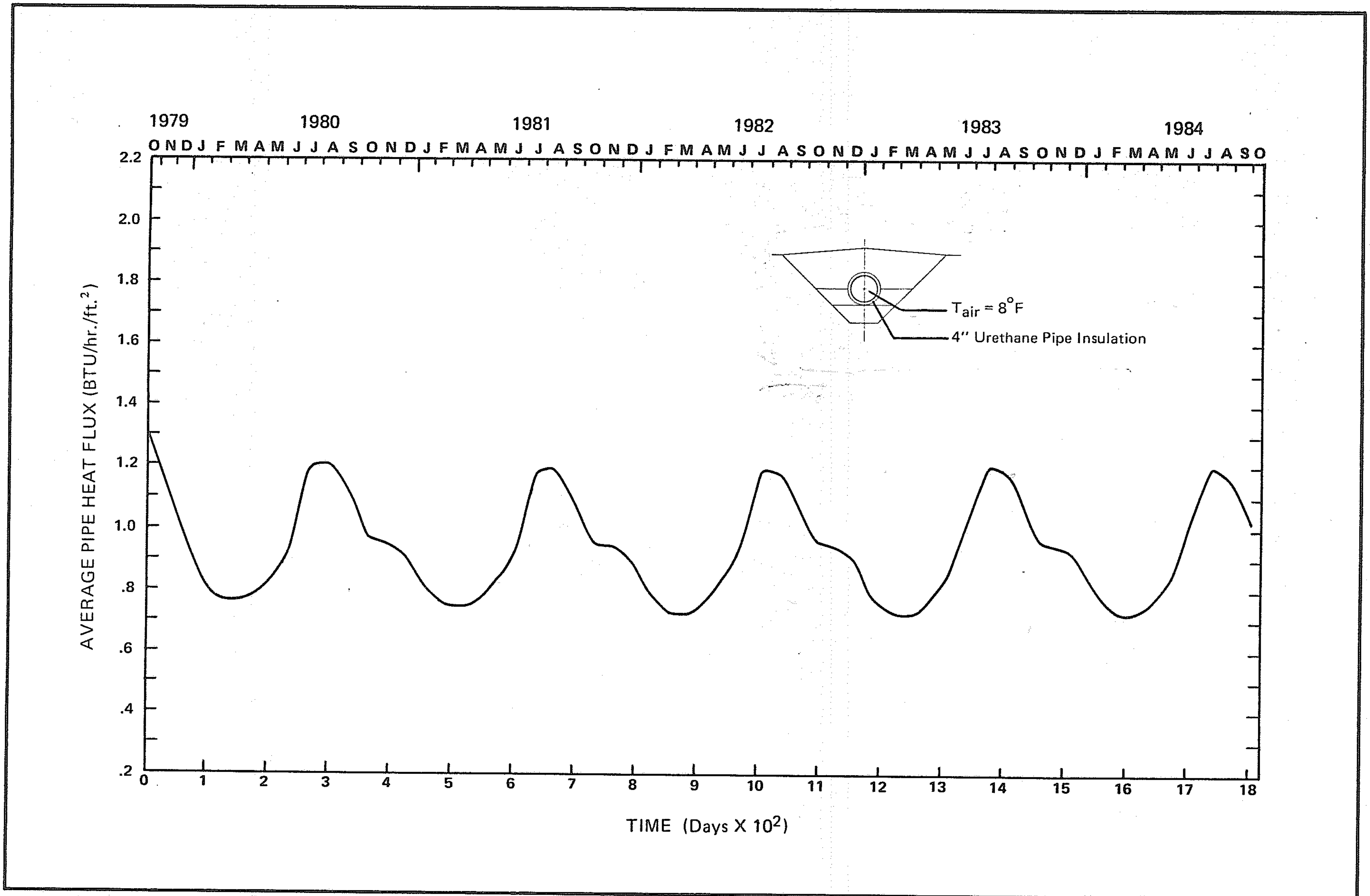


FIGURE 5.31 AVERAGE HEAT FLUX AROUND PIPE VERSUS TIME
TEST SECTION No. 8

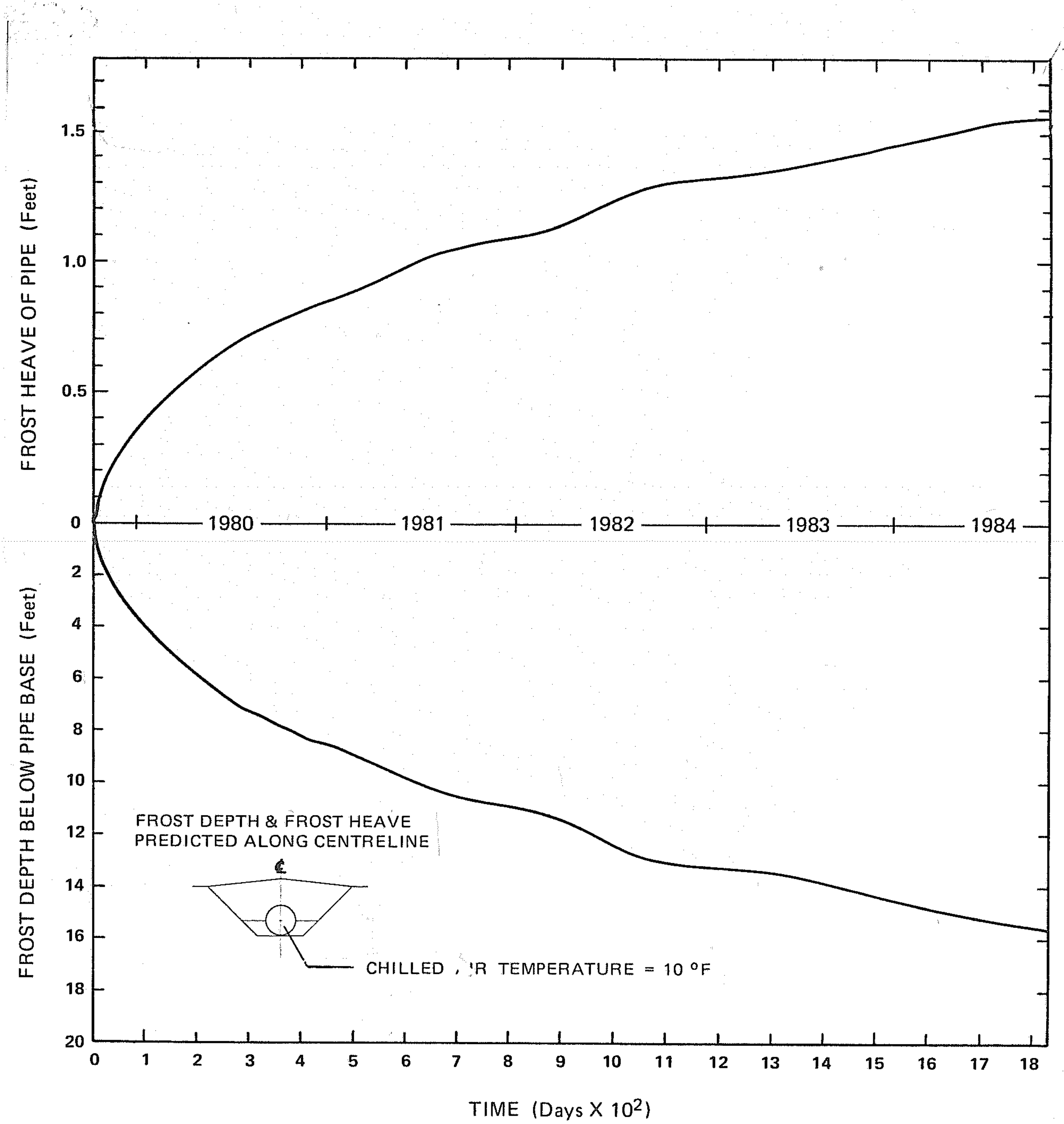


FIGURE 5.32 PREDICTED FROST HEAVE & FROST DEPTH vs. TIME
PIPE No. 1

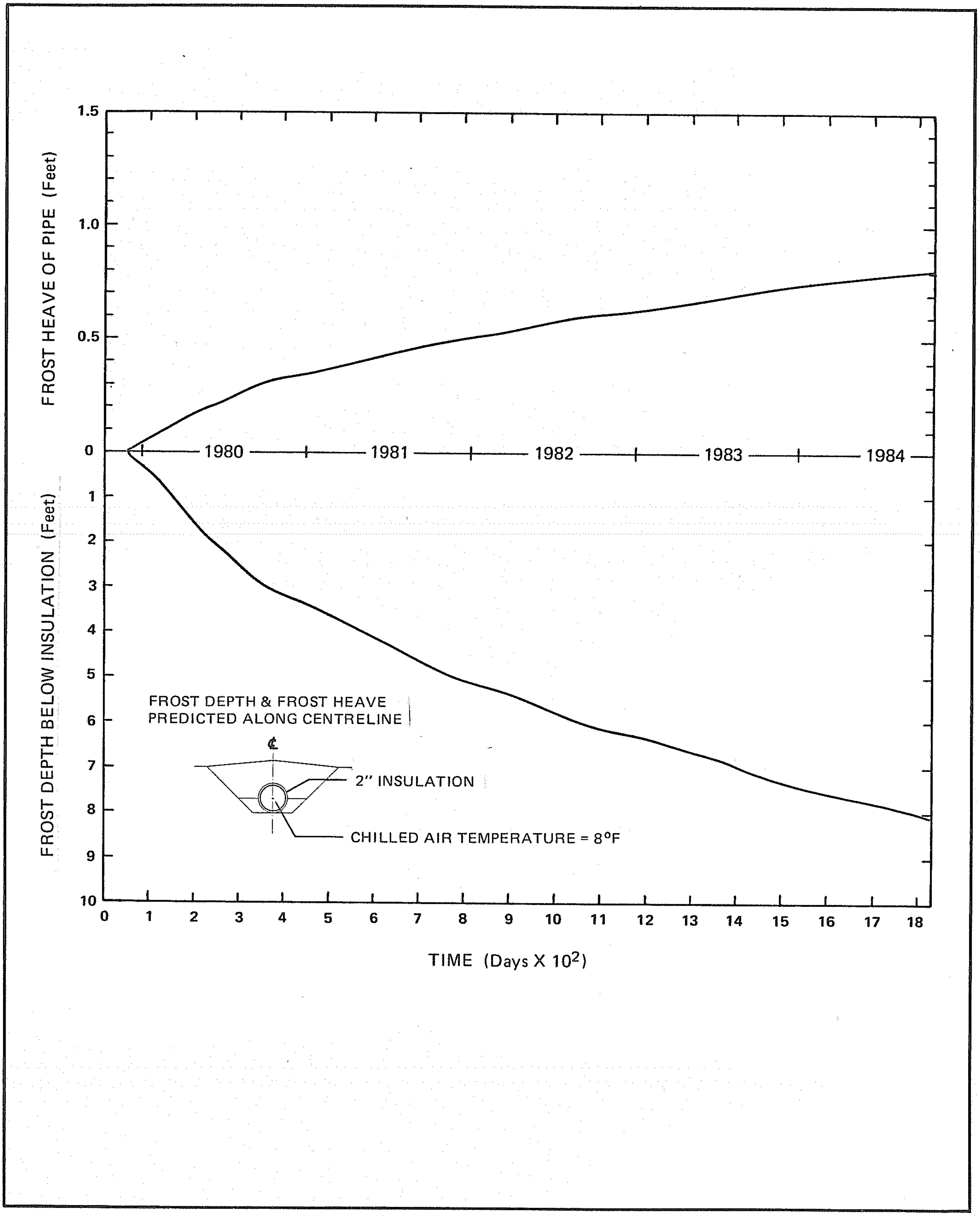


FIGURE 5.33 PREDICTED FROST HEAVE & FROST DEPTH vs. TIME
PIPE No. 2

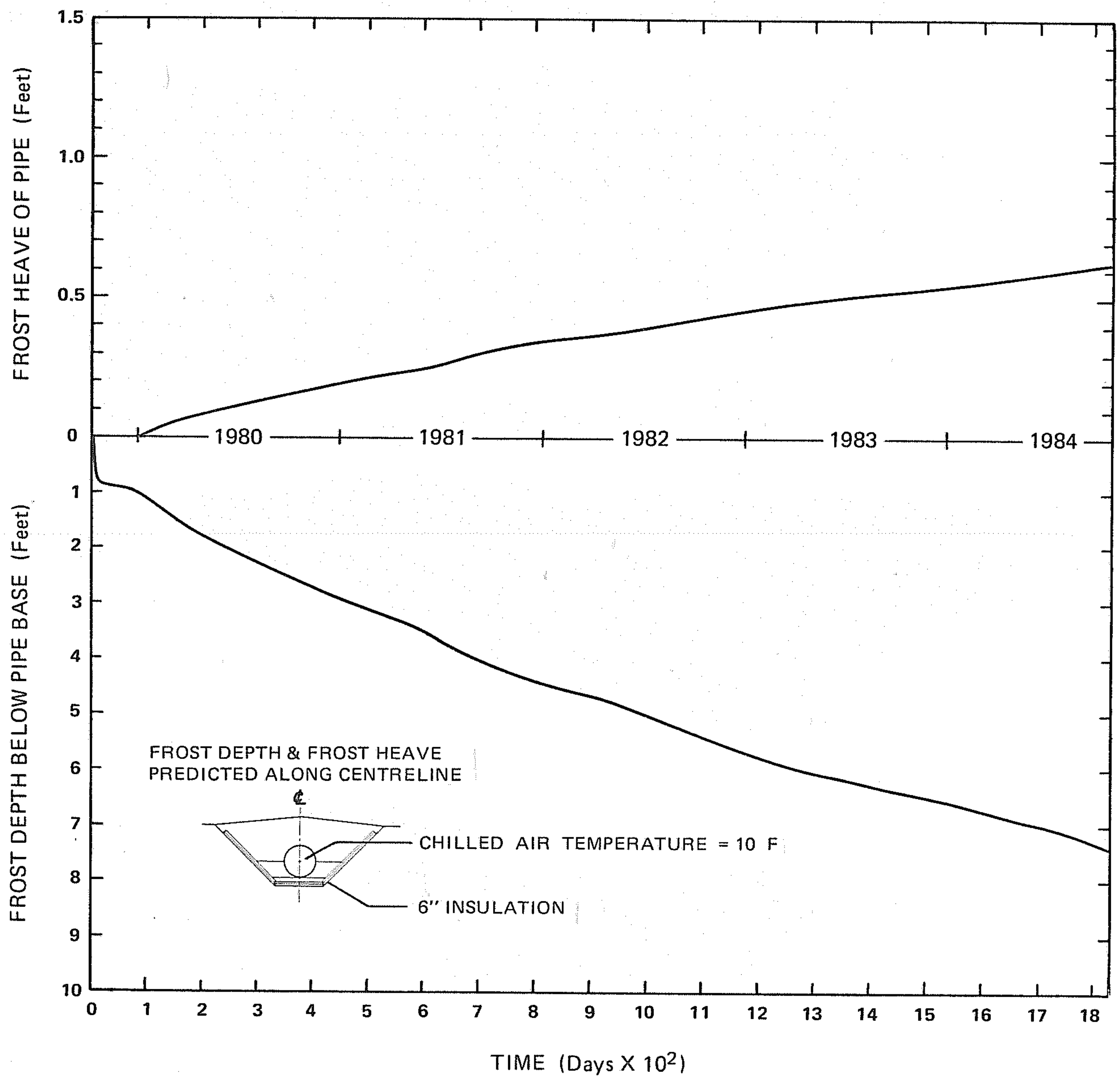


FIGURE 5.34 PREDICTED FROST HEAVE & FROST DEPTH vs. TIME
PIPE No. 3

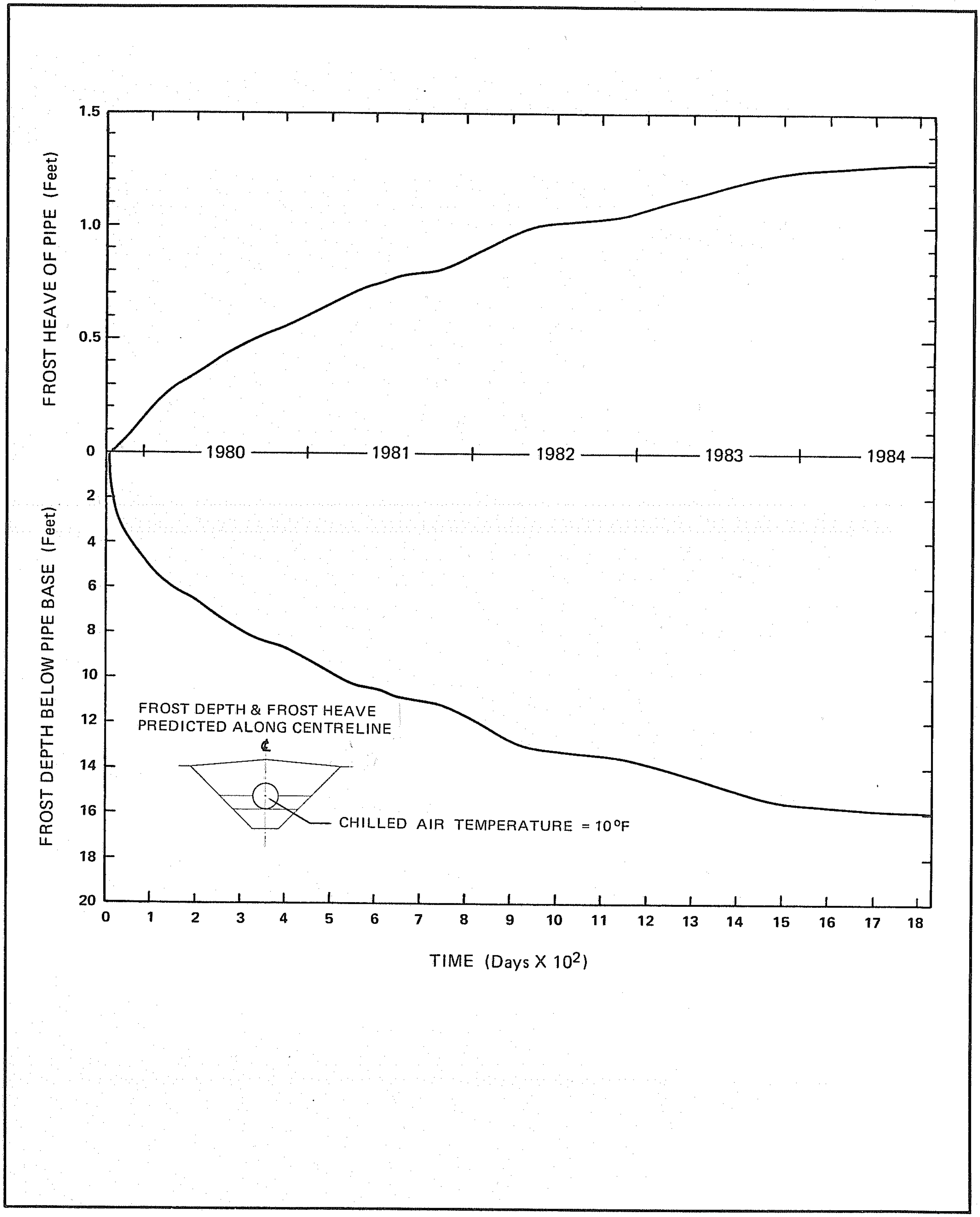


FIGURE 5.35 PREDICTED FROST HEAVE & FROST DEPTH vs. TIME
PIPE No. 4

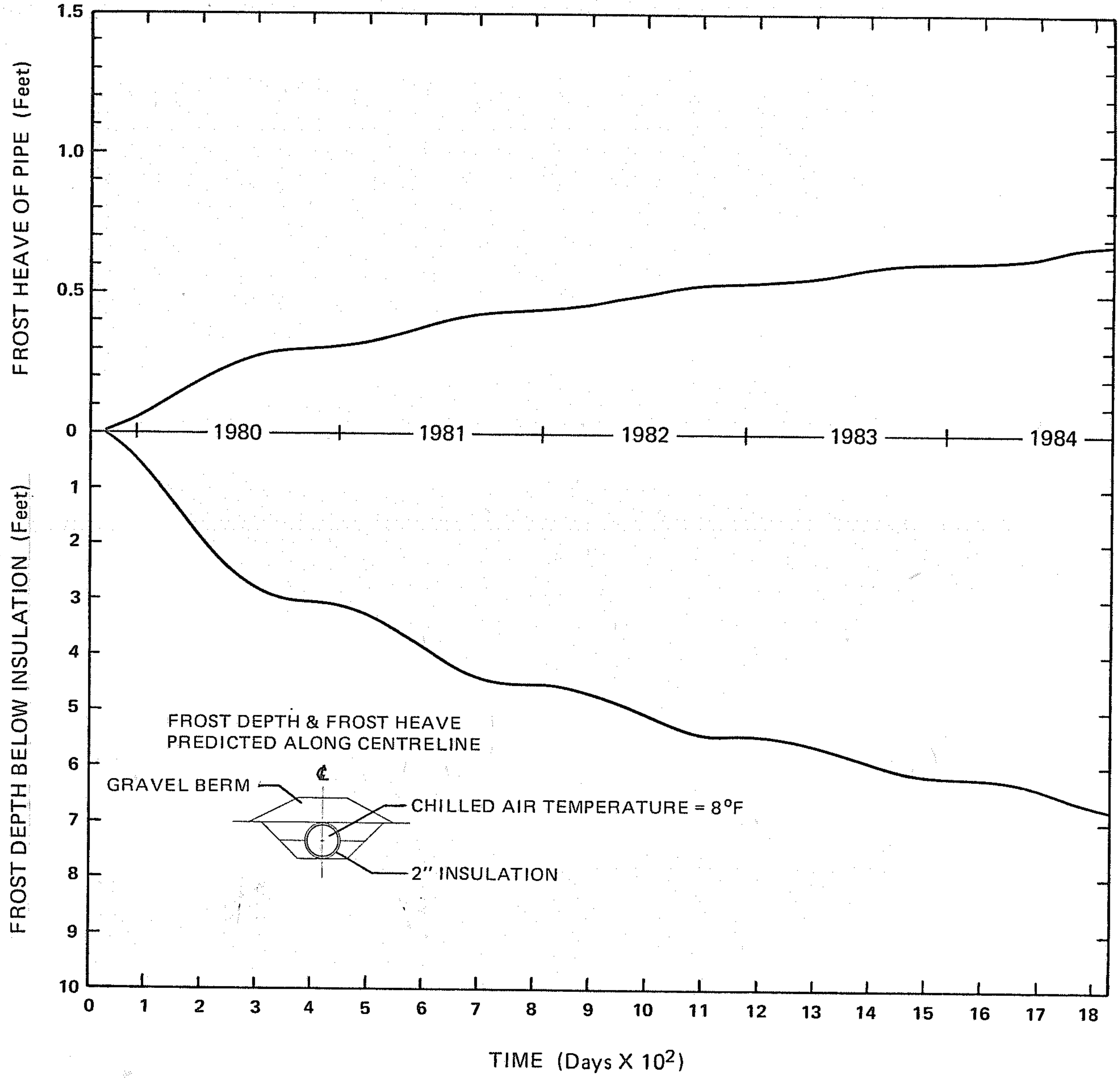


FIGURE 5.36 PREDICTED FROST HEAVE & FROST DEPTH vs. TIME
PIPE No. 5

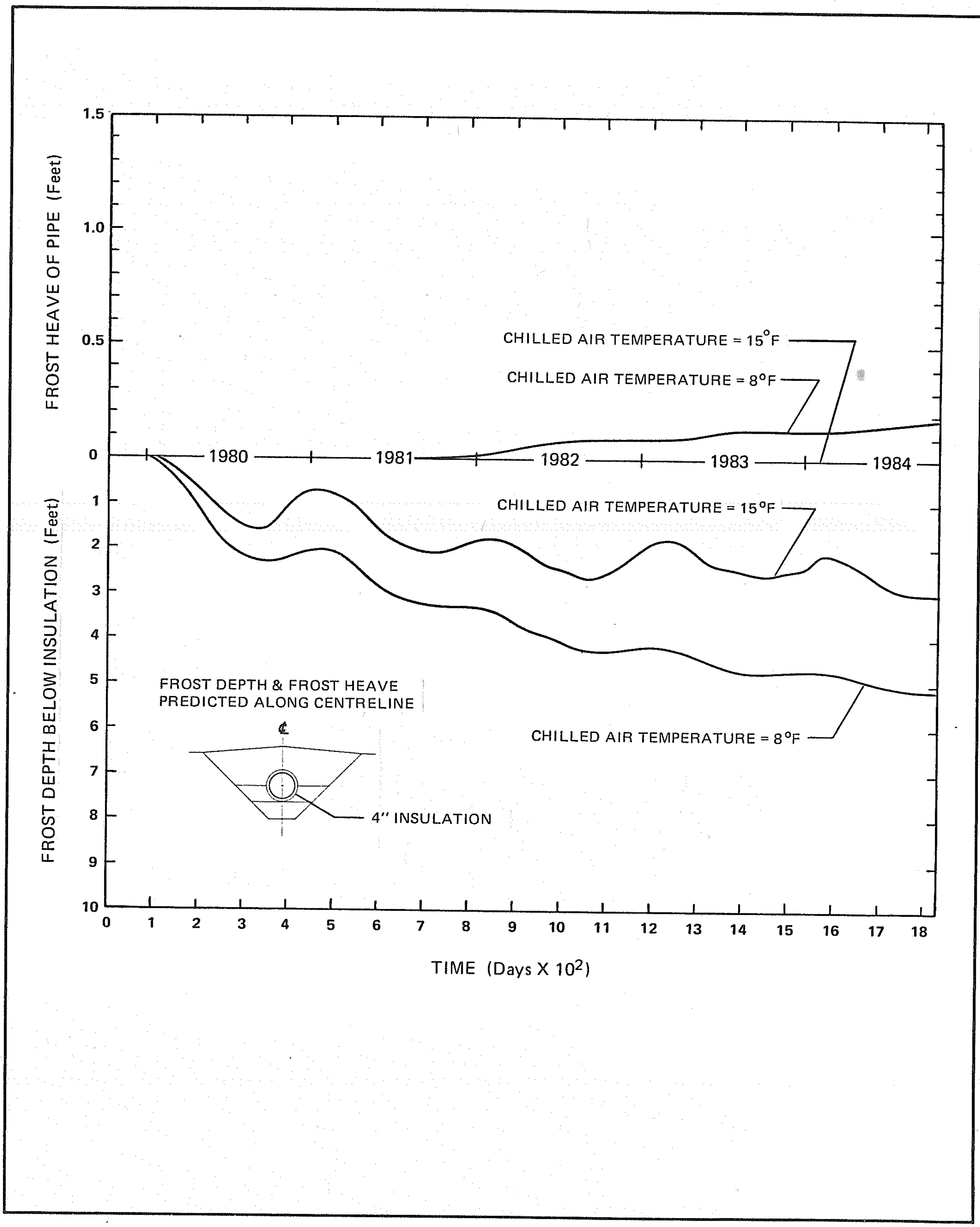


FIGURE 5.37 PREDICTED FROST HEAVE & FROST DEPTH vs. TIME
PIPE No. 8

APPENDIX A

ONE-DIMENSIONAL LABORATORY FROST HEAVE TESTING

I INTRODUCTION

One-dimensional laboratory frost heave tests have been conducted on soil samples believed representative of the subsurface conditions at the Fairbanks Frost Heave Test Facility.

The laboratory test models the ice segregation and frost heave characteristics of a soil element with free access to water, subjected to freezing by the operation of a chilled pipeline. The purpose of the frost heave test is to obtain the ice segregation ratio or heave strain for frost heave prediction.

In the following sections, the testing equipment and supportive facilities are described, the laboratory testing programme together with the testing procedure are reviewed, and the testing results are evaluated.

II TESTING EQUIPMENT AND SUPPORTIVE FACILITIES

2.1 Slurry Consolidation Apparatus

Soil samples utilized for frost heave tests are prepared from a slurry condition, and the slurry is consolidated to a pressure approximately equal to the insitu overburden pressure.

The cell which is utilized for slurry consolidation, by retaining the oedometer configuration, restrains the sample laterally so that all volume changes occur in the vertical direction. In addition, the load ram is threaded directly into the load cap to eliminate any tendency for tilting; ram alignment is maintained by a teflon bushing set into the guide bar.

2.2 Frost Heave Cell

The frost heave testing apparatus is a low friction cell which affords complete control of temperatures and allows free access of water.

The soil is contained within a sealed rubber membrane. The load is carried by an aluminum plate and the alignment is maintained by a load-centering arm lined with a teflon sleeve. The PVC barrel is also lined with a teflon sleeve in which two strings of thermistors are embedded; thermistors are also attached to the warm plate and sample base plate. In addition, to enhance control of the temperatures within the sample, the cell wall is insulated with 4 inches of Polyurethane.

Figure A.1 shows a cut view of a typical cell. Four cells are in use. Cells 1 and 2 have thermistors embedded in the walls to the height shown in Figure A.1 but in Cells 3 and 4, the thermistors extend for a further $2\frac{1}{2}$ inches. The spacing of the thermistors is constant in all cells.

Water is made available to the sample through the load cap. A burette included in the water supply system permits accurate monitoring of water flow into or out of the sample.

Temperature control during testing is accomplished by pumping fluid from thermostatically controlled constant temperature baths. This fluid moves through heat exchangers situated in the load cap (warm plate) and sample base plate (cold plate) to provide positive and stable control of thermal conditions in the sample throughout a test.

Vertical strain during the frost heave test is read on a dial gauge accurate to 0.005mm and with a direct current displacement transducer (DCDT).

2.3 Supportive Facilities

The cold room consists of two chambers in which the ambient air temperatures can be controlled independently. Maintaining the ambient air temperature at a relatively constant level ensures better performance of the temperature baths by minimizing room temperature fluctuations.

All the frost heave test data, except for water intake or expulsion by the sample, is recorded automatically, at selected time intervals, by a data acquisition system attached to the instrumentation. Subsequently, water flow measurements are manually input to the data tapes.

III LABORATORY TESTING

3.1 Testing Programme

Subsequent to the evaluation of the boreholes and the classification test results, three frost heave tests were considered necessary to determine the ice segregation characteristics of the soils at the Fairbanks Frost Heave Test Facility.

Samples from boreholes in the immediate vicinity of the test sections were selected for frost heave testing, wherever possible. Although it is recognized that the combination of soil samples from different boreholes is not desirable, small, similar samples had to be combined in order to form one test specimen.

Soil samples tested are shown in Table A.1.

3.2 General Procedure

The soil to be tested is allowed to soak overnight before being placed in slurry form in the oedometer where it is consolidated under two increments of load. After consolidation, the sample is transferred to the frost heave cell and is allowed to stand overnight under the test load. This allows the sample to attain equilibrium under the test load and come to a uniform temperature.

To initiate freezing in the sample, coolant at a very low temperature (-4^{0}F) is circulated through the base plate. After nucleation, the supply lines are switched over to another bath containing coolant at the desired cold-side temperature.

Readings of heave, water intake/expulsion and temperature distribution are taken very frequently in the early stages of the test and daily once the test has stabilized. Readings are plotted immediately in order to permit early detection of any malfunction. The test is run until steady state is reached.

After testing, the cell is dismantled, the samples are photographed, examined and any special characteristics are noted. Moisture content determinations and soil classification tests are then run on both the frozen and unfrozen sections.

3.3 Frost Heave Tests

3.3.1 General

Typically, the samples behaved as follows:
Upon nucleation, water expulsion began immediately and a very slight expansion of the specimen was noted. The 32^{0}F isotherm penetrated rapidly at first but slowed until it became almost stationary. Heave began very slowly, built to a maximum rate and then entered a long decay phase. Water expulsion ceased after a time and intake began. The slowing of the penetration rate, the maximum heave rate and the end of expulsion all occurred early in the test.

Throughout each test, the warm and cold plates were subject to slight ($\pm 0.1^{O}F$) temperature fluctuations which, in the early stages, had no visible effect on heave. However, as the test approached steady state, it became sensitive to these fluctuations. This sensitivity shows up in the plots of the test data in the form of advance or retreat of the $32^{O}F$ isotherm. Specific characteristics of each test are discussed below.

3.3.2 Frost Heave Test 15

By approximately 25 hours into the test, the maximum heave rate had been reached and water expulsion had ceased (6.2 cm^3). The rate of penetration of the $32^{O}F$ isotherm was slowing and stabilized at approximately 2.4 inches into the sample.

The cold plate stabilized at approximately $30.1^{O}F$ but the warm plate temperature tended to creep upwards. After 167 hours, the warm bath temperature was reduced by $0.18^{O}F$ in an attempt to restore initial conditions. For the remainder of the test, the cold side temperature was very steady but the warm side temperature continued to fluctuate slightly ($0.18^{O}F$). The test proceeded for 77 days at which point, maximum total heave was 5.115mm (0.20 inches) and the $32^{O}F$ isotherm penetration was 61.5mm (2.42 inches). The ice segregation ratio was 8%.

The test data are plotted in Figures A.2, A.3 and A.4 and are summarized in Table A.2. The values of heave plotted are those measured by DCDT and those in Table A.2 are dial guage headings. Very slight differences between the two exist as the DCDT is temperature sensitive. Upon completion of the test, the specimen was examined. The amount of ice lensing was small and the most visible ice lensing was in the vicinity of the junction between the frozen and unfrozen zones.

The moisture contents of the frozen, and the unfrozen portions were determined. Grain sizes and organic contents were measured for both the frozen and unfrozen sections. Table A.3 presents a summary of the sample soil properties. The grain size curves are shown in Figures A.5 and A.6.

3.3.3 Frost Heave Test 16

Test 16 ran concurrently with Test 15 and so comments concerning warm bath fluctuations also apply. The temperatures in the warm and cold plates are slightly different from Test 15 due to the different lengths of supply lines carrying the coolant and different pump flow rates.

The heave rate began to increase considerably between 13 hours and 24 hours into the test, reached its peak between 33 and 48 hours, and then decayed until the end of the test. Water expulsion ceased after approximately 20 hours (6.1 cm^3) and the position of the 32^0F isotherm stabilized at around 2 inches into the sample.

At the end of the test, the maximum heave was 4.48mm (0.18 inches) and 32^0F isotherm penetration was 51.5mm (2.03 inches). The ice segregation ratio or heave strain was 9%.

Test results are plotted as Figures A.7, A.8 and A.9 and are summarized in Table A.2.

Upon examination of the sample after test completion, a band of very thin ice lenses was observed. Moisture content and soil classification tests were run on both the frozen and unfrozen sections. Table A.3 presents a summary of the results.

3.3.4 Frost Heave Test 18

The sample behaved normally upon nucleation. Maximum water expulsion was 3.3ml (0.20in^3) and intake began after 20 hours of the test. The heave rate built to a maximum after approximately 55 hours. The test then proceeded normally with decreasing heave rate and reached a maximum heave of 3.78mm (0.149 inches) at a 32^{0}F isotherm penetration of 38.4mm (1.51 inches). The ice segregation ratio or heave strain was 10%.

The test results are plotted in Figures A.10, A.11 and A.12 and are summarized in Table A.2. The step shown in the position of the 32^{O}F isotherm (Figure A.10) was due to a calibration error in one thermistor which resulted in an artifically low value of the calculated position.

Dismantling of the cell revealed very thin ice lensing. Results of the soil tests on the unfrozen and frozen portions are given in Table A.3 and the grain size curves are shown in Figures A.13 and A.14.

IV CLOSURE

The laboratory testing equipment and supportive facilities have been described in detail. The testing programme has been reviewed and the frost heave test results evaluated.

The one-dimensional laboratory frost heave tests of a finite length soil element with free access of water have been conducted until the steady-state condition was reached; as a consequence, it is believed they have provided the maximum heave strain to be anticipated for soils encountered at the Fairbanks Frost Heave Test Facility. The heave strain or ice segregation ratio thus obtained is the primary input parameter for the prediction of frost heave the test pipes may be subjected to.

TABLE A.1
BOREHOLE AND SAMPLE LOCATIONS

Test No.	Borehole No.*	Sample No.	Depth in Borehole
FH15	G-5	S-4	10-12½
FH16	G-3	S-4	10-12½
FH18	G36 and G33	S-5 S-5	12-14 12-14

* Borehole and sample locations shown in Figures 2.1 and 4.2.

TABLE A.2: SUMMARY OF FROST HEAVE TEST RESULTS

Test No.	Consolidation Pressure kPa	Test Pressure kPa	Warm Side Temperature (0^oC)	Cold Side Temperature (0^oC)	Test Duration (days)	Water Intake (ml)	Heave (mm)	Penetration of 0^oC Isotherm (mm)	Heave Strain
15	51	51	1.04 to 1.17	-1.01 to -1.08	77	13.8	5.115	61.5	8%
16	56	56	1.17 to 1.36	-1.05 to -1.10	77	15.5	4.48	51.5	9%
18	57	57	1.26 to 1.34	-0.60 to -0.67	64	23.3	3.78	38.4	10%

TABLE A.3: SOIL PROPERTIES OF FROST HEAVE TEST SPECIMENS

Test No.		15	16	18
Permeability k (ft/day)		4.5×10^{-3}	2.07×10^{-3}	10×10^{-3}
Coefficient of Consolidation, C_v (ft^2/day)		1.8	1.97	6
Moisture Content (%)		38	28	26
Unfrozen Zone	L.L.	26		27
	P.L.	-		-(Non-plastic)
	P.I.	-		-
Organic Content		3.2		3.8
Moisture Content (%)		44	32	33
Frozen Zone	L.L.	27		28
	P.L.	-	-	-(Non-plastic)
	P.I.	-	-	-
Organic Content		3.1		3.9

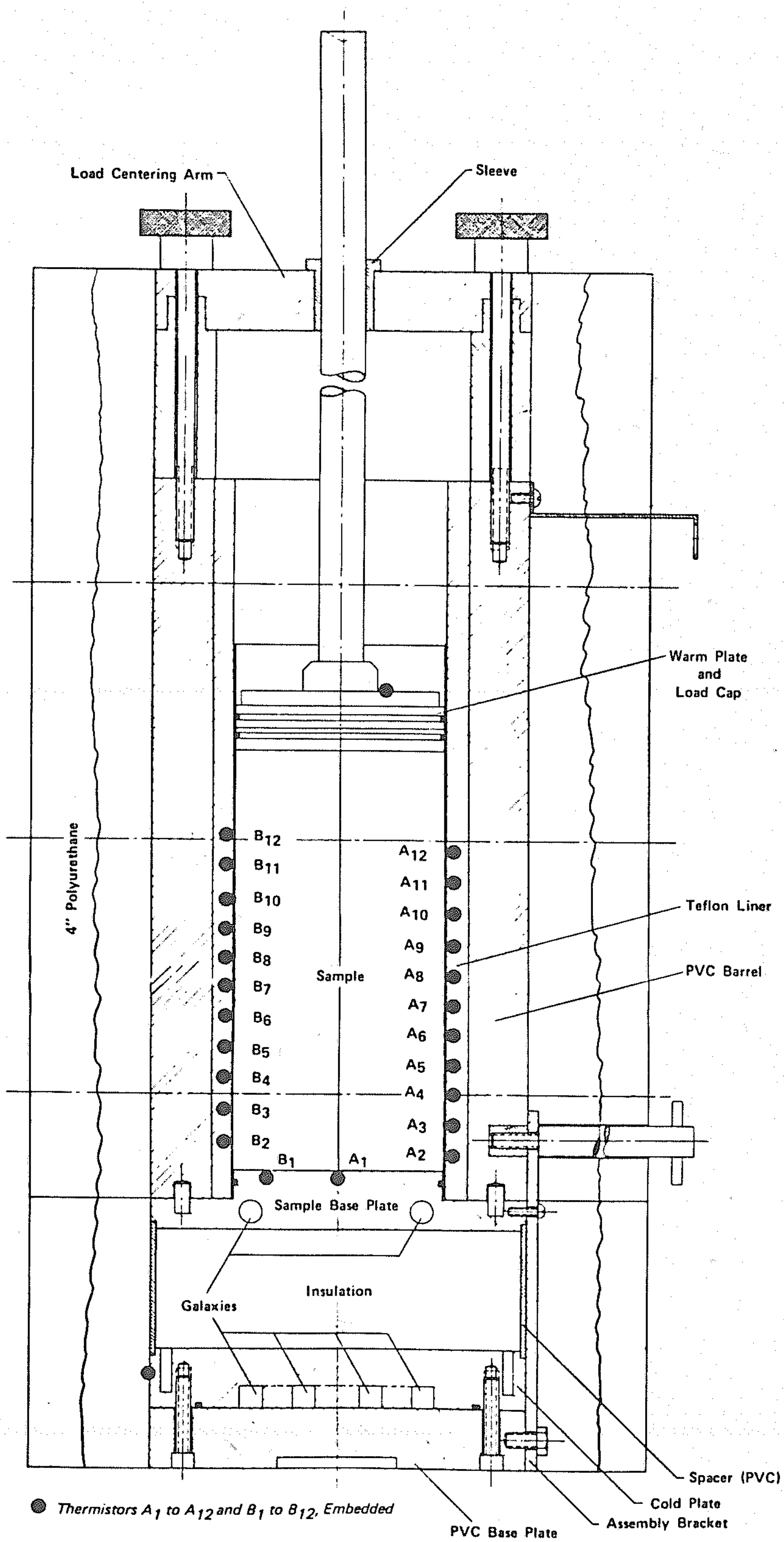


FIGURE A.1 FOOTHILLS FROST HEAVE TEST CELL

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5564 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

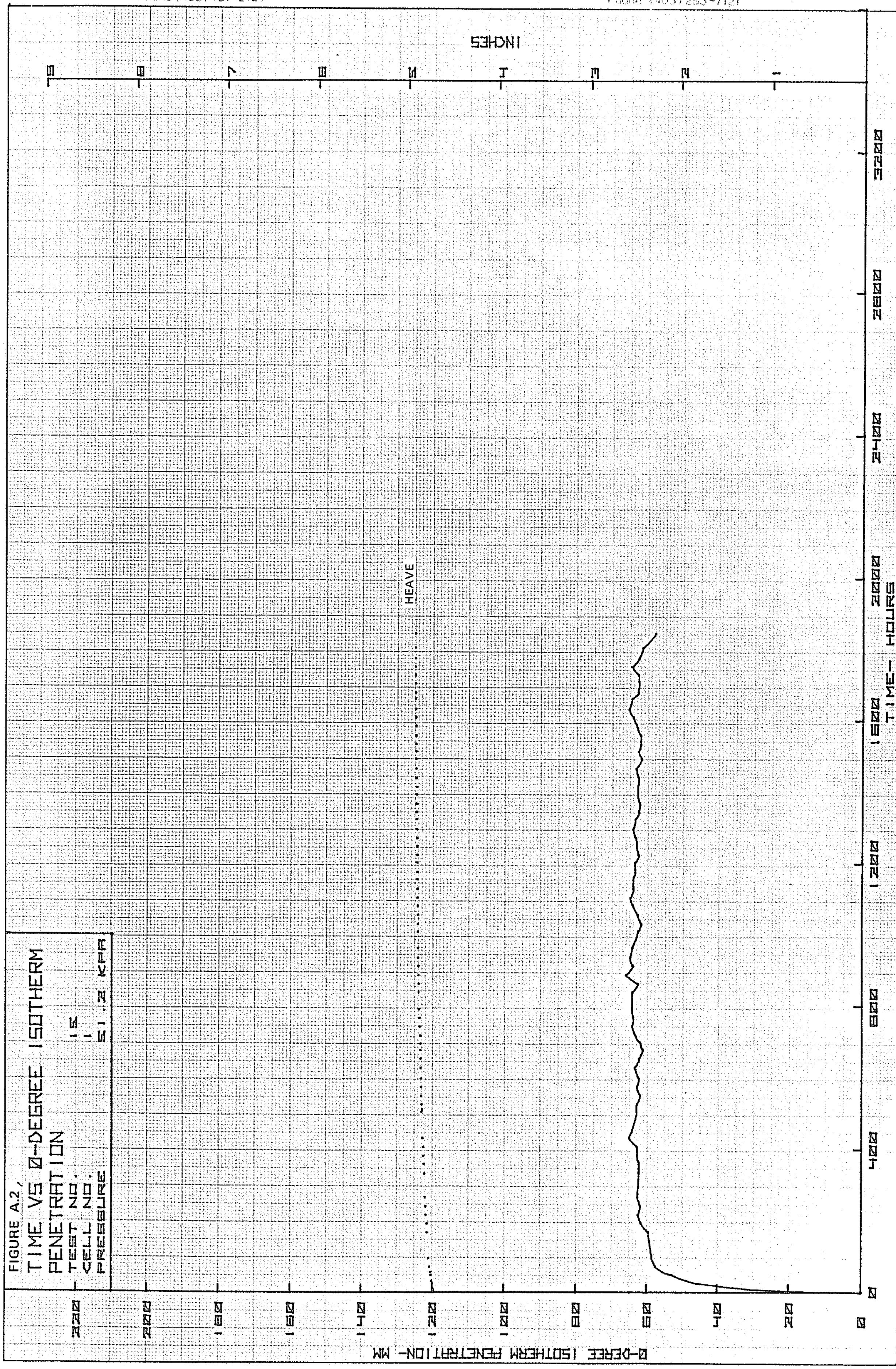


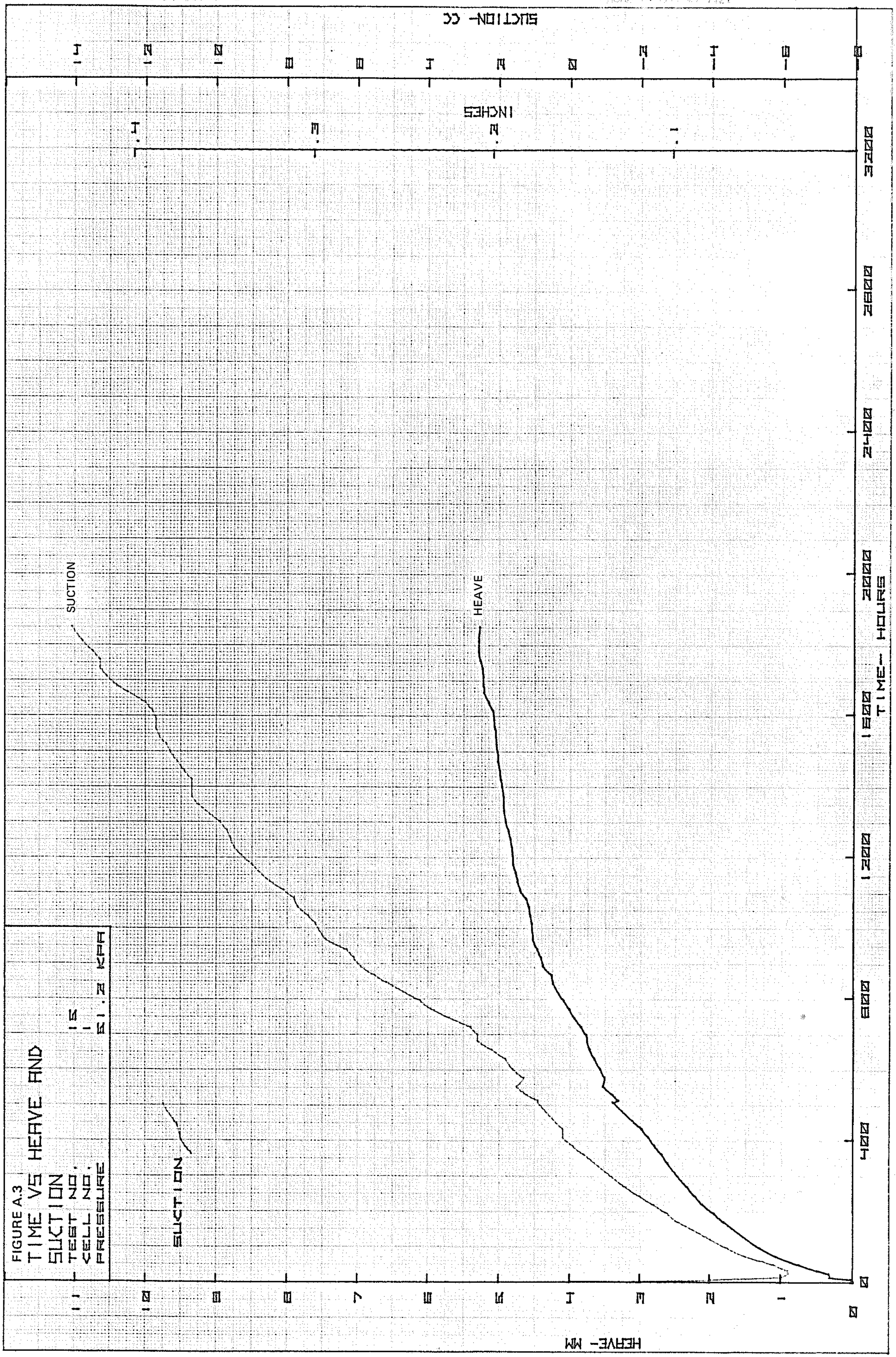
FIGURE A.2,
TIME VS 0-DEGREE ISOTHERM
PENETRATION
TEST NO. 15
CELL NO. 1
PRESSURE 51.2 KPA

10 X 10 TO THE CENTIMETER

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

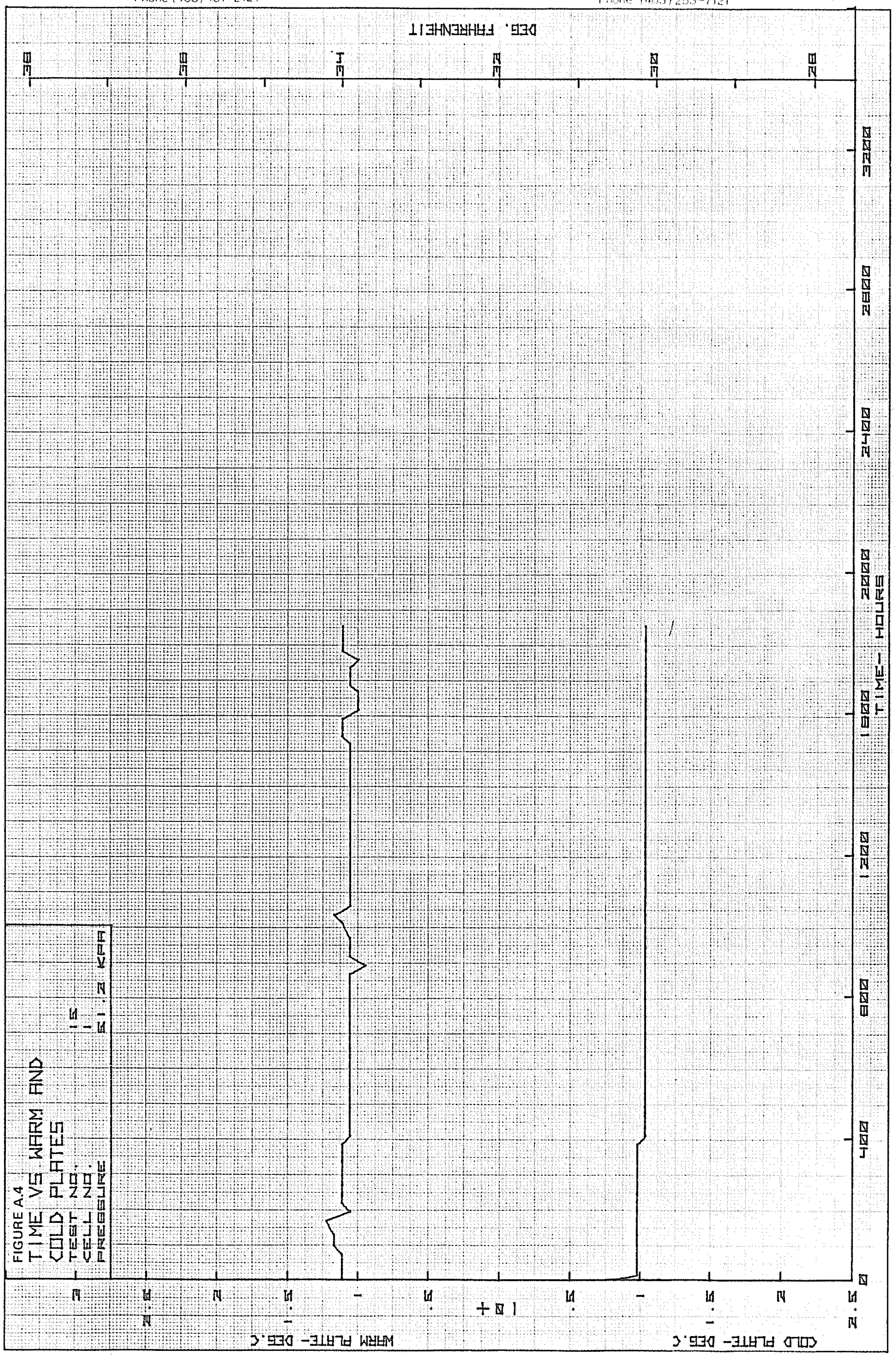
5654 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121



EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121



10 X 10 TO THE CENTIMETER

EBA Engineering Consultants ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project: ....

Project Number: 102-2658

Date Tested: 11-12-79

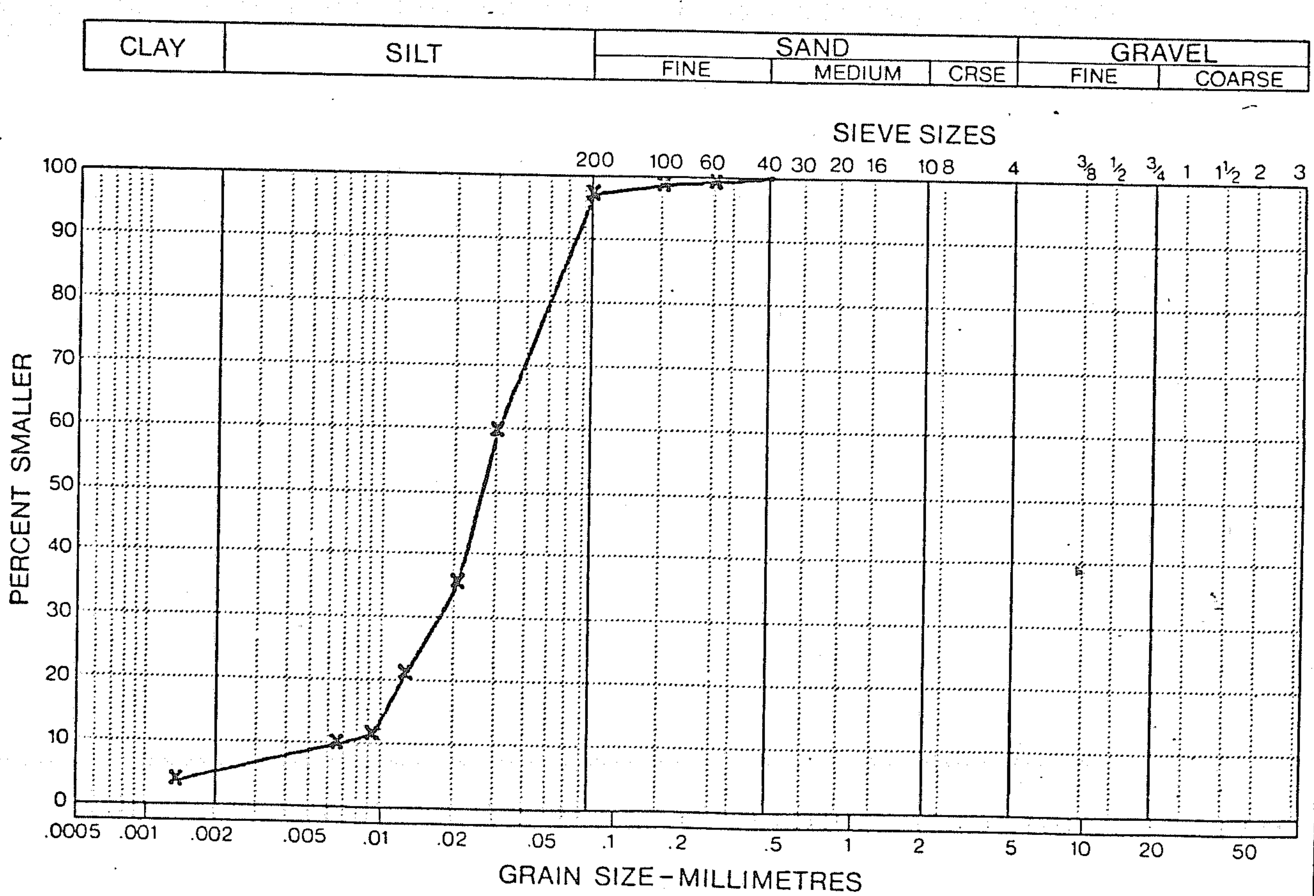
Remarks: FH 15
FROZEN PORTION

Test Hole Number: ....

Depth: ....

Sample Description

Gravel: 0
Sand: 3
Silt: 91
Clay: 6



Reviewed By: .... P. Eng.

All tests performed in accordance with ASTM and CSA standards unless otherwise noted.

Figure A.5 Grain Size Curve for FH15 (Frozen Zone).

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

eba

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

GRAIN SIZE DISTRIBUTION

Project:

Project Number: 102-2658

Date Tested: 11-12-79

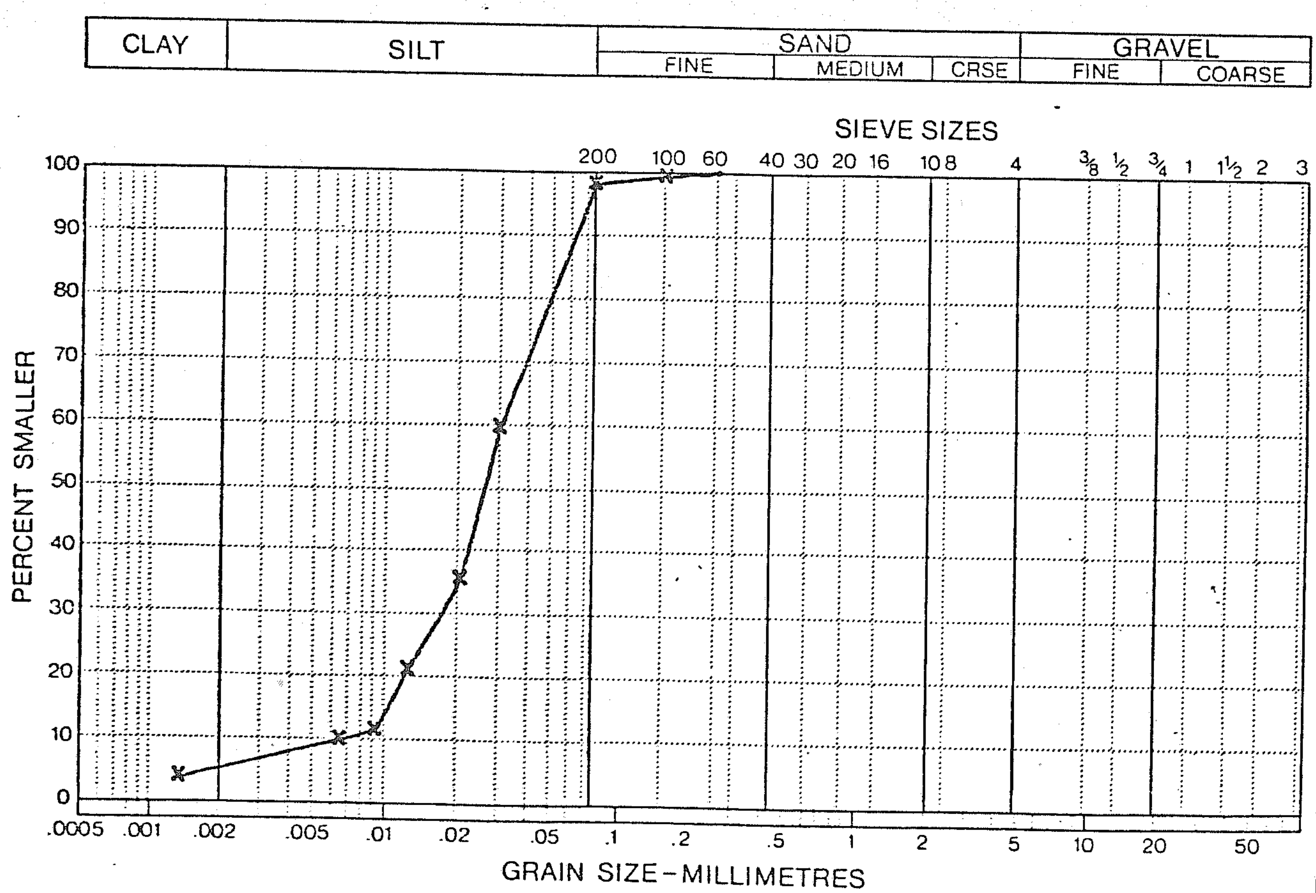
Remarks: FH 15
UNFROZEN PORTION

Test Hole Number:

Depth:

Sample Description

Gravel: 0
Sand: 2
Silt: 92
Clay: 6



Reviewed By: .... P. Eng.

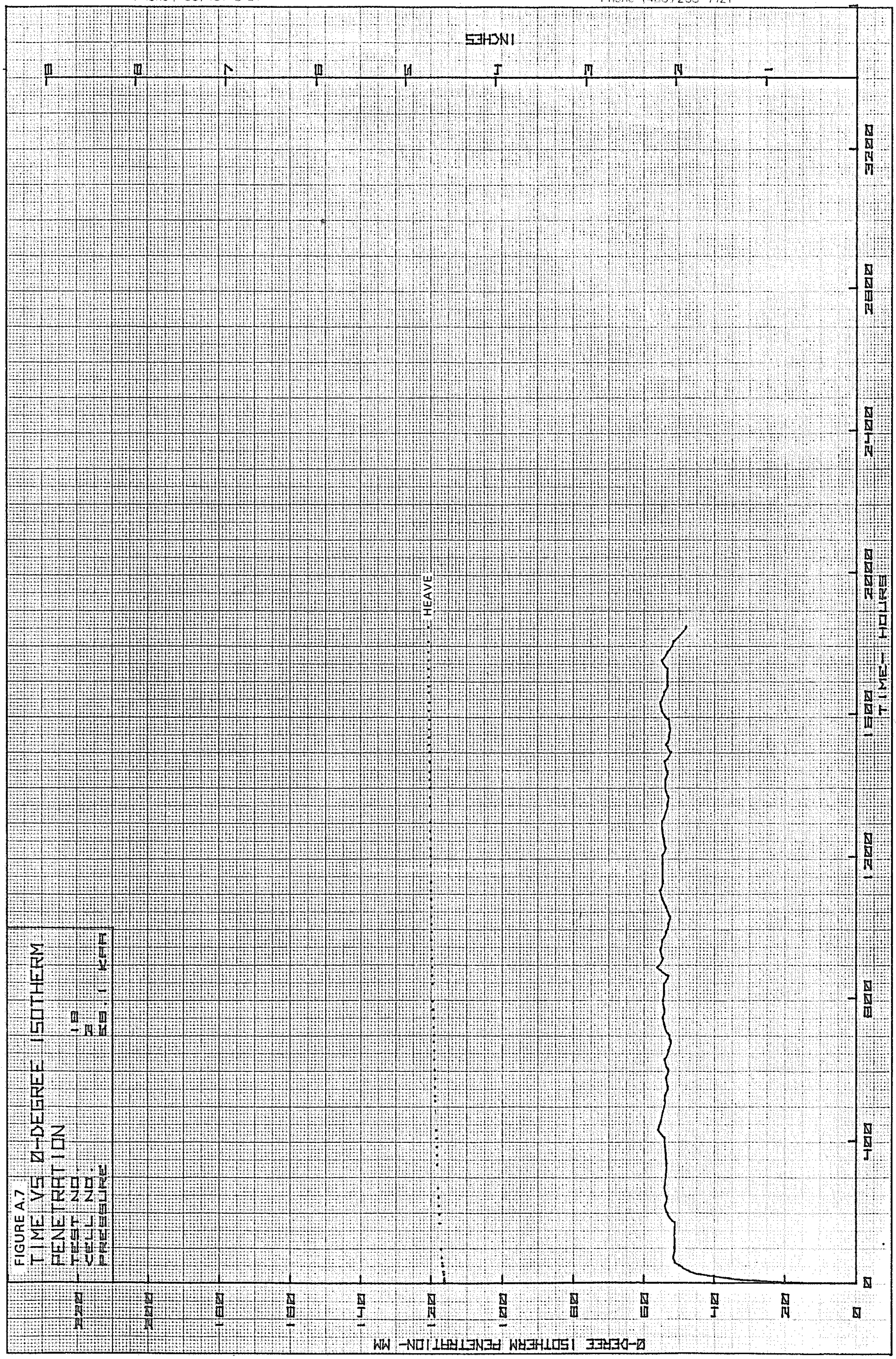
All tests performed in accordance with ASTM and CSA standards unless otherwise noted

Figure A.6 Grain Size Curve for FH15 (Unfrozen Zone).

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121



10 X 10 TO THE CENTIMETER

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5584 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

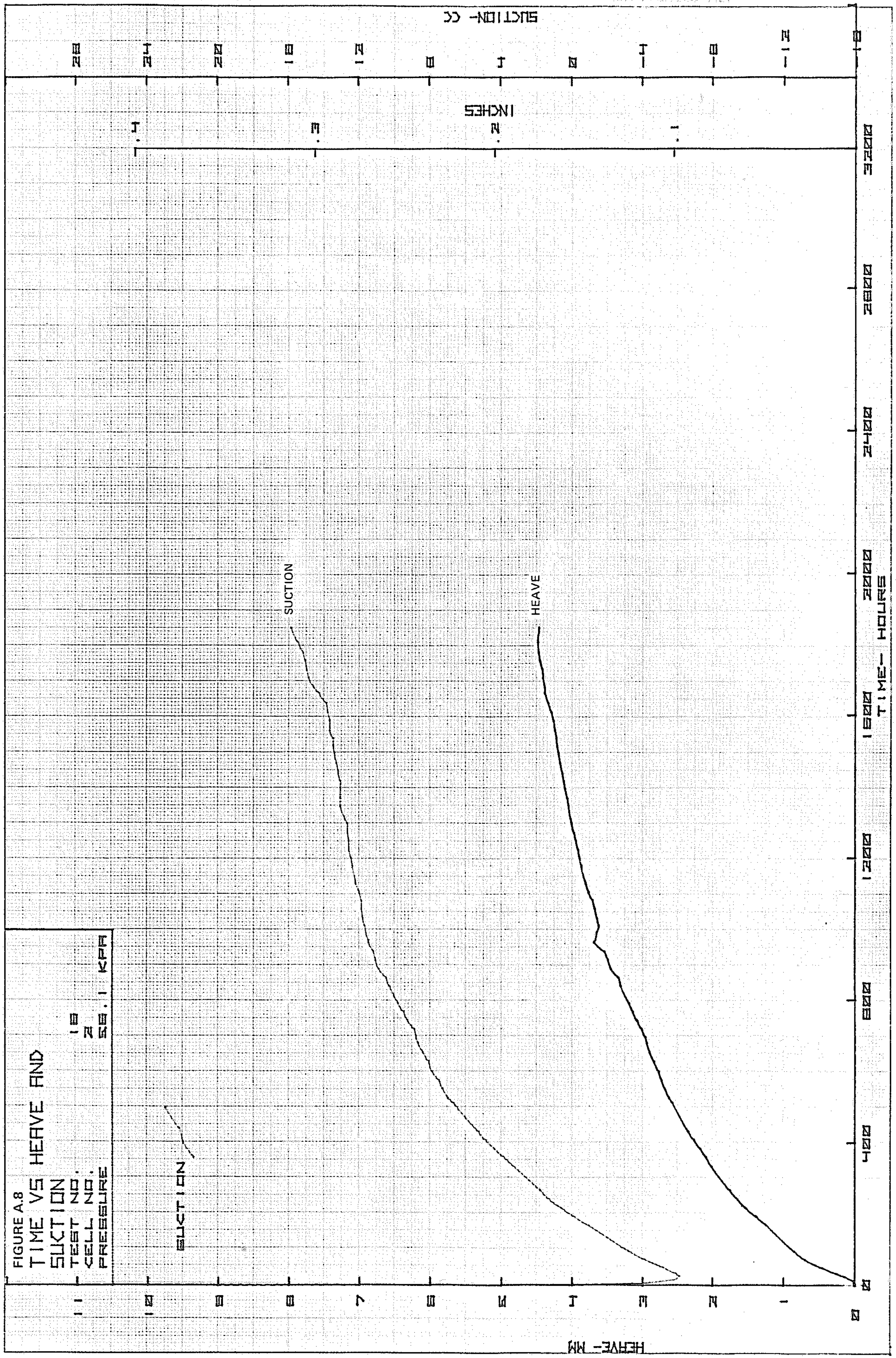


FIGURE A.8
TIME VS HEAVE AND SUCTION
TEST NO. 18
CELL NO. 2
PRESSURE 59.1 KPA

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

eba

3764 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

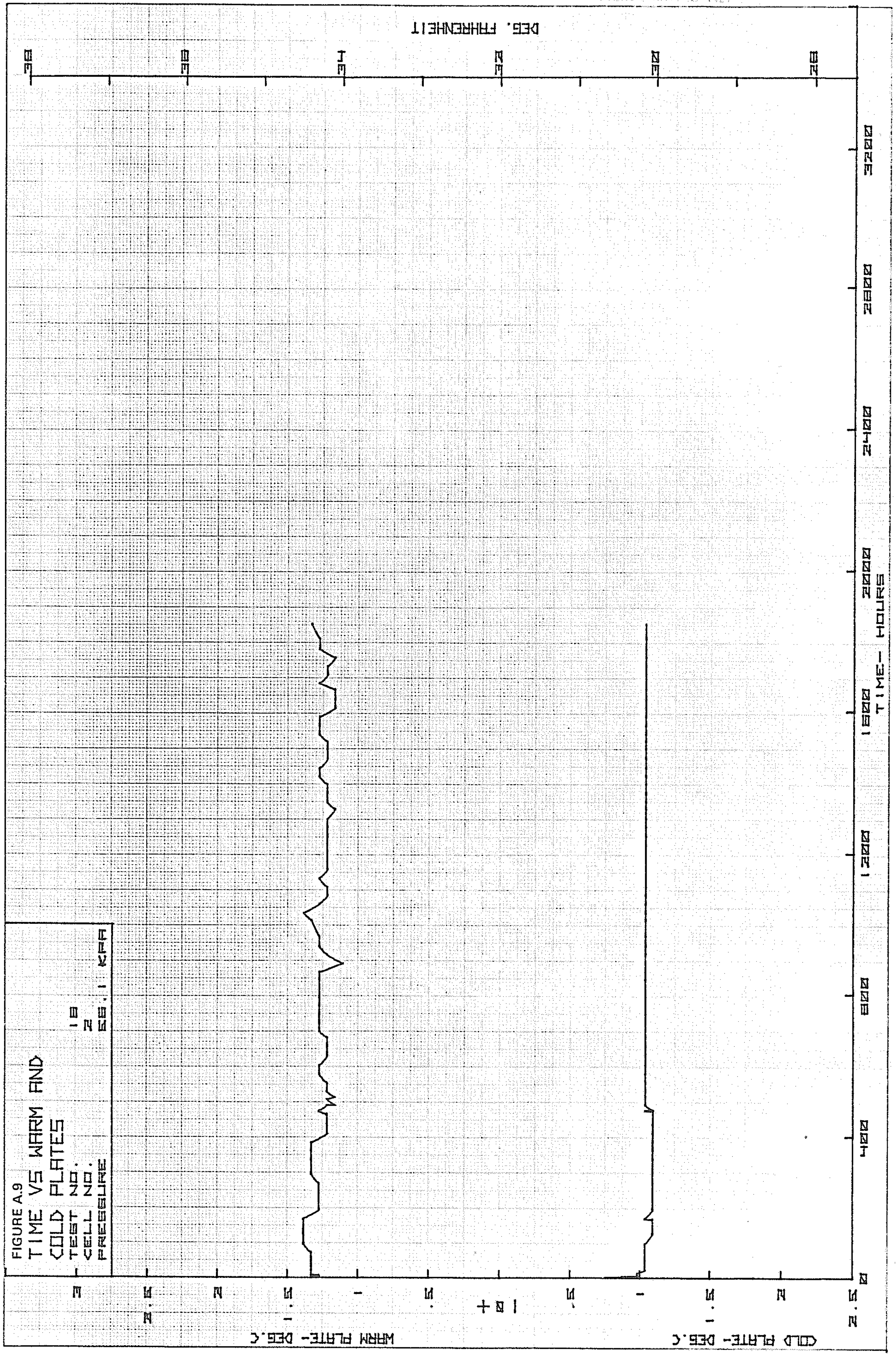


FIGURE A.9
TIME VS WARM AND COLD PLATES

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

1664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

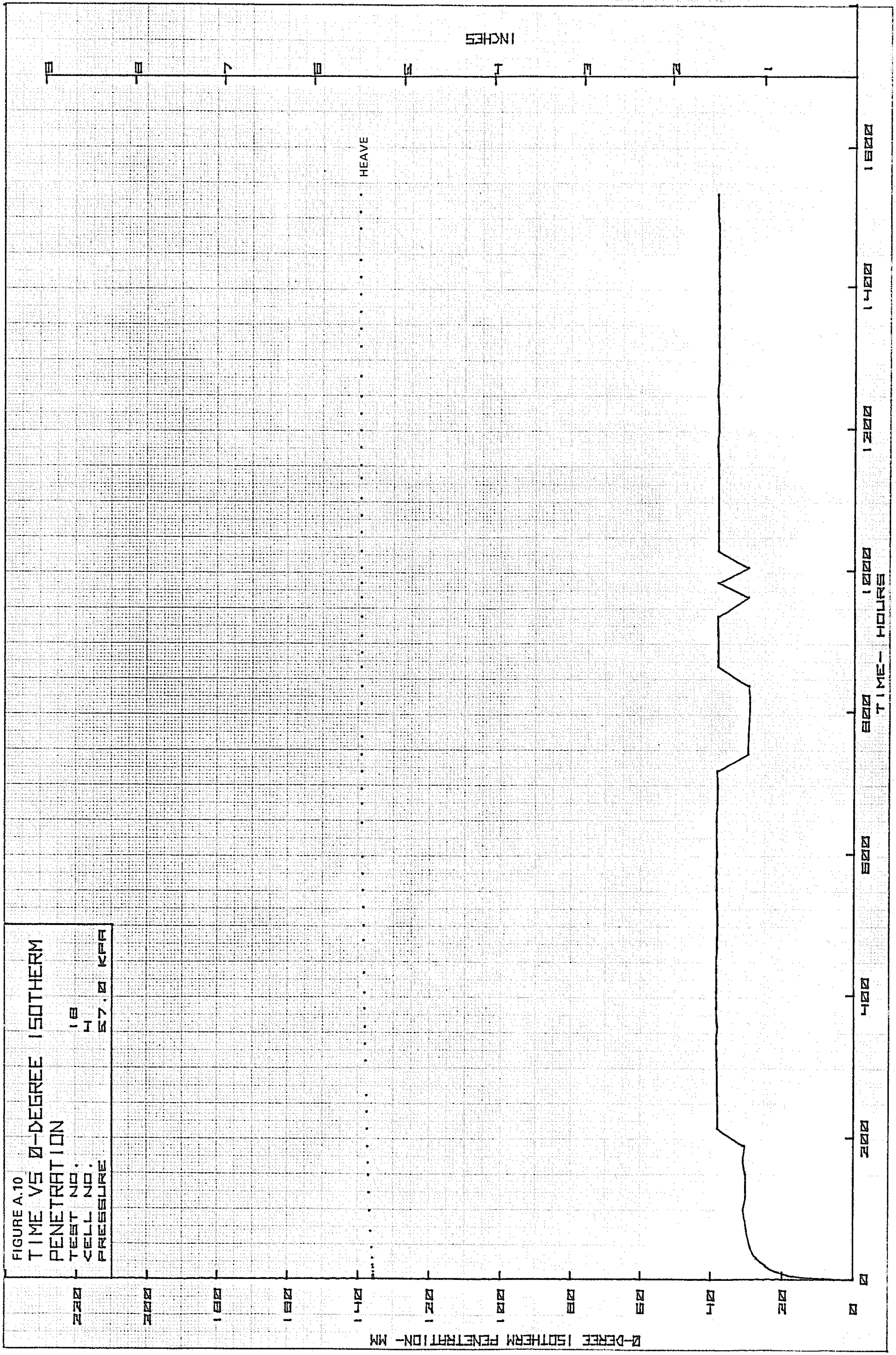


FIGURE A.10
TIME VS 0-DEGREE ISOTHERM PENETRATION
TEST NO. 18
CELL NO. 4
PRESSURE 57.0 KPA

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5684 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

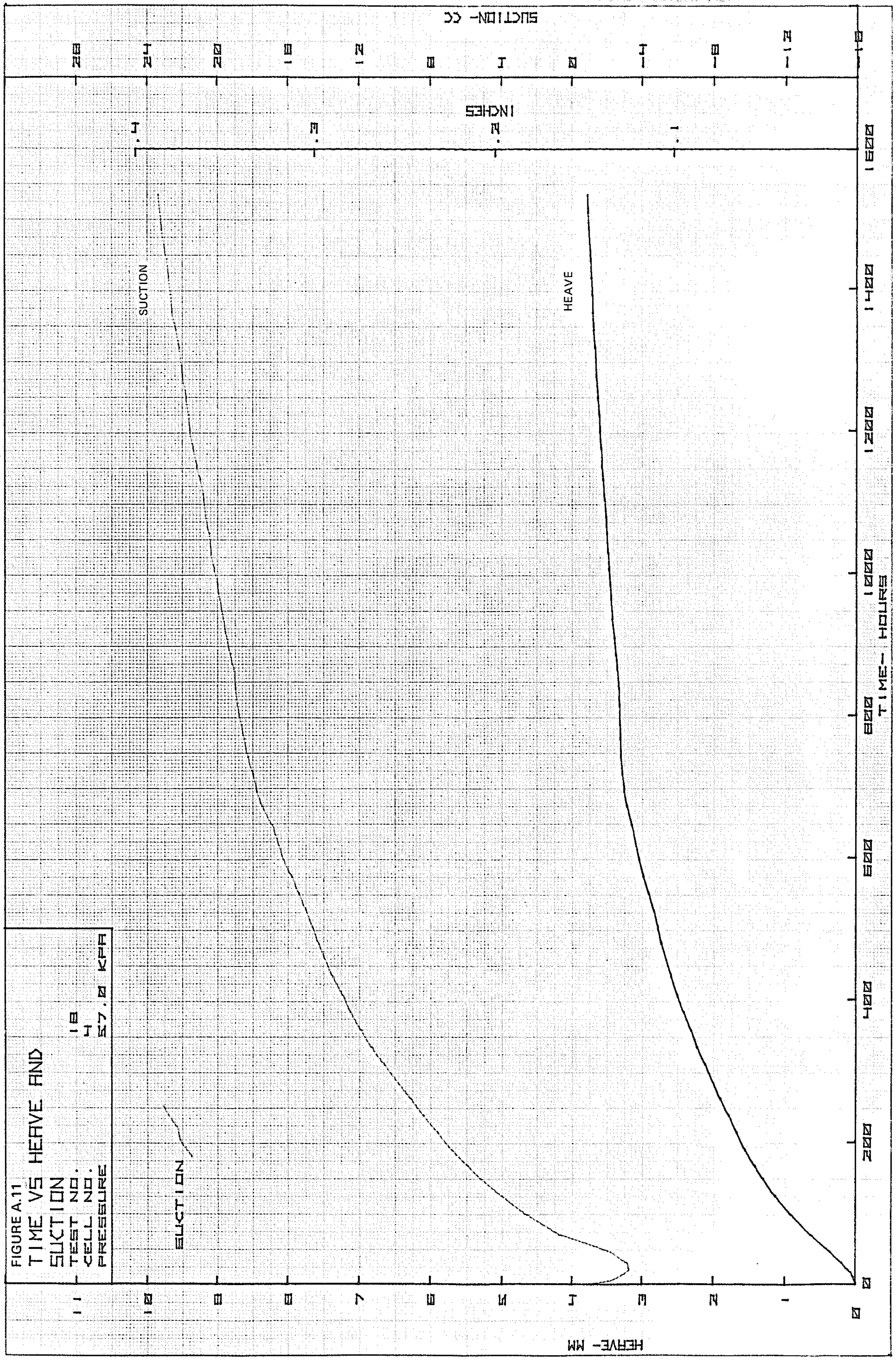


FIGURE A.11
TIME VS HEAVE AND SUCTION
TEST NO. 18
CELL NO. 4
PRESSURE 57.0 KPA

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

CALGARY, ALBERTA

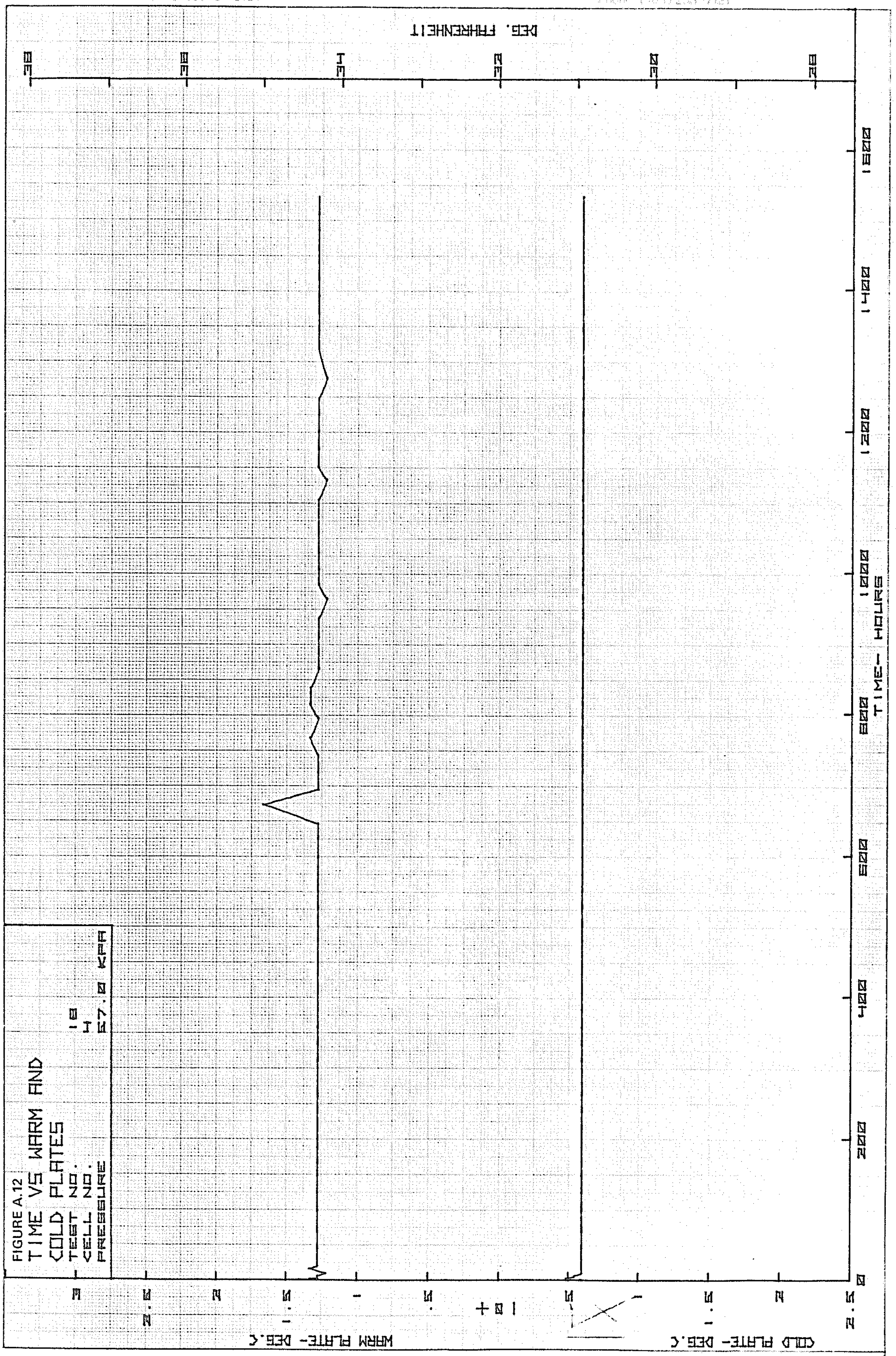


FIGURE A.12
TIME VS WARM AND
COLD PLATES
TEST NO. 18
CELL NO. 4
PRESSURE 67.0 KPA

EBA Engineering Consultants Ltd.

14535 - 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

PARTICLE - SIZE ANALYSIS OF SOILS

Project:

Project Number: 102-2558

Date Tested: 800109

Borehole Number:

Depth:

Soil Description:

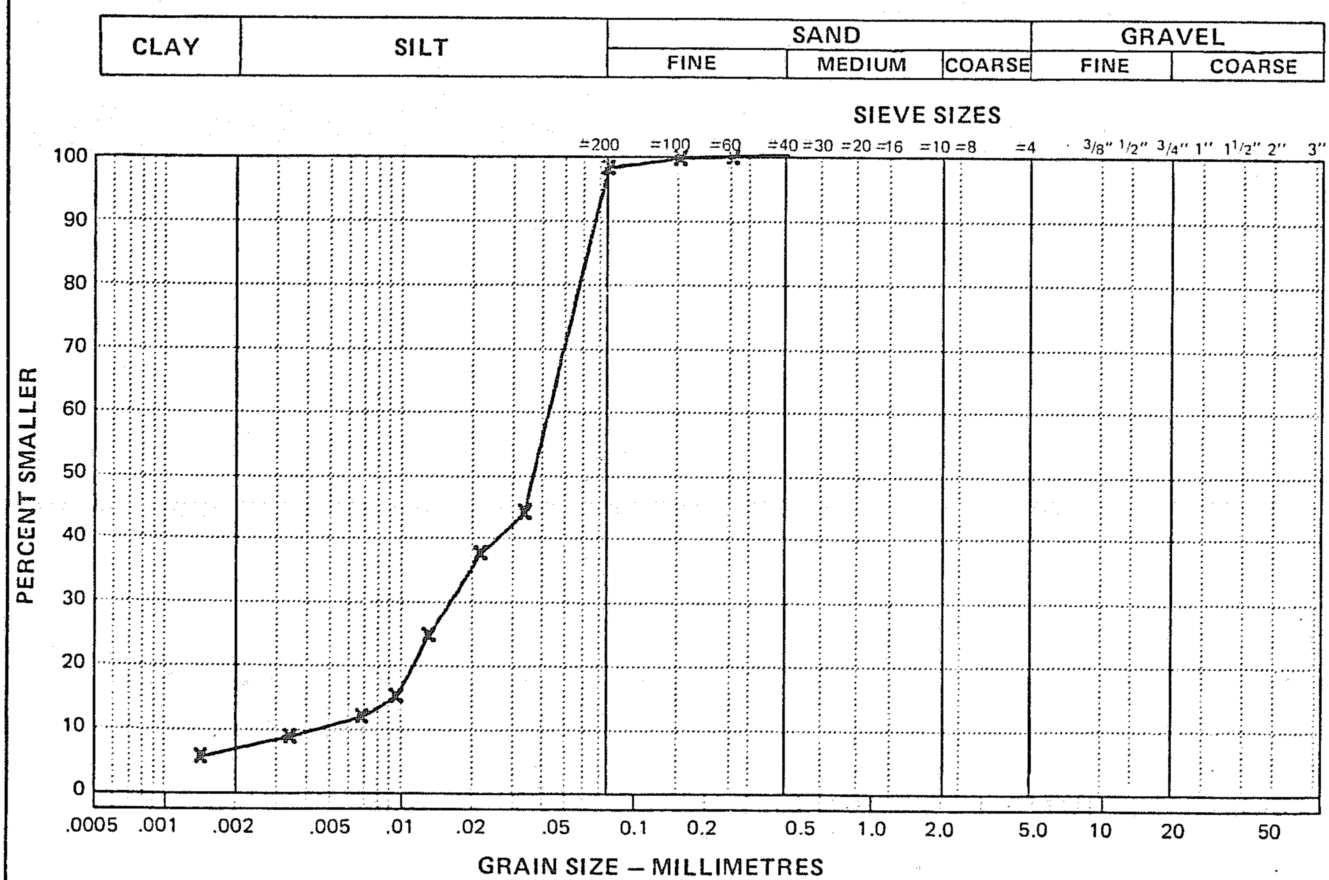
Cu:

Cc:

Natural Moisture Content: %

Remarks: FH 18
FROZEN PORTION

SIEVE	PERCENTAGE PASSING
3"	
2"	
1 1/2"	
1"	
3/4"	
3/8"	
No. 4	
No. 10	
No. 20	
No. 40	100.0
No. 60	99.8
No. 100	99.6
No. 200	98.2



Tested in accordance with ASTM D422 unless otherwise noted.

Figure A.13

EBA Engineering Consultants Ltd.

14535 – 118th AVENUE
EDMONTON, ALBERTA
Phone (403) 451-2121

5664 BURLEIGH CRES. S.E.
CALGARY, ALBERTA
Phone (403) 253-7121

PARTICLE - SIZE ANALYSIS OF SOILS

Project:

Project Number: 102-2658

Date Tested: 800109

Borehole Number:

Depth:

Soil Description:

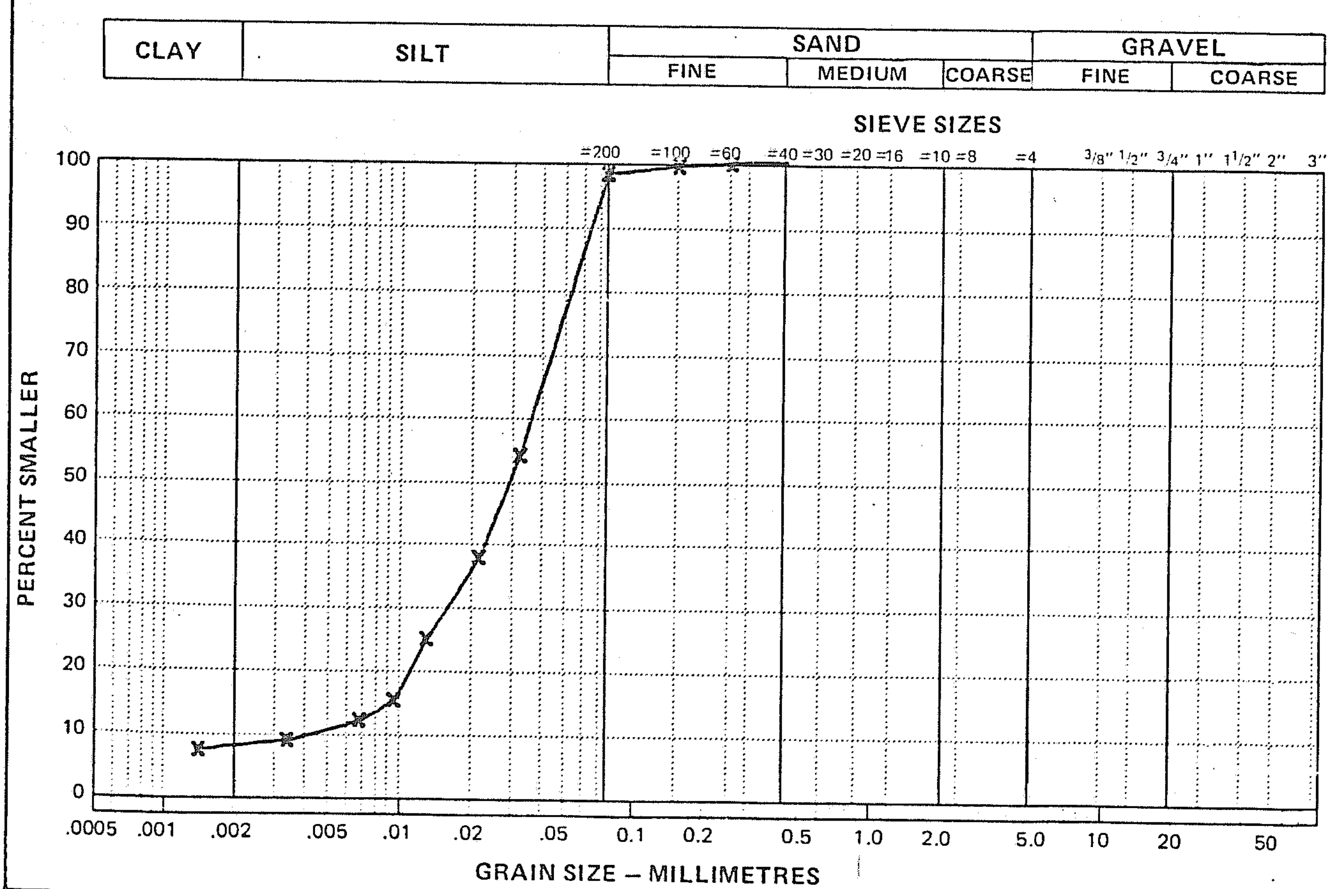
Cu:

Cc:

Natural Moisture Content: %

Remarks: FH 18
UNFROZEN BOTTOM

SIEVE	PERCENTAGE PASSING
3"	
2"	
1 1/2"	
1"	
3/4"	
3/8"	
No. 4	
No. 10	
No. 20	
No. 40	100.0
No. 60	99.8
No. 100	99.4
No. 200	98.2



Tested in accordance with ASTM D422 unless otherwise noted.

Figure A.14