PREVENTATIVE FROST HEAVE DESIGN EVALUATION

REVISION NO. 1

for

THE ALASKA SEGMENT OF THE

ALASKA NATURAL GAS TRANSPORTATION SYSTEM

CONTRACT NO. 4780-9-K089

DOC. IDENT. NO.: H-GBJV/PMC-1001

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

APRIL 1981

GULF INTERSTATE ENGINEERING COMPANY — MICHAEL BAKER, JR., INC.
A Joint Venture

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PREFACE

The Preventative Frost Heave Design Evaluation report, Revision No. 1 (H-GBJV/PMC-1001), supersedes the Preventative Frost Heave Design Evaluation report, dated February 1981 (H-GBJV/PMC-0747).

PREVENTATIVE FROST HEAVE DESIGN EVALUATION

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PREVENTATIVE FROST HEAVE DESIGN EVALUATION

1.0 INTRODUCTION

The Alaska Segment of the Alaska Natural Gas Transportation System (ANGTS) will be operated in a chilled state i.e., below 32°F and buried both in frozen and unfrozen soils. In areas where unfrozen frost susceptible soils are encountered along the pipeline alignment, the potential for frost heave due to frost action below the pipe exists. Frost heave will occur if the following three conditions exist simultaneously: 1) below freezing temperatures below the pipe, 2) unfrozen frost susceptible soils below the pipe, and 3) water available for migration to the freezing front. If these conditions are present, the water migrating (due to attractive forces) to the freezing front, through the frost susceptible soils, can cause the formation of ice lenses. The formation of ice lenses will expand the soil beneath the pipe and upwardly displace the buried pipeline. The amount of pipe displacement will depend on the type of soil, water availability, penetration of the frost front into the frost susceptible soil, the resisting forces acting on the pipe (i.e., the backfill uplift resistance, weight of the pipe and soil above the pipe, the stiffness of the pipe and/or frost bulb) and the effect of these resisting forces on the ice lense formation.

The Preventative Frost Heave Design Evaluation investigates and assesses the technical aspects and concerns of a preventative frost heave design[1] as it applies to the unfrozen frost-susceptible soil segments along the pipeline right-of-way. The following modes were developed and have been thermally evaluated preliminarily to investigate their ability to preclude or minimize frost penetration in the underlying soil: embankment, semi-embankment, shallow burial, normal burial, normal burial with heat tracing and normal burial with snow accumulated on top of the ditch. The preliminary thermal studies have been made conservatively, ignoring the existence of an organic surface layer, and assuming a constant surface temperature of 32.1°F and a soil temperature of 32.1°F at start-up. The results of these studies are presented in APPENDICES A and B.

1 A preventative frost heave design is defined as a design which impedes the occurrence of differential movement in a buried chilled pipeline by not allowing the frost bulb to penetrate into the surrounding frost-susceptible material.

The embankment and normal burial modes, which represent aboveground and below ground configurations, were selected for further analysis using revised criteria which included an organic surface layer, a pre-construction thermal history, and the effects of construction disturbance on the surface organic layer. The analyses based on these criteria yielded pre-startup soil temperatures greater than 32.1°F at the pipe bottom for both modes. The results of the geothermal simulations based on these criteria indicate that burying the pipeline in a ditch with circular insulation on the pipe and overexcavating some frost susceptible soils below the bottom of the pipe and replacing them with non-frost susceptible soil will prevent frost heave. The results of these studies are presented in this report.

1.1 SCOPE

The scope of work for this evaluation of preventative frost heave design specifically encompassed:

- Review and analysis of existing project reports: e.g. thermal studies and design modes
- Development of design philosophy and criteria
- Analysis and preparation of climatological and soils data for geothermal study
- Review of measures for Preventative Heave Design
- Development of modes for Preventative Heave Design
- Geothermal analysis of preliminary and selected modes
- Evaluation of the results of the geothermal analysis of selected modes
- Conclusions

1.2 METHODOLOGY

A two-dimensional thermal model, EPR[2] developed by Exxon Production Research Company, was used to investigate and evaluate the preventative heave modes. This program simulated heat conduction with a change of state

[2] EPR is the 2-D finite element computer program, "General-Purpose Permafrost Simulator," developed by Exxon Production Research Company.

for a variety of boundary conditions. The heat of fusion, the heat capacity and thermal conductivity changes, caused by thawing and freezing were taken into account in this model. The specific input parameters used in the simulation for the preliminary modes are presented in APPENDIX B. Specific input parameters for the selected modes, embankment and normal burial, are presented in SECTION 3.0.

2.0 REVIEW OF MEASURES TO REDUCE FROST HEAVE

The following preventative measures could be employed to minimize frost penetration in frost susceptible soils and to reduce the effects of ground frost heaving forces acting on the pipeline.

1) Insulating the buried pipeline and/or the ditch to reduce the heat flux through the frost-susceptible soil.
2) Overexcavating the frost-susceptible soil beneath the buried pipeline and replacing it with non-frost susceptible soils.
3) Insulating the ground surface above the pipe by snow accumulation. (The heat flux between air and the ground would be minimized during the cold winter months; the soil would retain more of the heat gained during the summer, thus limiting frost bulb growth.)
4) Elevating the pipeline aboveground, placing it in an embankment. (Elevating the pipe would reduce or eliminate the heat extracted from the ground.)
5) Elevating the pipeline aboveground, placing it on overhead supports. (Elevating the pipe would eliminate the heat extracted from the ground.)
6) Heat tracing the soil underneath the pipe to counteract frost penetration.
7) Combining compatible concepts presented above.

Measures 1, 2, 3, 4, and 6 were thermally analyzed as part of the evaluation of the preliminary modes and the results of the analyses are presented in APPENDIX A.

Other measures were reviewed in this study, but were not analyzed, such as prefreezing, and application of additives and/or densification of native soils. Some of these measures were considered impractical for geothermal and/or construction reasons, and were not evaluated further.

3.0 ANALYSES OF SELECTED MODES

Geothermal data were the most important parameters used to select the embankment (FIGURE 3-1) and the normal burial (FIGURE 3-2) modes for the Preventative Frost Heave Design. Meteorological data, thermal aspects of the soils, preconstruction history and organic layer were used to evaluate further the selected modes.

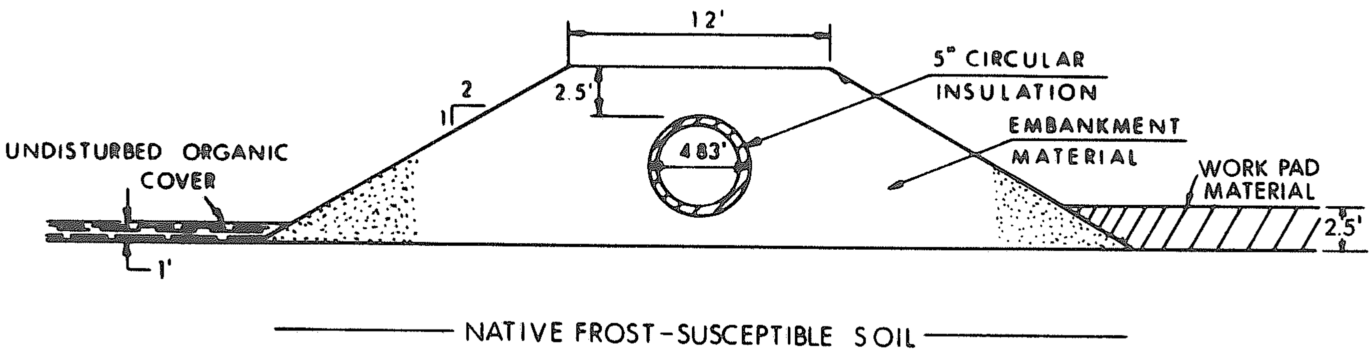
Specific geotechnical factors, such as terrain stability, berm stability, grading, erosion control, and surface and groundwater effects were considered in the development of the these modes, but were not analyzed in detail.

In this study, pipe stress analysis is reduced to conventional methods because the prevention of frost heave precludes pipe stress caused by frost heave forces.

The technical factors and inputs required for the geothermal analyses are listed below.

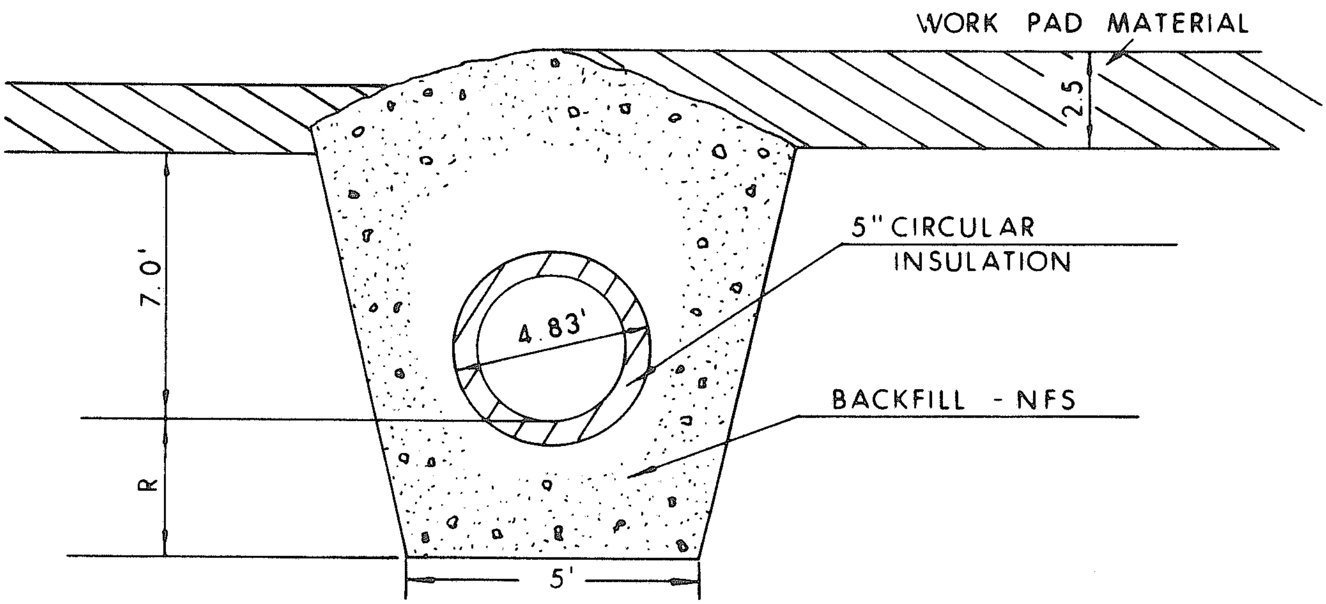
3.1 EPR GEOTHERMAL MODEL

The thermal simulator developed by Exxon Production Research (EPR) was used to predict frost depth penetrations for the selected modes. The following factors were included in the geothermal assessment of each of the modes where applicable: gas temperature, soil thermal properties, climatological data, initial soil and surface ground temperatures, construction modes and geometry, pipe diameter, depth of burial, insulation properties and geometry and pipeline operating life. A detailed discussion of the geothermal evaluation method, input parameters and results of the evaluations is presented in the subsequent sections.



EMBANKMENT AND SOIL PROFILE

FIGURE 3-1



NATIVE FROST SUSCEPTIBLE SOIL

NORMAL
BURIAL AND SOIL PROFILE

FIGURE 3-2

3.2 INPUT PARAMETERS

A generalized soils stratigraphy and meteorological data base was used in the thermal evaluation of the selected modes. As route soil geotechnical and geothermal data become available, the analyses will be updated on a site-specific basis.

3.2.1 Soil Data Used For The Embankment and Normal Burial Modes

A native frost-susceptible soil and an undisturbed organic surface layer were used for the one-dimensional initial calibrations. The same native soil, and an assumed embankment/workpad/backfill material, were used for the final simulations. Soil and backfill thermal and index properties are presented in TABLES 3-1 and 3-2. All analyses assumed the organic layer was to be stripped prior to placing the workpad or embankment material. The soil materials used in the thermal simulations can be generally described as follows:

- The native soil was a nearly saturated, mixed coarse and fine-grained frost-susceptible material
- The backfill was an unsaturated non-frost susceptible granular material
- Both the embankment and workpad materials were unsaturated, granular materials
- The undisturbed surface organic layer was wet, but unsaturated

3.2.2 Meteorological Data

EPR runs for the embankment and buried modes were made with an adjusted full surface heat balance, i.e., meteorological data input with an organic cover and a pre-construction history with four computational time increments per simulation month.

TABLE 3-1

SOIL THERMAL PROPERTIES USED FOR ONE-DIMENSIONAL INITIAL CALIBRATIONS

	W (% dry wt)	γ_d (pcf)	S (%)	Kf (Btu/ft-hr-°F)	Ku (Btu/ft-hr-°F)	Cf (Btu/ft^3-°F)	Cu (Btu/ft^3-°F)	HFUS* (Btu/ft^3)	ALP (°F)	GAM
UNDISTURBED ORGANICS**	175%	20	71%	0.4	0.2	27.0	44.0	5640	0.1	1.0
NATIVE SILTY SANDY GRAVEL	19%	110	96%	2.1	1.4	28.0	39.0	3000	0.3	1.0

* Latent heat varies as a function of temperature below 32°F. The listed values constitute the total extractable latent heat.

** The assumed thickness of the undisturbed organic/vegetated surface layer was 1.0 ft.

LEGEND

- W - initial moixture content
- γ_d - initial dry density
- S - initial degree of saturation
- K_f - thermal conductivity in frozen state
- K_u - thermal conductivity in unfrozen state
- C_f - specific heat in frozen state
- C_u - specific heat in unfrozen state
- HFUS - latent heat of fusion
- ALP - parameter which determines the shape of the curve of unfrozen moisture versus temperature
- GAM - the fraction of the moisture which freezes at temperatures below 32°F

TABLE 3-2

SOIL THERMAL PROPERTIES FOR MODE STUDIES*

	W (% dry wt)	Yd (pcf)	S (%)	Kf (Btu/ft-hr-°F)	Ku (Btu/ft-hr-°F)	Cf (Btu/ft^3-°F)	Cu (Btu/ft^3-°F)	HFUS* (Btu/ft^3)	ALP (°F)	GAM
NATIVE SILTY SANDY GRAVEL	19%	110	96%	2.1	1.4	28.0	39.0	3000	0.3	1.0
EMBANKMENT WORKPAD MATERIAL	8%	110	41%	1.0	1.1	22.0	27.0	1270	0.1	1.0
BACKFILL MATERIAL	13%	100	50%	1.1	1.0	22.0	29.0	1830	0.1	1.0

* See Legend in TABLE 3-1 for explanation of terms

** Latent heat varies as a function of temperature below 32°F. The listed values constitute the total extractable latent heat.

3.2.3 Initial Temperature Profiles

The effects of an organic surface layer and a probable construction history were considered in the simulations. The use of these conditions yielded a pre-startup soil temperature of 32.8°F and 35°F at the pipe bottom for the embankment and the normal burial modes, respectively. The higher temperatures occurred as the subsoils gradually warmed once the organic layer was removed during construction. The assumption that the entire organic layer will be removed during construction may not be applicable in some situations. Further studies will be performed to evaluate the effects of a compressed organic mat on the thermal regime of the soil.

3.3 INSULATION PROPERTIES USED FOR GEOTHERMAL ANALYSIS

The computer simulations of the selected modes were performed using circular insulation jacketing around the pipe. The insulation parameters are presented in TABLE 3-3.

3.4 STEP-BY-STEP GEOTHERMAL SIMULATION PROCESS

The thermal analyses consisted of a three-step sequence of computer simulations. First, the snow depth was adjusted from run to run until the average annual equilibrium temperature was 32.1°F, 8.0 feet below the surface of an undisturbed native organic surface layer (see FIGURE 3-3; TABLE 3-1 lists the associated thermal properties). The adjustment simulated conservatively cold non-permafrost pre-construction conditions that may exist along the alignment. Second, the climatic parameters determined during step 1, including snow depth, were input into a 2-year simulation of the pre-startup profile with a stripped organic layer (see FIGURES 3-1 and 3-2; TABLE 3-2 lists the associated thermal properties). During this simulation, the pipe was at ambient soil temperature. The 2-year simulation generated initial ground temperature conditions that could exist at the time of pipe start-up. Third, the start-up was simulated using the ground temperature distribution obtained during step 2 and using the expected operating gas temperature.

TABLE 3-3

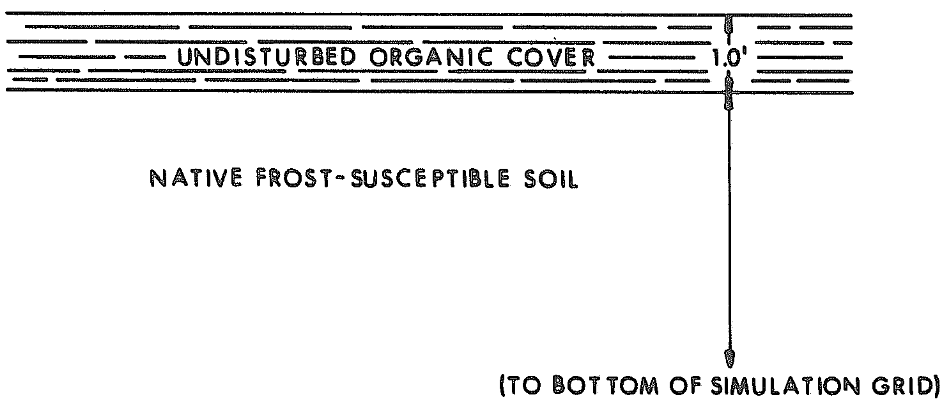
INSULATION THERMAL PROPERTIES*

	W (% dry wt)	Yd (pcf)	S (%)	Kf (Btu/ft-hr-°F)	Ku (Btu/ft-hr-°F)	Cf (Btu/ft^3-°F)	Cu (Btu/ft^3-°F)	HFUS** (Btu/ft^3)	ALP (°F)	GAM
CIRCULAR PIPE INSULATION (polyurethane foam)	78%***	2.0	-	0.015	0.015	2.4	3.2	225	0.1	1.0

* See legend in TABLE 3-1 for explanation of terms.

** The EPR model requires input for the total extractable latent heat (HFUS) and for the parameters that govern the extraction of this latent heat is a function of temperature below 32.0°F (ALP and GAM).

*** Calculated from the following: W (% dry wt) = (W % vol)/(γd/γw). Water absorbtion (w = 2.5% vol) for polyurethane foam - See CRREL Special Report 76-3, "THERMOINSULATIVE MEDIA WITHIN EMBANKMENTS ON PERENNIALLY FROZEN SOIL." Richard L. Berg, May 1976, Appendix B, Page 140.



UNDISTURBED SOIL PROFILE

FIGURE 3 - 3

The results of the analyses indicated the frost depth below the pipe bottom reached equilibrium within the first 5 years of simulation i.e., no further penetration of the frost bulb was observed. Consequently, this study considered only 5 years of pipeline operation.

3.5 RESULTS OF GEOTHERMAL SIMULATIONS FOR THE SELECTED MODES

The results of the geothermal simulations of the embankment and normal burial pipeline modes are described in the following paragraphs.

3.5.1 Embankment Mode

A pipeline jacketed with 5-inch circular insulation installed in an embankment was analyzed. (See FIGURE 3-1.) Five years of operation were geothermally simulated for a gas temperature of 10°F. The frost bulb penetration below the pipe bottom versus time for this configuration is shown in FIGURES 3-4 and 3-5.

The results of the analysis indicate, as shown in FIGURES 3-4 and 3-5, that the depth of frost penetration in the embankment for a gas temperature of 10°F never exceeded 3.8 feet below the pipe bottom.

3.5.2 Normal Burial Mode

A pipeline with 5-inch circular insulation placed in a ditch with 2.5 feet of cover was analyzed to compare it with the pipeline with 5-inch circular insulation buried in the embankment. Five years of operation were geothermally simulated for a gas temperature of 10°F. The frost bulb penetration below the pipe bottom versus time for this configuration is shown in FIGURES 3-6 and 3-7.

As shown on FIGURES 3-6 and 3-7, the frost depth below the pipe bottom for 10°F gas temperature does not exceed 1.1 feet. This result shows that, based on the climatological assumptions made, 5-inch circular insulation on a pipeline buried in a ditch excavated to a depth of about 9 feet will prevent frost heave.

FROST PENETRATION VS. TIME FOR EMBANKMENT (5 YEARS)

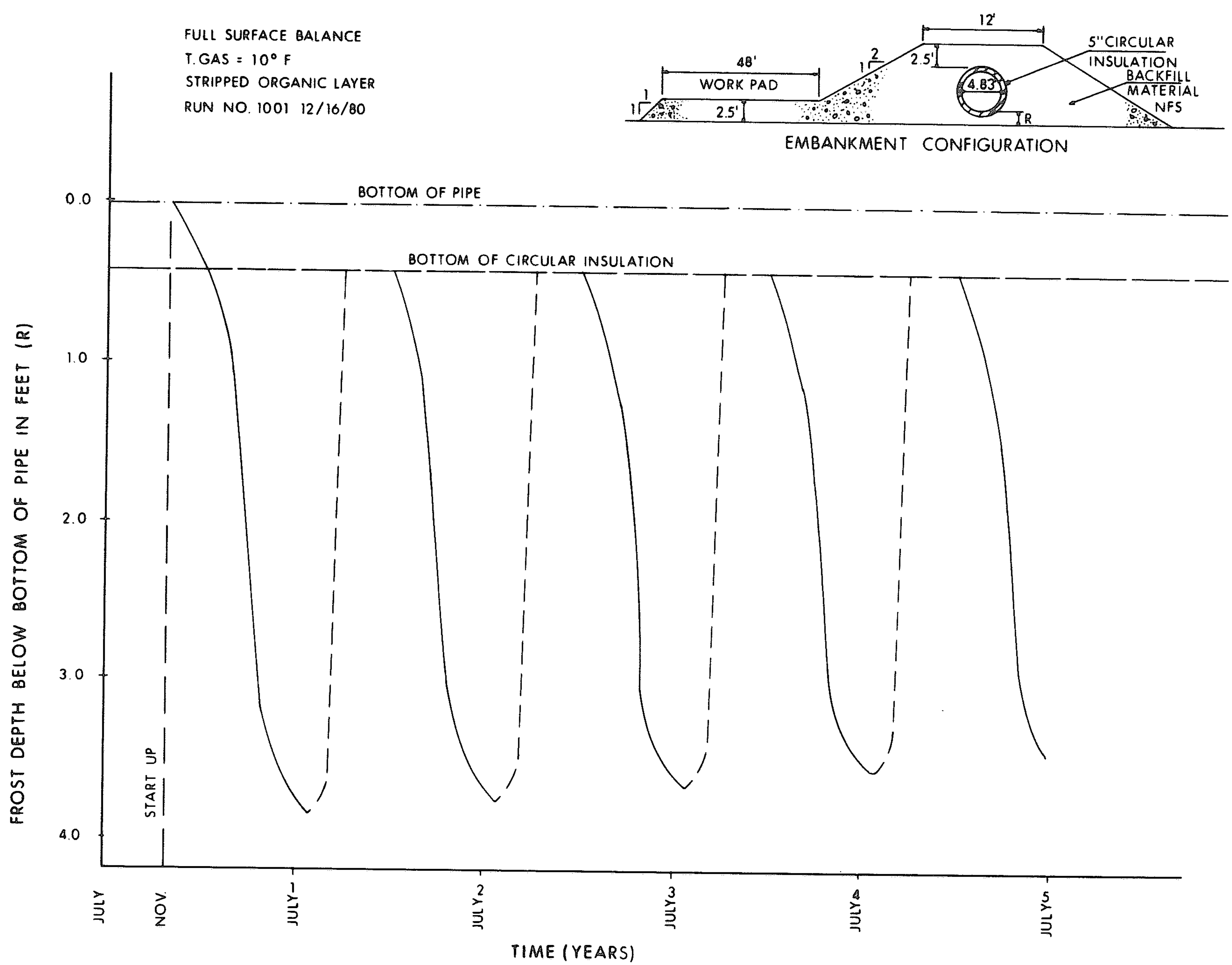


FIGURE 3-4

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MAXIMUM FROST DEPTH BELOW THE PIPE BOTTOM OCCURRING IN AUGUST OF EACH YEAR

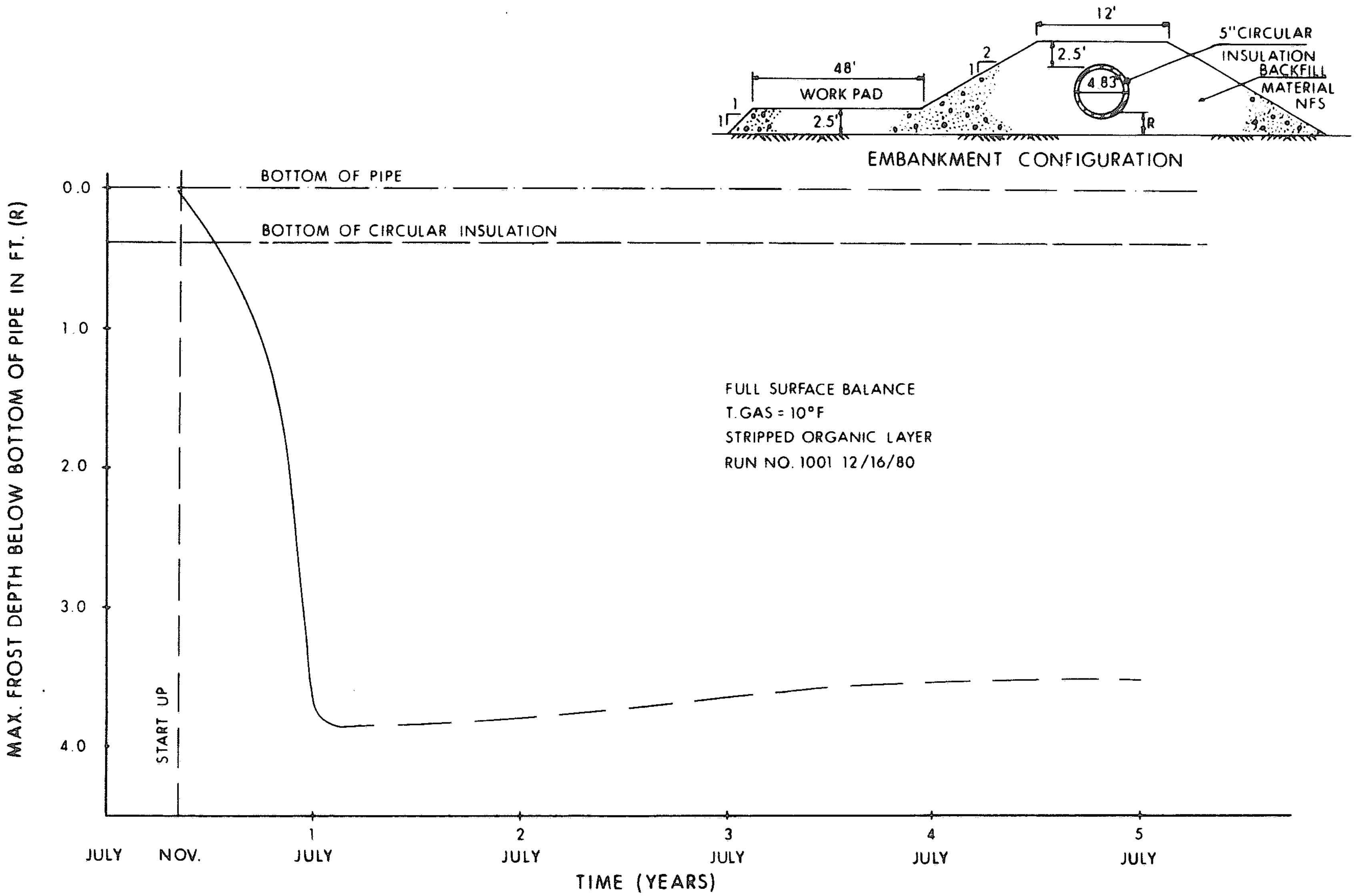

FIGURE 3-5

REV.-1

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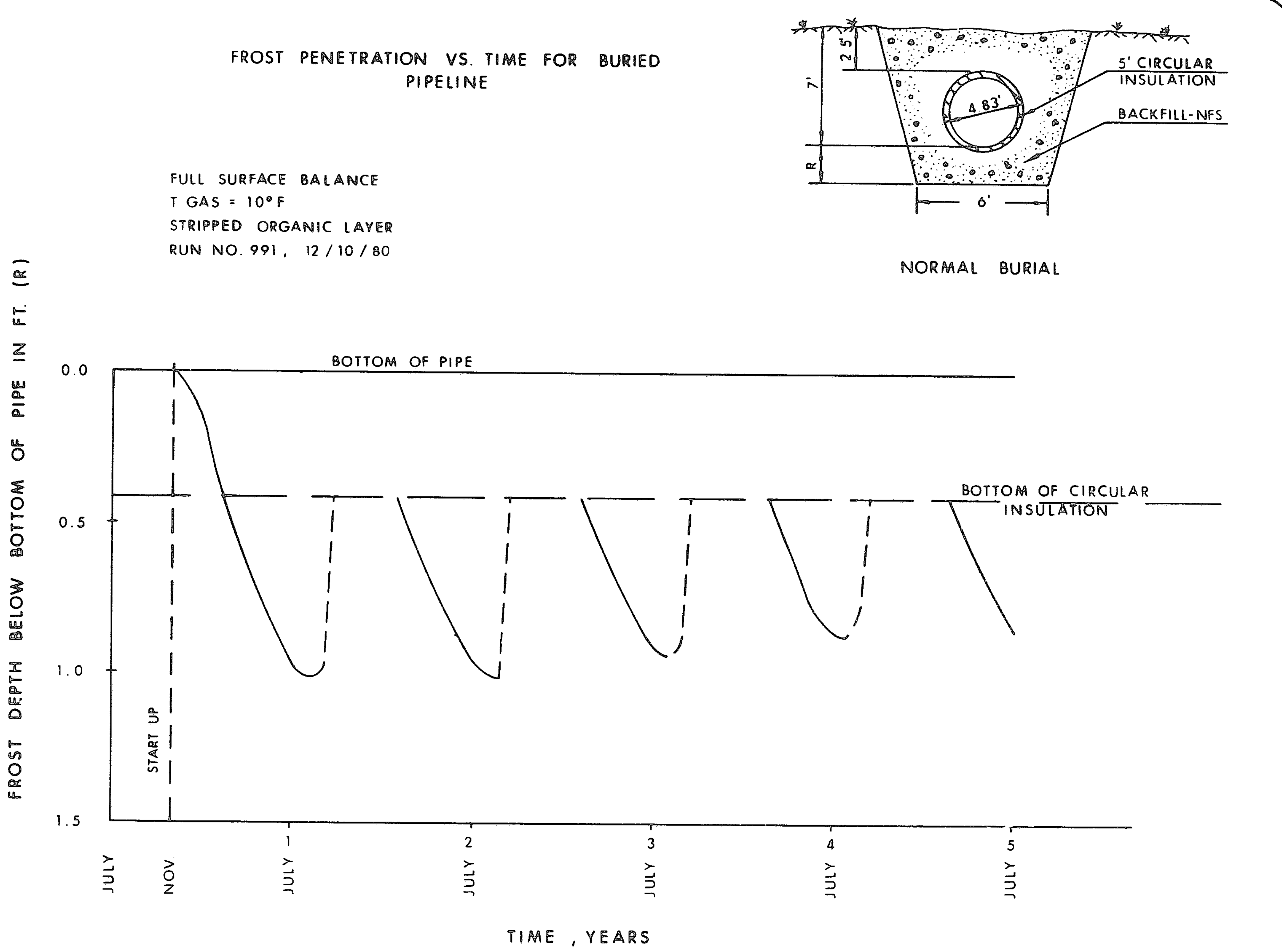

FROST PENETRATION VS. TIME FOR BURIED PIPELINE
FULL SURFACE BALANCE
T GAS = 10°F
STRIPPED ORGANIC LAYER
RUN NO. 991, 12 / 10 / 80
2.5'
7'
R
4.83'
6'
5' CIRCULAR INSULATION
BACKFILL-NFS
NORMAL BURIAL
BOTTOM OF PIPE
BOTTOM OF CIRCULAR INSULATION
START UP
FROST DEPTH BELOW BOTTOM OF PIPE IN FT. (R)
0.0
0.5
1.0
1.5
1
2
3
4
5
JULY
NOV.
JULY
JULY
JULY
JULY
JULY
TIME , YEARS

FIGURE 3-6

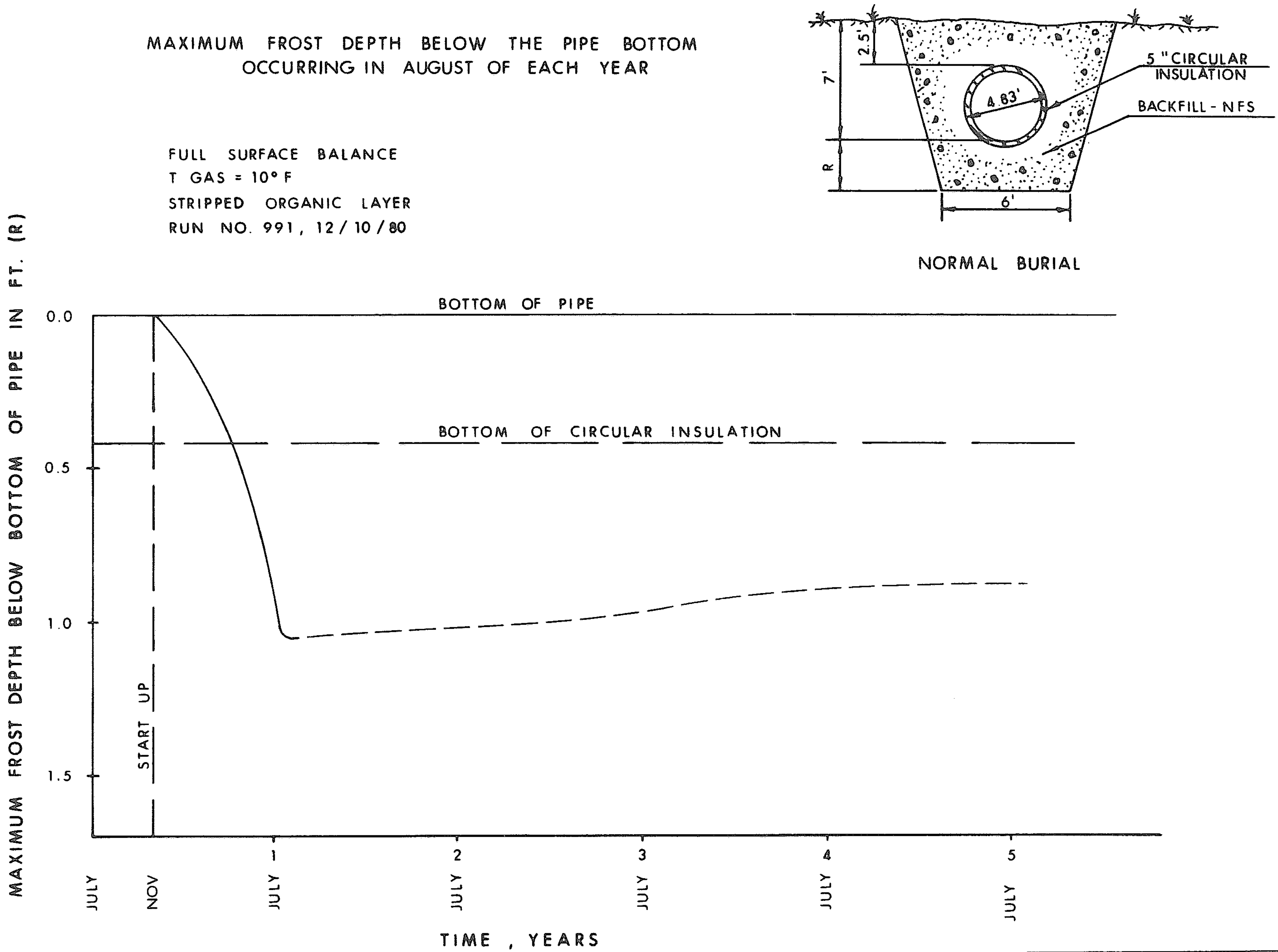

FIGURE 3-7

REV.-1

GG-07-A-010

3.5.3 Comparison and Application of Results

The results of geothermal analyses, based on the climatological assumption made for this evaluation, demonstrate that 5-inch circular insulation around the pipeline, placed in an embankment or buried in unfrozen ground, having an initial (pre-construction) soil temperature of 32.1°F, can be used to prevent frost heave. However, the embankment mode would present several disadvantages when compared to the normal burial mode, including:

- An additional 3.3 feet of non-frost susceptible material between the pipe bottom and the original ground level.
- More complicated construction schedule, logistics and additional equipment requirements for pre-pipe laying activities.
- Possible barrier for animal crossings.
- Substantial additional civil work for cross drainage control.
- Additional workpad material to construct the embankment.
- Potential embankment instability on steep slopes.

The application of these modes on a mile-by-mile basis would require consideration of geotechnical aspects, as well as incorporation of new gas temperature and climatological data as they become available.

3.6 NORMAL BURIAL WITH REDUCED INSULATION THICKNESS

The comparison between the embankment and the normal burial modes using 5-inch of insulation around the pipe, indicated that the normal burial mode was more effective in reducing the penetration of the frost bulb in the underlying soils. Based on this, further studies were made with reduced thicknesses of insulation around the pipe buried in a normal burial mode configuration. The pipe was thermally analyzed under the same climatological conditions as before, using 2, 3, and 4 inches of insulation around the pipe. The results of these analyses are presented in FIGURE 3-8, which indicates the progression of the frost depth below the bottom of pipe as a function of time. The results of the analyses performed using 5 inches of insulation are also included on the figure for comparison purposes. It is observed that the frost penetration below the bottom of the pipe ranges from 1.1 feet to 3.3 feet under a pipe having 5 inches and 2 inches of insulation, respectively.

4.0 CONCLUSIONS

The following conclusions, based on the climatological assumptions discussed in SECTION 3.2, may be drawn from the geothermal analyses performed for the embankment and normal burial modes.

1. Normal burial with circular insulation and some overexcavation of frost susceptible soil below the pipe may be able to prevent frost heave.
2. Further analyses should be performed to determine the effects of:
   - Other climates with less snow
   - Compression, in lieu of stripping, of the organic mat during construction
   - Different thicknesses of the organic layer
   - No snow on the top of the workpad

APPENDICES

APPENDICES

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APPENDICES (Continued)

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APPENDIX A

RESULTS OF GEOTHERMAL SIMULATIONS FOR PRELIMINARY MODES

APPENDIX A

RESULTS OF GEOTHERMAL SIMULATIONS FOR PRELIMINARY MODES

Shallow burial (and semi-embankment), normal burial and heat tracing modes were studied for a buried chilled gas pipeline at the constant surface temperature of 32.1°F.* Input parameters used for the preliminary mode simulations are as presented in APPENDIX B.

The results of the analysis of the preliminary modes and various insulation configurations are described in detail in the following paragraphs. The embankment mode was not analyzed using the constant surface temperature because it was not applicable to this mode. The data for full surface heat balance was applied to the embankment as they became available. The results of this analysis are discussed in SECTION 3.0 of the report.

1. Shallow Burial (and Semi-Embankment**)

   A pipeline, with six inches of circular insulation and 8-inch thick x 8-foot wide boardstock insulation placed six inches below the bottom of the insulated pipe, was geothermally analyzed for the following modes: a) shallow burial, i.e., pipe installed in a shallow ditch with the top of pipe at ground surface and with a 2.5-foot high berm constructed above the pipe; and b) normal burial, i.e., pipe installed in normal depth ditch without a berm above ground level.

   Computer simulations compared the predicted frost penetration rates and depths for the shallow burial and normal burial configurations described below. The frost penetration depths after 25 years for these two simulations were, 8.2

* Constant surface temperature of 32.1°F had a significant effect on the results of the preliminary study and yielded an extremely conservative Preventative Heave Design.

** Semi-embankment, i.e., a pipe installed in a shallow ditch to the pipe springline with a 2.5-foot high berm constructed over the top of the insulated pipe, was considered to be geothermally equivalent to the shallow burial described above, if the thermal properties of the embankment and the native soil were the same. This mode is, consequently, considered within the discussion of the shallow burial.

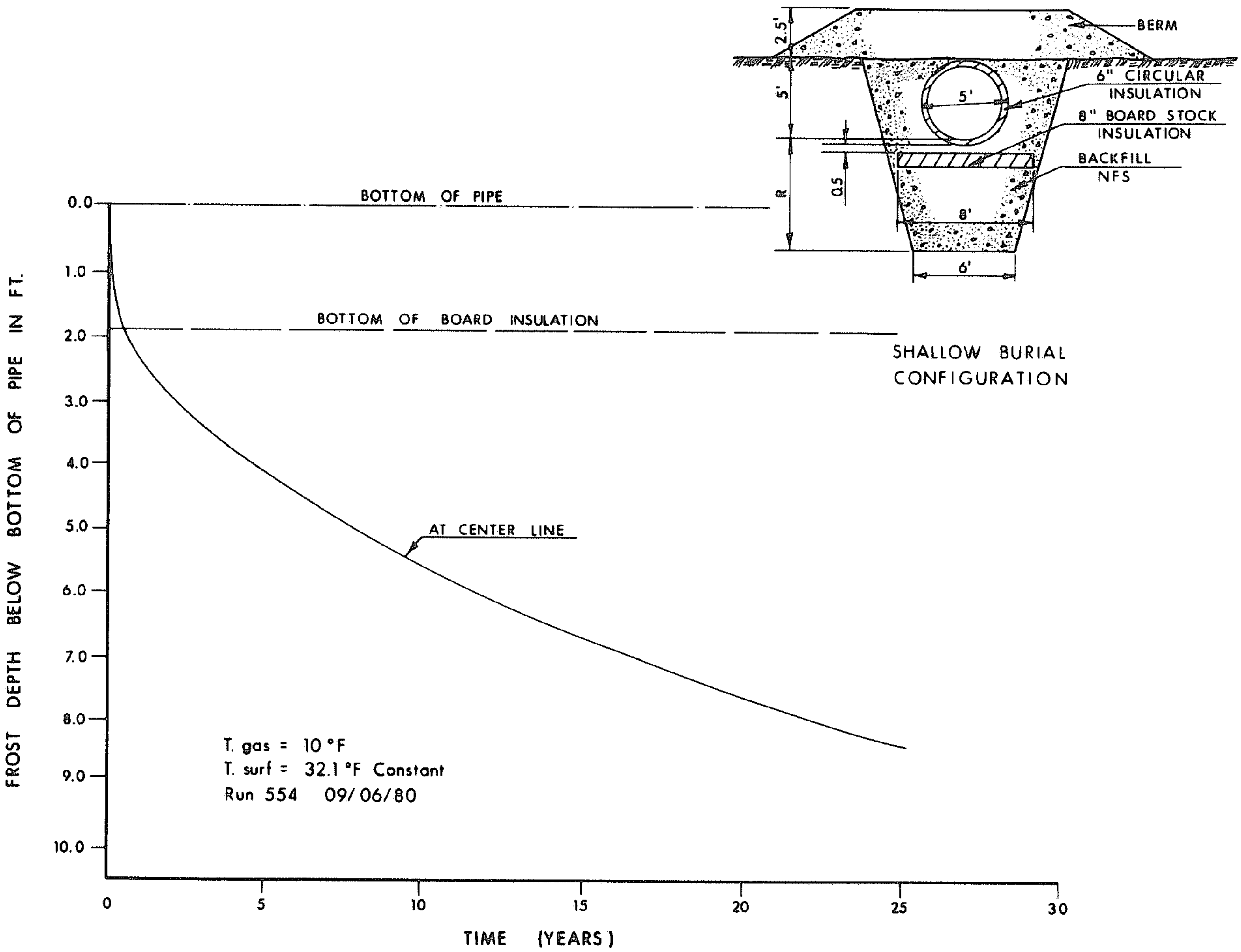
and 8.5 feet, respectively, using 8-inch boardstock insulation (see FIGURES A-1 and A-2). The results, for all practical purposes, were the same. Subsequent computer simulations were similarly performed for a buried pipe. The results of the buried pipe analysis, regarding frost penetration, can be applied directly to the shallow burial and semi-embankment configurations, if the same climatic conditions are assumed.

2. Normal Burial

Three insulation configurations were considered for the normal burial mode. A pipe with six inches of circular insulation was assessed using: a) 8-foot wide x 12-inch-thick boardstock insulation placed six inches below the pipe; b) box insulation (8-foot x 8-foot) with side and bottom insulation 12 inches thick; and, c) a foam module insulation.

The effectiveness of the boardstock was evaluated by comparing the frost penetration under circularly insulated pipe with boardstock, circularly insulated pipe and bare pipe. As indicated on FIGURE A-3, the depth of frost penetration is greatly reduced when an insulated pipe is combined with boardstock insulation. FIGURES A-4, A-5, A-6, and A-7 show frost penetration below the normal burial pipe mode with boardstock insulation for 10, 15, 20 and 25°F gas temperatures at both the centerline and 5 feet from the centerline. The frost front moved down more rapidly 5 feet from the centerline than below the centerline, during the first 10 years.

Comparative studies, similar to those done for boardstock insulation, were conducted for insulated pipe with box insulation. Computer runs indicated that, with 10°F gas temperature and 5 years of operation, the box insulation mode greatly reduced the frost penetration depth (3.1 feet) when compared to bare pipe (26.0 feet) and to the pipe with 6 inches of circular insulation (5.9 feet). During the analysis, the predicted amount of frost depth below the pipe centerline was reduced, and the box insulation did not exhibit greater predicted frost depths 5 feet from the pipe centerline as the boardstock insulation did. FIGURES A-8, A-9 and A-10 show frost penetration below the pipe bottom for the box insulation configuration for 10, 15 and 20°F gas temperatures. (The



FROST PENETRATION VS TIME FOR SHALLOW BURIAL

FIGURE A-1

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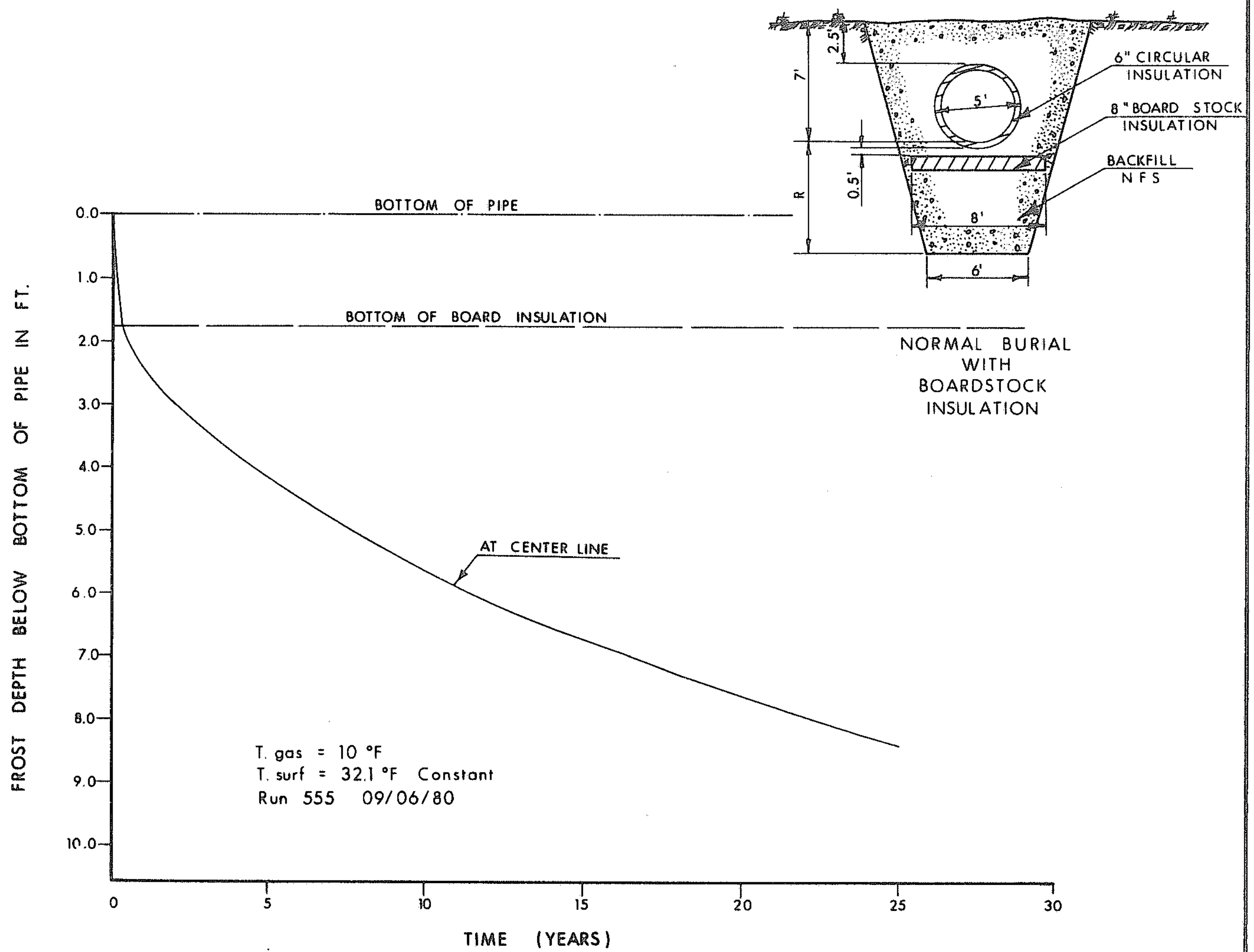
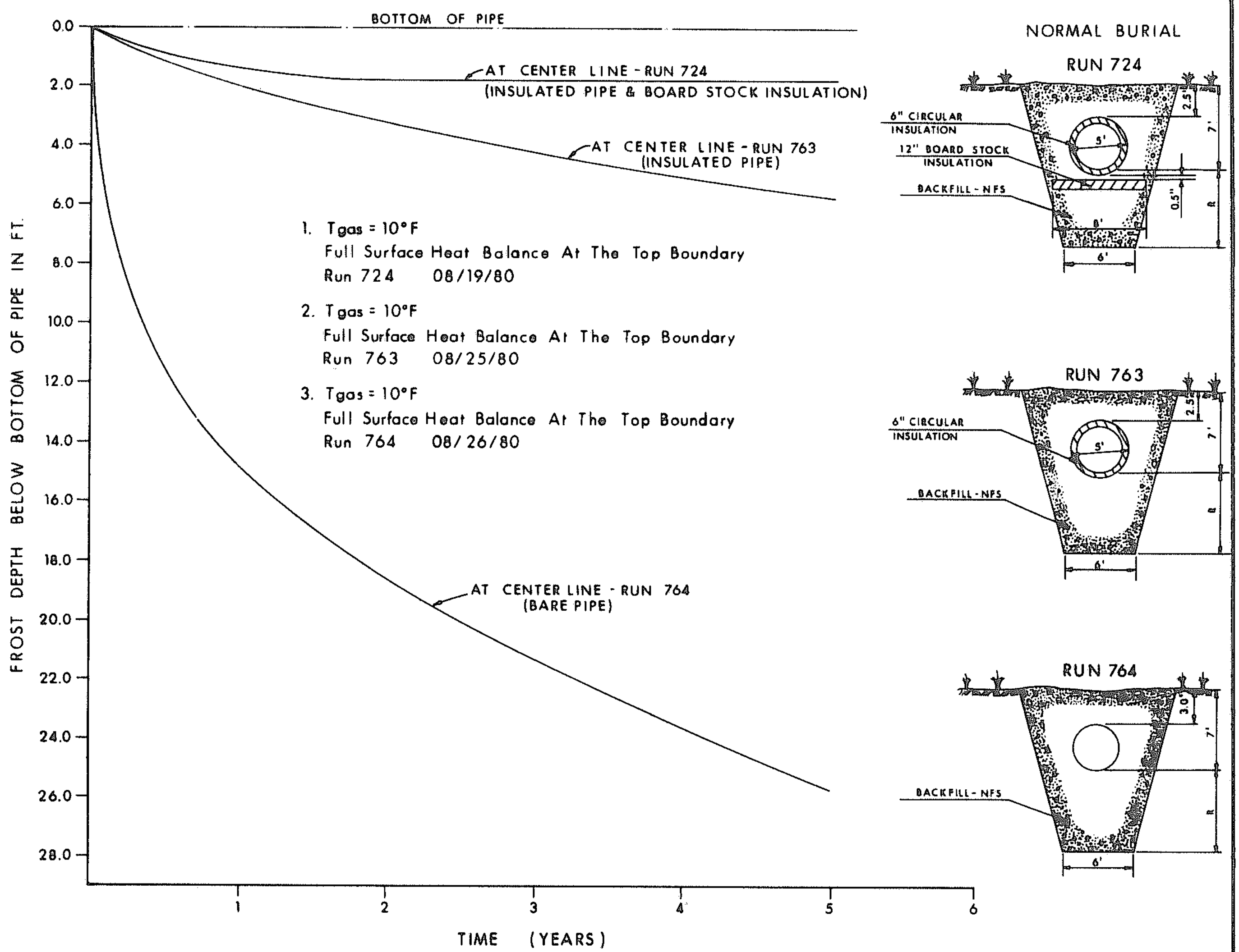


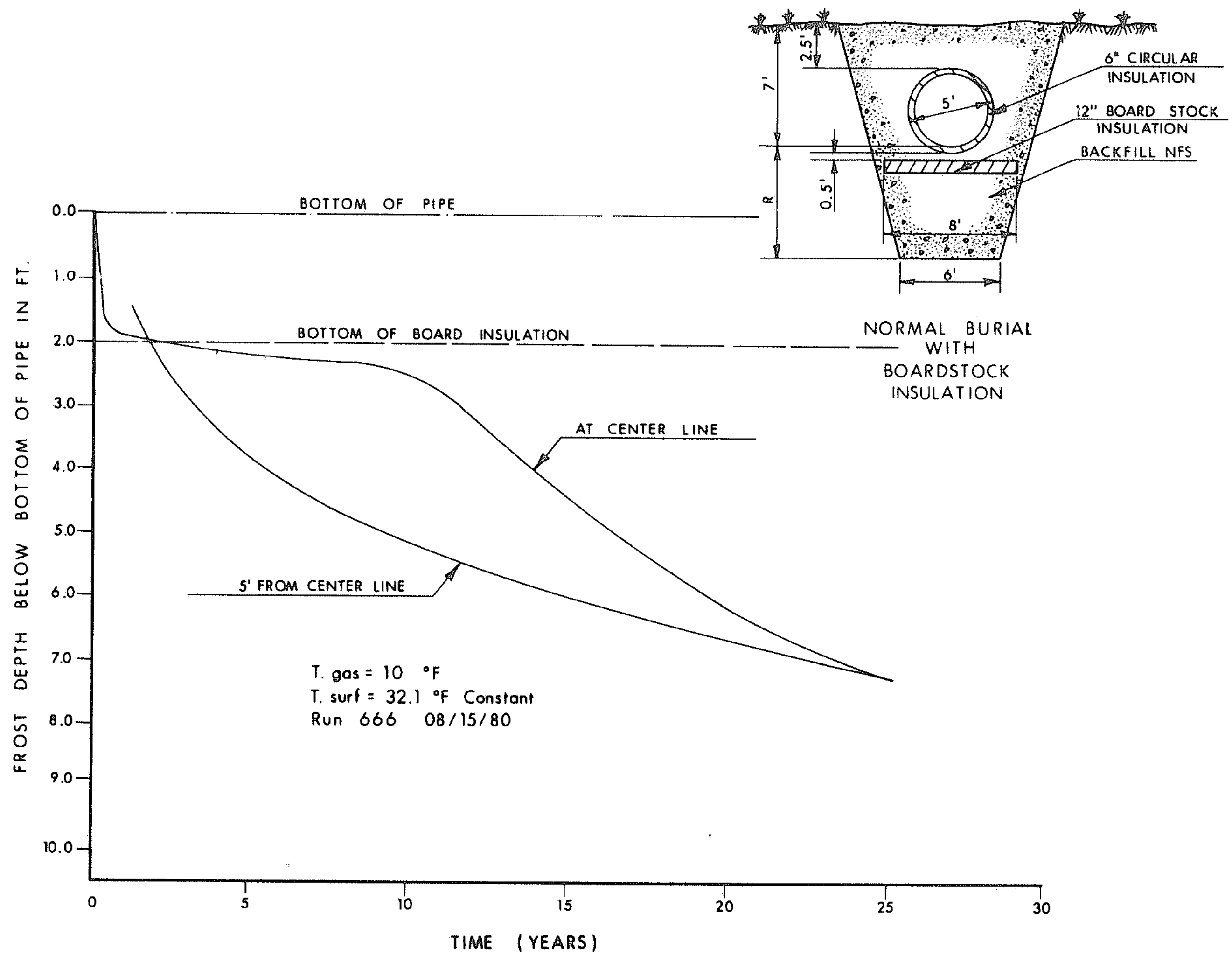
FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH CIRCULAR AND BOARDSTOCK INSULATION

FIGURE A-2



FROST PENETRATION VS TIME FOR NORMAL BURIAL: INSULATED PIPE WITH BOARDSTOCK, INSULATED PIPE AND BARE PIPE

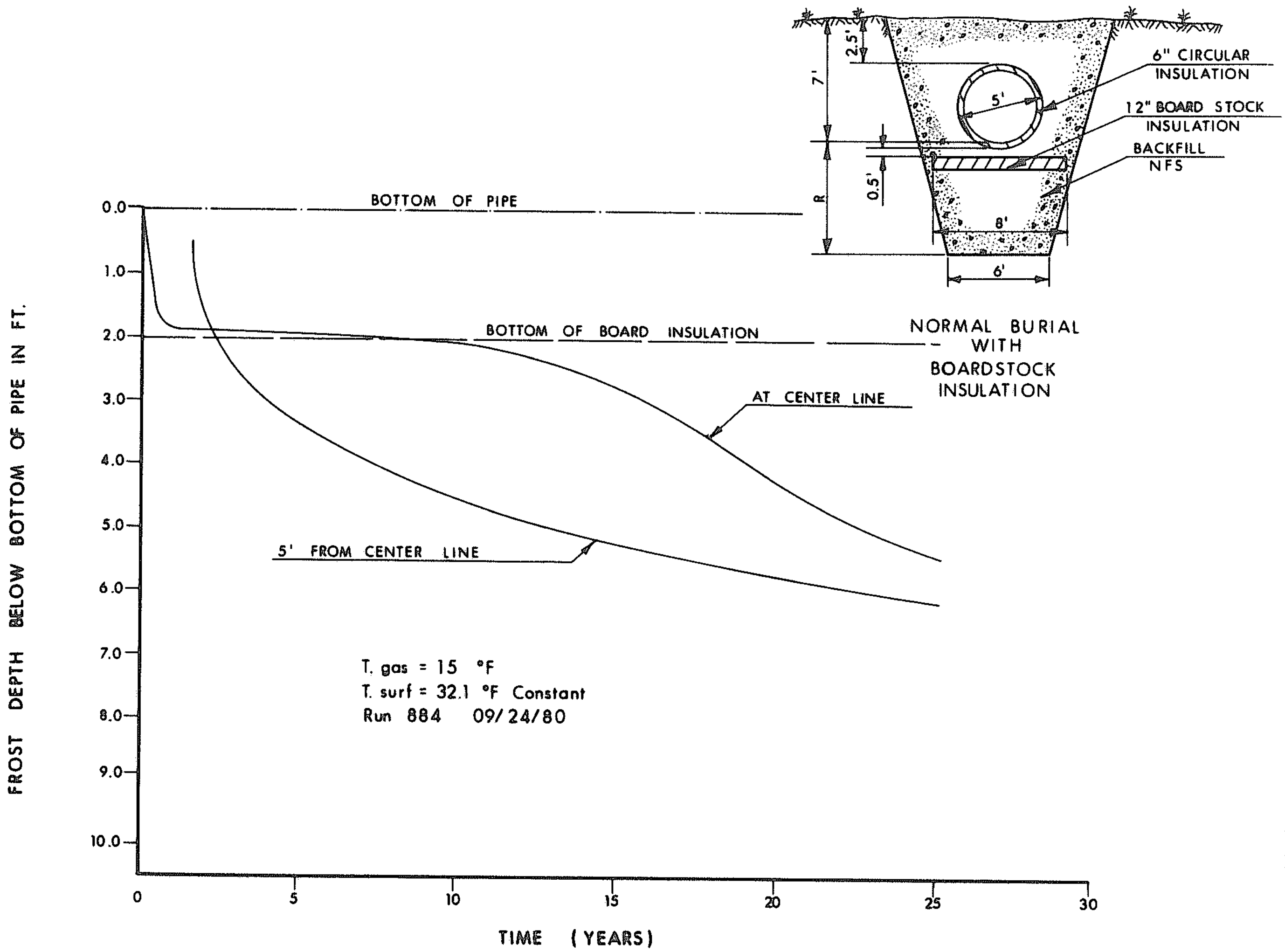
FIGURE A-3



FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOARDSTOCK AND 10°F GAS TEMPERATURE

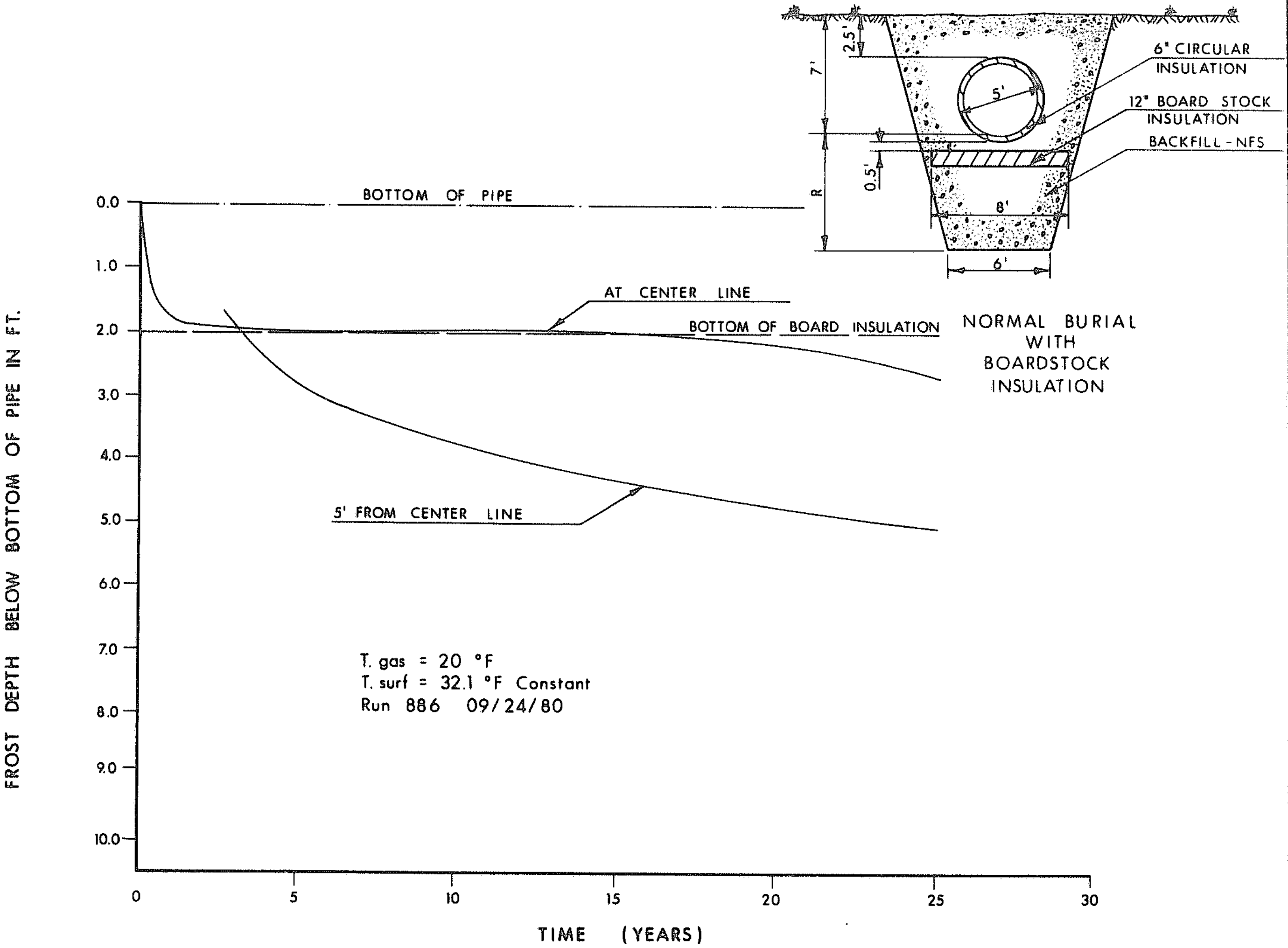
FIGURE A - 4

GG-07-A-015



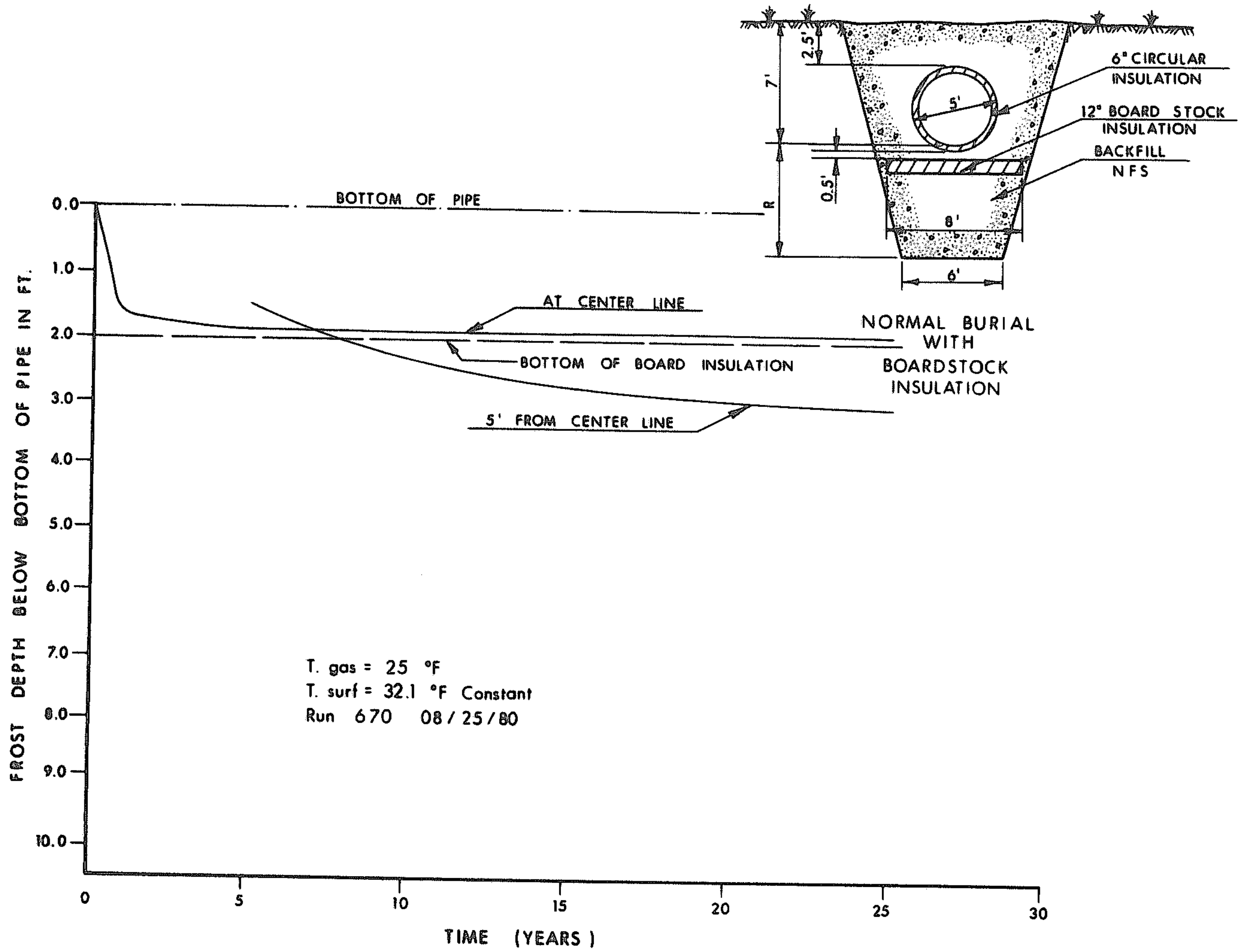
FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOARDSTOCK AND 15°F GAS TEMPERATURE

FIGURE A - 5



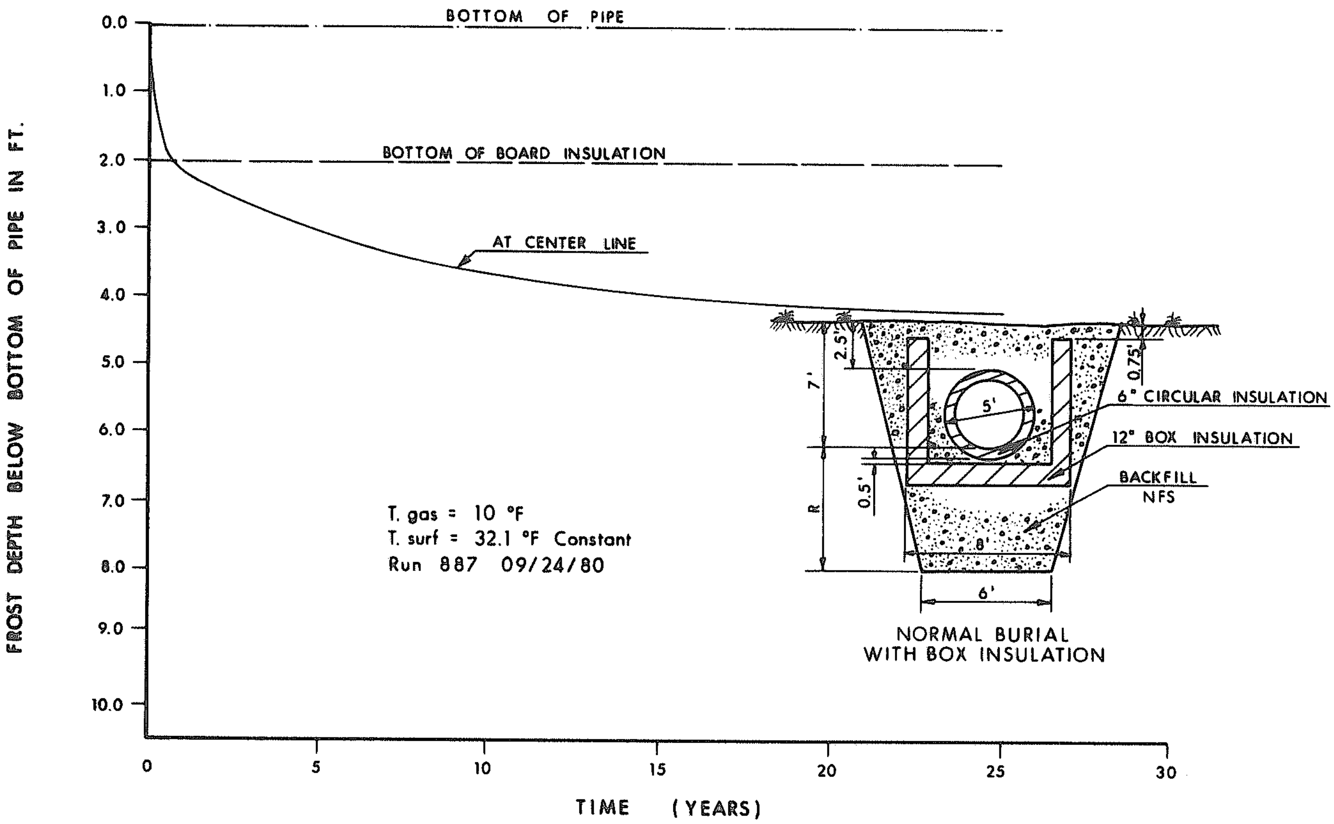
FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOARDSTOCK AND 20°F GAS TEMPERATURE

FIGURE A - 6



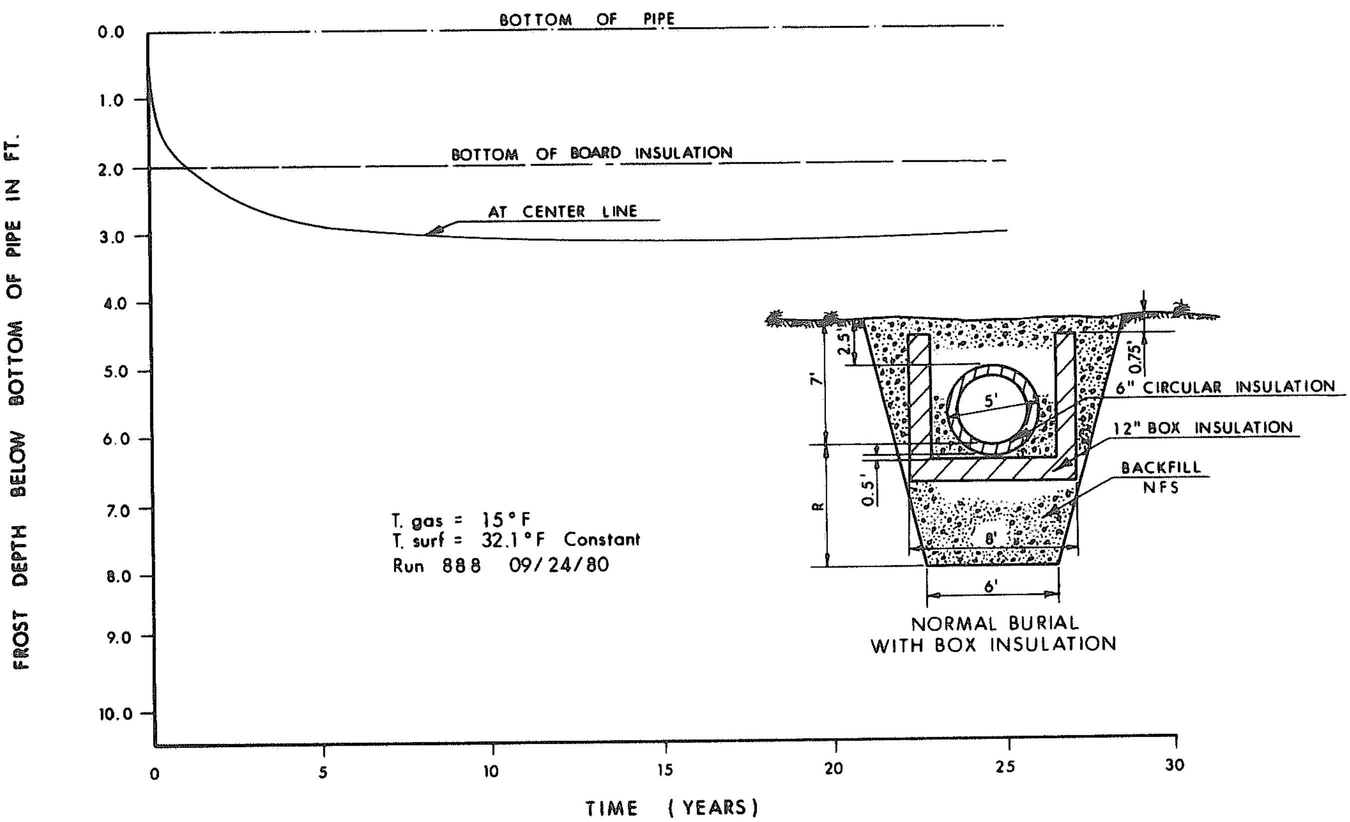
FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOARDSTOCK AND 25°F GAS TEMPERATURE

FIGURE A - 7



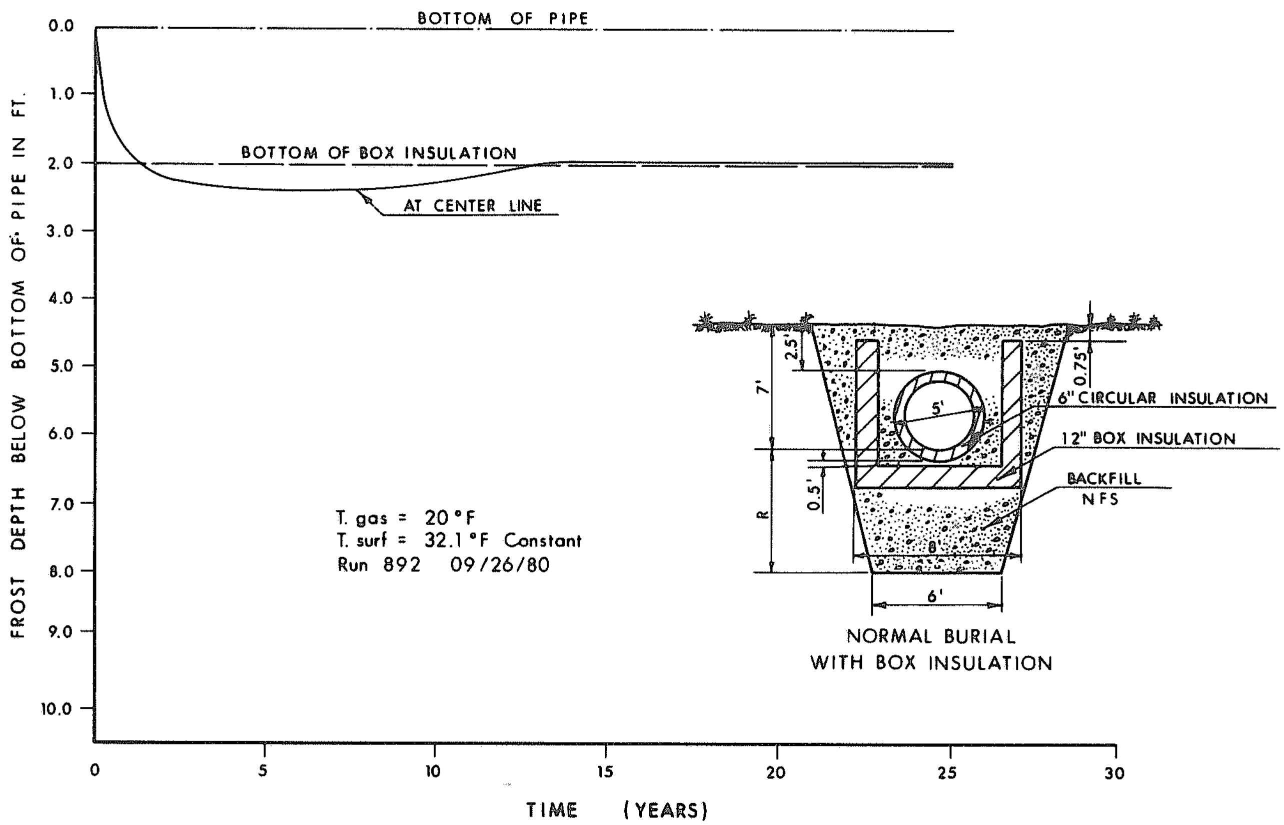
FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOX AND 10°F GAS TEMPERATURE

FIGURE A-8



FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOX AND 15° F GAS TEMPERATURE

FIGURE A-9



FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH BOX AND 20° F GAS TEMPERATURE

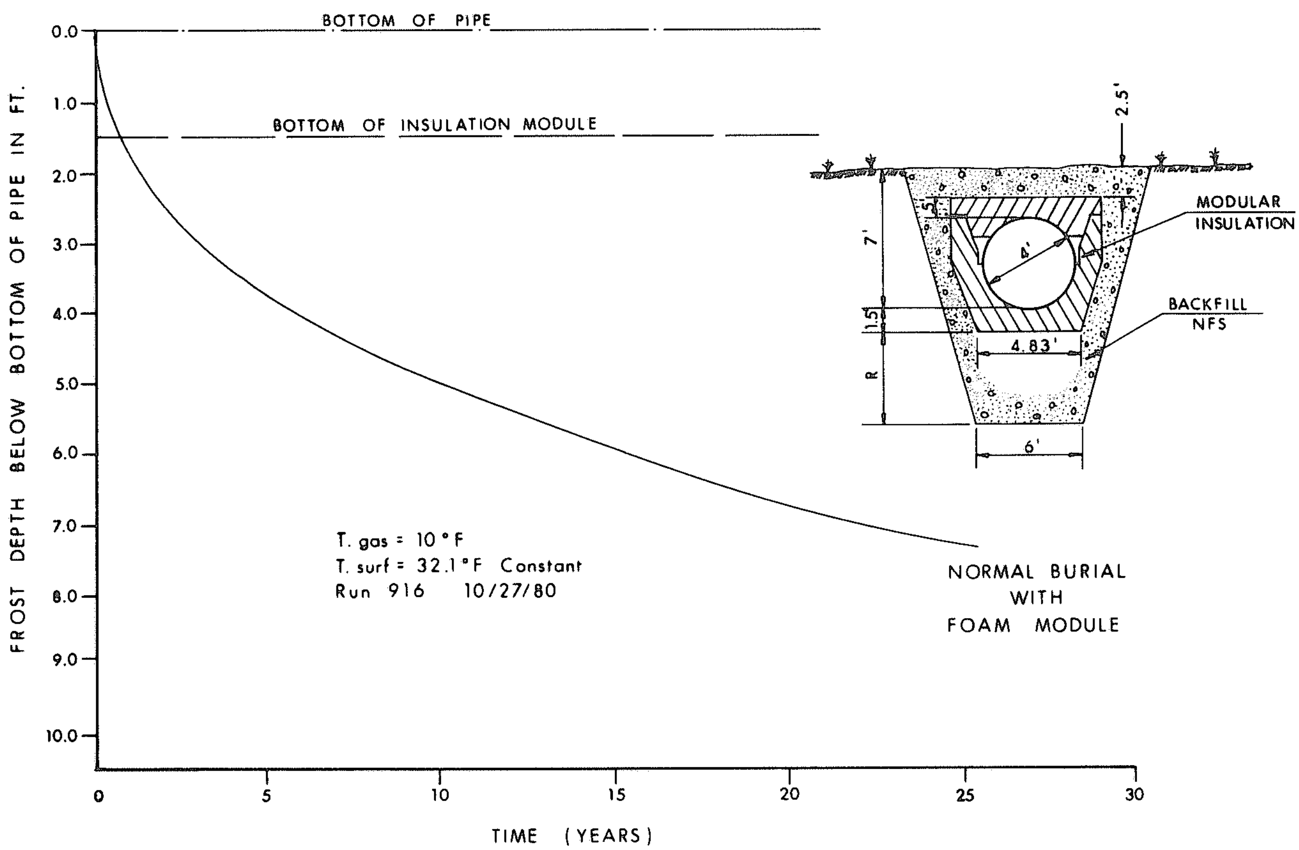
FIGURE A-10

decrease in frost penetration depth after approximately a 7-year span, shown on FIGURE A-10, is due to the existence of a thermal gradient of 0.01 °F/ft at the bottom boundary of the simulation grid.) The box configuration was the most effective ditch-type insulation that prevented frost penetration.

The results of the computer simulation for the foam module configuration indicated a good correlation with the results for the insulated pipe and the boardstock configuration. FIGURE A-11 shows the frost penetration below the pipe bottom for the foam module configuration and a 10°F gas temperature. The frost front moved down uniformly below the pipe in the foam module configuration. Other foam module configurations might possibly reduce frost penetration further.

As FIGURES A-4 through A-11 indicate, the 32°F isotherm may not remain inside of the box, board or foam module insulation for the full range of gas temperatures during the 25-year design life. Gas temperatures below 25°F for boardstock insulation, and below 20°F for box insulation, would require removal of some frost-susceptible material and replacement with non-frost susceptible material. For example, the overexcavation required for the three insulation configurations and several gas temperatures is presented in TABLE A-1.

In addition to the three basic insulation configurations previously discussed in this section for a buried pipeline, the effect of artificially increasing the snow depth accumulation above the pipe, via snow fences or other means, was geothermally analyzed. A pipeline with 6-inch circular insulation, buried to normal depth, operating at a constant gas temperature of 10°F, and having 50 percent increase in snow depth over the normal depth was simulated. FIGURE A-12 illustrates this mode and FIGURE A-13 indicates the results of the simulation. The frost front would not propagate outside of the pipe insulation during the 25-year design life. The practicality of controlling snow accumulation would require investigations beyond the scope of this report.



FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH FOAM MODULE INSULATION AT GAS TEMPERATURE OF 10°F

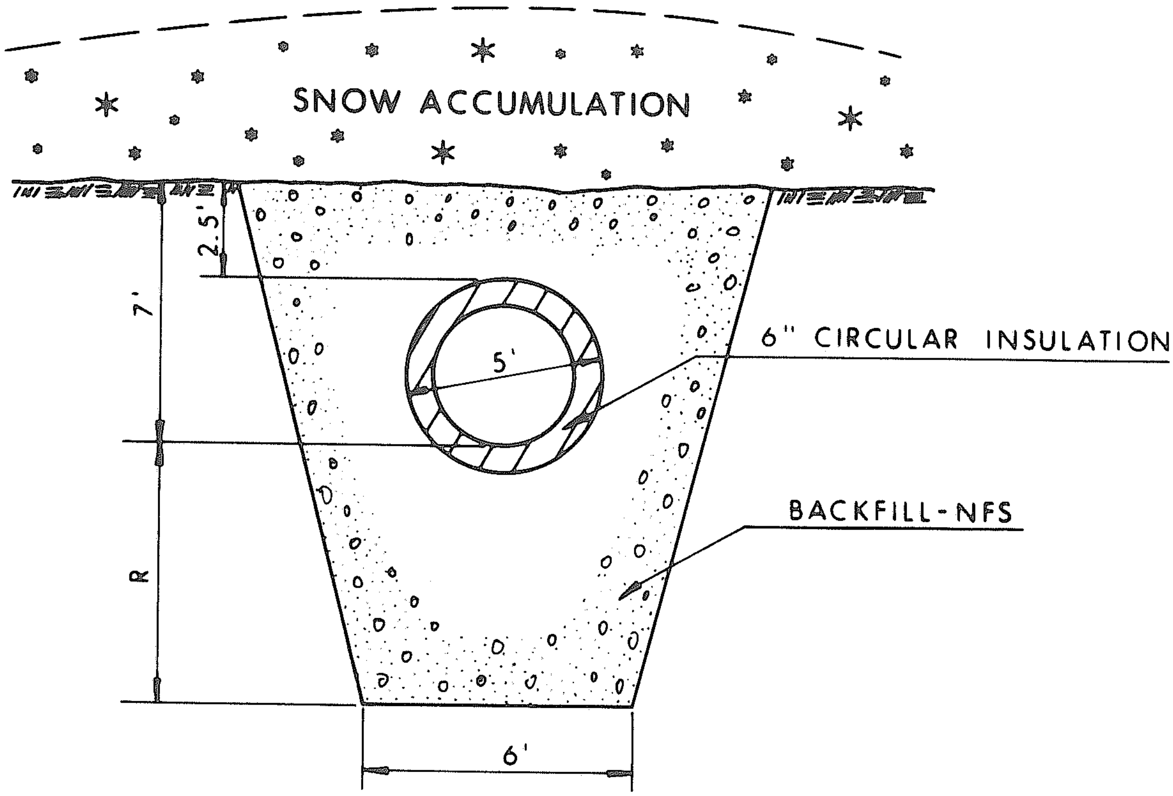
FIGURE A-11

TABLE A-1

REQUIRED OVEREXCAVATION BELOW THE PIPE BOTTOM FOR 25-YEAR OPERATION ASSUMING A SURFACE TEMPERATURE OF 32.1°F

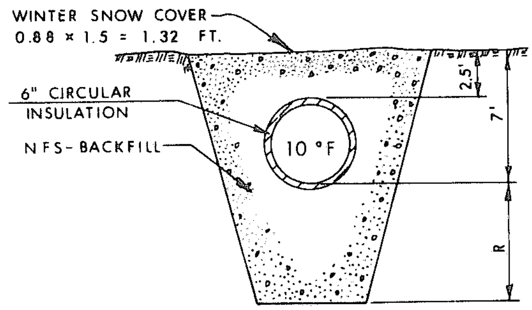
Gas Temperature, °F	DEPTH OF OVEREXCAVATION BELOW PIPE BOTTOM (R), FT. Insulated pipe and Boardstock Insulation	Insulated pipe and Box Insulation	Foam Module
10	7.7	4.2	7.4
15	5.5	3.2	--
20	2.7	2.4*	--
25	2.0*	2.0*	--

*Normal excavation

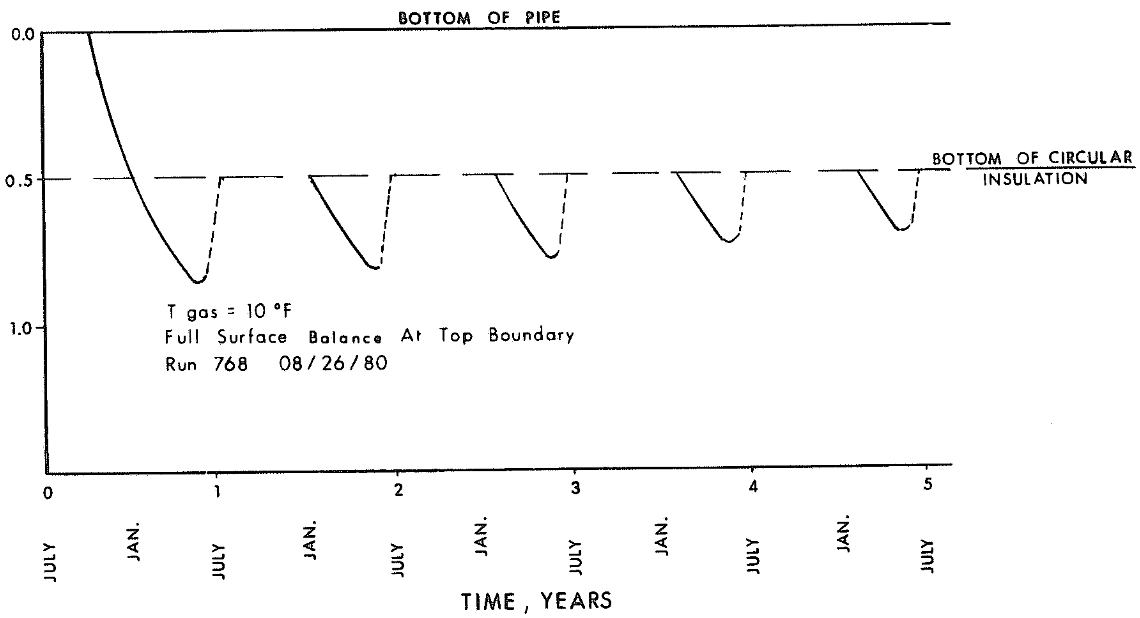


NORMAL BURIAL
WITH
SNOW ACCUMULATION
AND
INSULATED PIPE

FIGURE A-12



NORMAL BURIAL
(INCREASED SNOW COVER)



FROST PENETRATION VS TIME FOR NORMAL BURIAL WITH SNOW ACCUMULATION

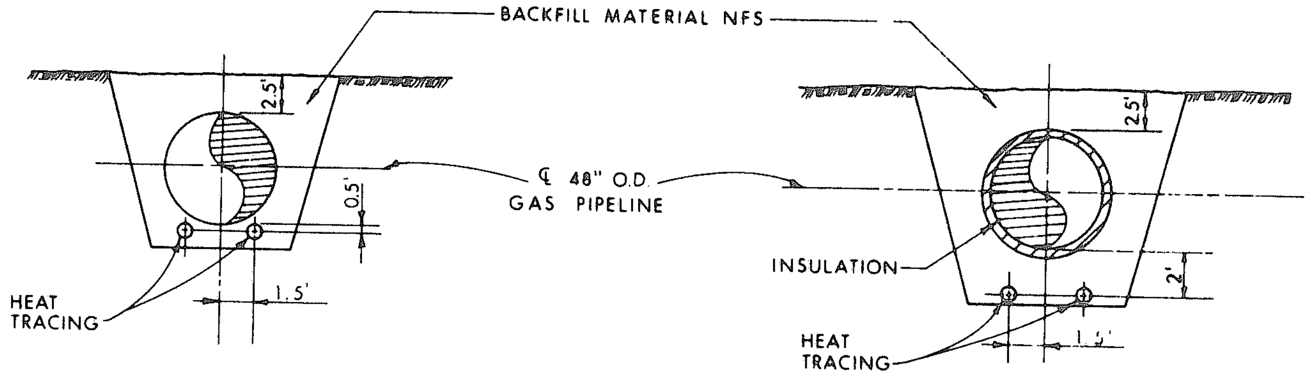
FIGURE A - 13

3. Heat Tracing

Two modes for a buried pipeline with heat tracing elements* were geothermally analyzed over a 25-year-period. The two modes: a) heat tracing below a bare pipeline, and, b) heat tracing below a pipeline with 6-inch circular insulation, were considered. FIGURE A-14 illustrates these modes.

The EPR model used to analyze heat tracing was not well suited for this analysis. The results of the 25-year computer geothermal simulations for the two modes and for various heat tracing element surface temperatures are shown in TABLE A-2. The results indicate two possible heat tracing options for preventing frost heave: a) operate the heat tracing at 35°F and place six inches of circular insulation on the pipe; and, b) operate the heat tracing at 33°F, insulate the pipe with six inches of circular insulation, and remove and replace about 3 feet of the frost-susceptible soil beneath the pipe with non-frost susceptible material. The additional cost for providing electrical energy to operate heat tracing at the higher temperature (35°F vs 33°F) should be compared to the cost for removing and replacing 3 feet of frost-susceptible soil to determine the more economical approach. This mode would be limited to site-specific locations where power requirements and practical operational element length constraints could be met.

* The heat tracing elements to be employed in these modes (see a and b above) would be commercially available products, requiring an external electrical power source. Approximately 4000 feet of heat tracing elements could be powered from a single energy source, assuming the maximum practical continuous length of the heat tracing element were approximately 2000 feet. The elements would be placed in protective (polyethylene) conduits located near the ditch bottom.



HEAT TRACING BELOW
BARE PIPELINE

HEAT TRACING BELOW
PIPELINE WITH 6" CIRCULAR INSULATION

PIPELINE MODES WITH HEAT TRACING

FIGURE A-14

TABLE A-2

RESULTS OF 25-YEAR COMPUTER SIMULATIONS FOR HEAT TRACING
ASSUMING A SURFACE TEMPERATURE OF 32.1°F

Mode	Bare Pipe		6" Circular Insulation		
Heat Tracing Temp. (°F)	40	35	40	35	33
Frost Depth Below Pipe Bottom (Ft.)	27.5	30.8	0.4	0.5	3.2

APPENDIX B

INPUT PARAMETERS
FOR PRELIMINARY MODE SIMULATIONS

APPENDIX B

INPUT PARAMETERS FOR PRELIMINARY MODE SIMULATIONS

A. Soil Data

The following input parameters were utilized in the geothermal analysis of preliminary modes:

- A moderately dense saturated frost-susceptible silt (native soils)
- A dense saturated frost-susceptible predominantly sandy soil (native soil)
- A sandy non-frost susceptible soil for the embankment/workpad material
- A sandy non-frost susceptible soil for the backfill material

The thermal soil properties (thermal conductivities, latent heat, etc.) for the above materials are presented in TABLE B-1.

B. Meteorological Data

Comparative EPR runs for buried pipe modes were made with an adjusted full surface heat balance and a constant surface temperature of 32.1°F. (The full surface heat balance was adjusted to give a soil annual equilibrium temperature of 32.1°F with a stripped organic layer.) The analysis of these runs shows that the predicted frost penetration below the pipe, for either method, is very similar (see FIGURE B-1); therefore, all of the runs for a buried pipe were made with constant surface temperature of 32.1°F without regard to specific meteorological data.

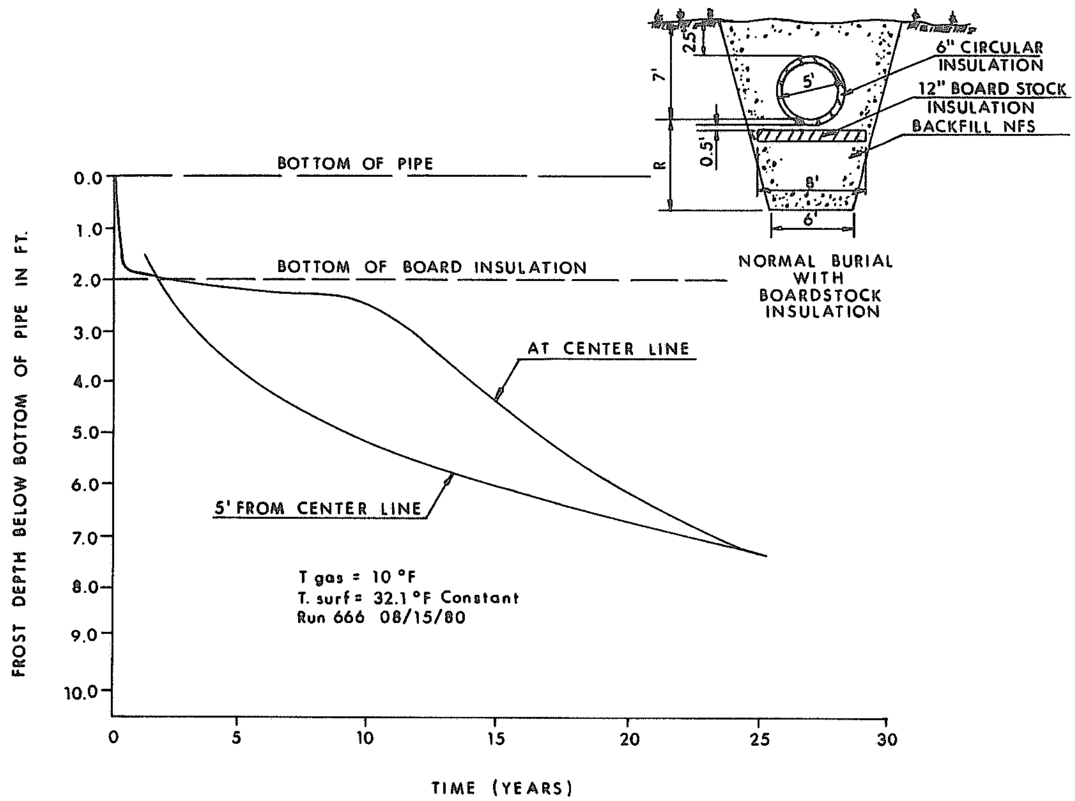
The effect of deviating from the initial soil temperature and surface temperature of 32.1°F was analyzed. A buried pipeline with 6-inch insulation mode with a 12-inch thick x 8-foot wide boardstock insulation (placed six inches below the insulated pipe) was used. The mode was simulated at a constant gas temperature of 10°F with initial soil and surface temperatures of 32.1, 33, 34 and 36°F. Results of these analyses are shown on FIGURE B-2. The frost front, after a 25-year simulation for initial soil and surface temperatures above 32.1°F, remained inside the boardstock.

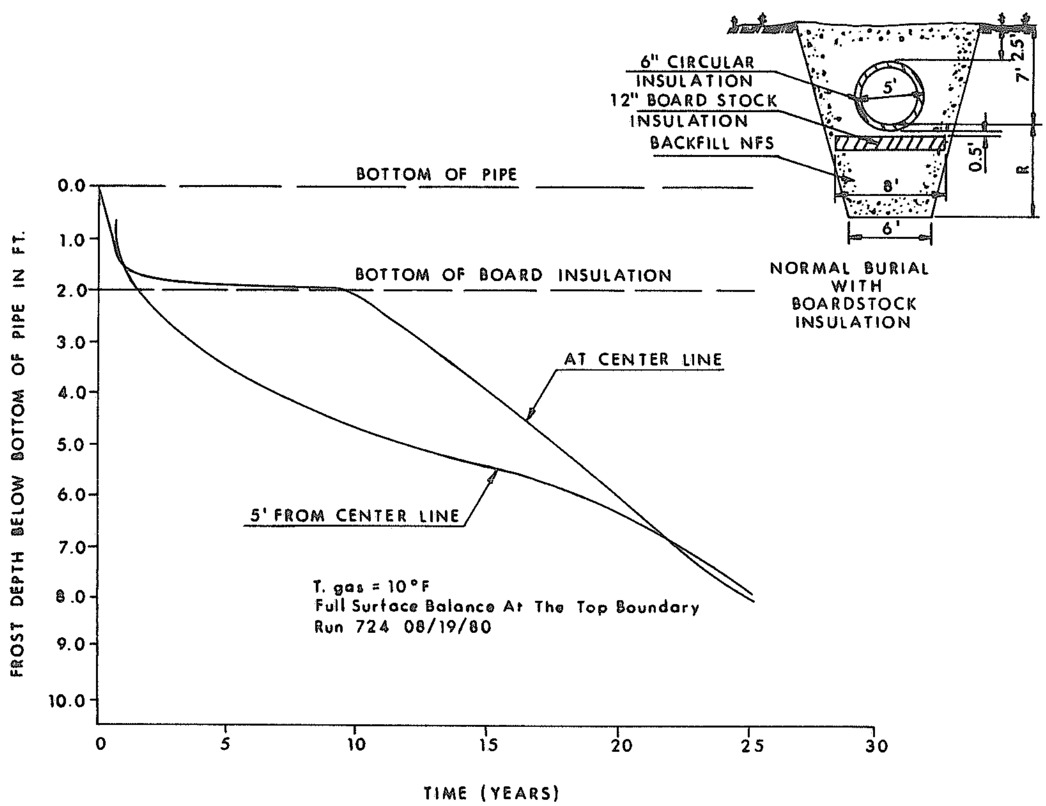
TABLE B-1

THERMAL SOIL PROPERTIES FOR BURIED PIPE STUDIES

Material	Heat Capacity BTU/cu.ft.-°F		Thermal Conductivity BTU/ft. -hr.- °F		Latent Heat* BTU/cu.ft.
	Frozen	Thawed	Frozen	Thawed	Heaved
Silt	29.0	46.0	1.2	0.6	5400
Sandy Soil	27.0	35.0	1.7	1.3	2200
Embankment/ Workpad	22.0	26.0	1.0	1.1	1200
Backfill	25.0	40.0	2.5	1.5	2000

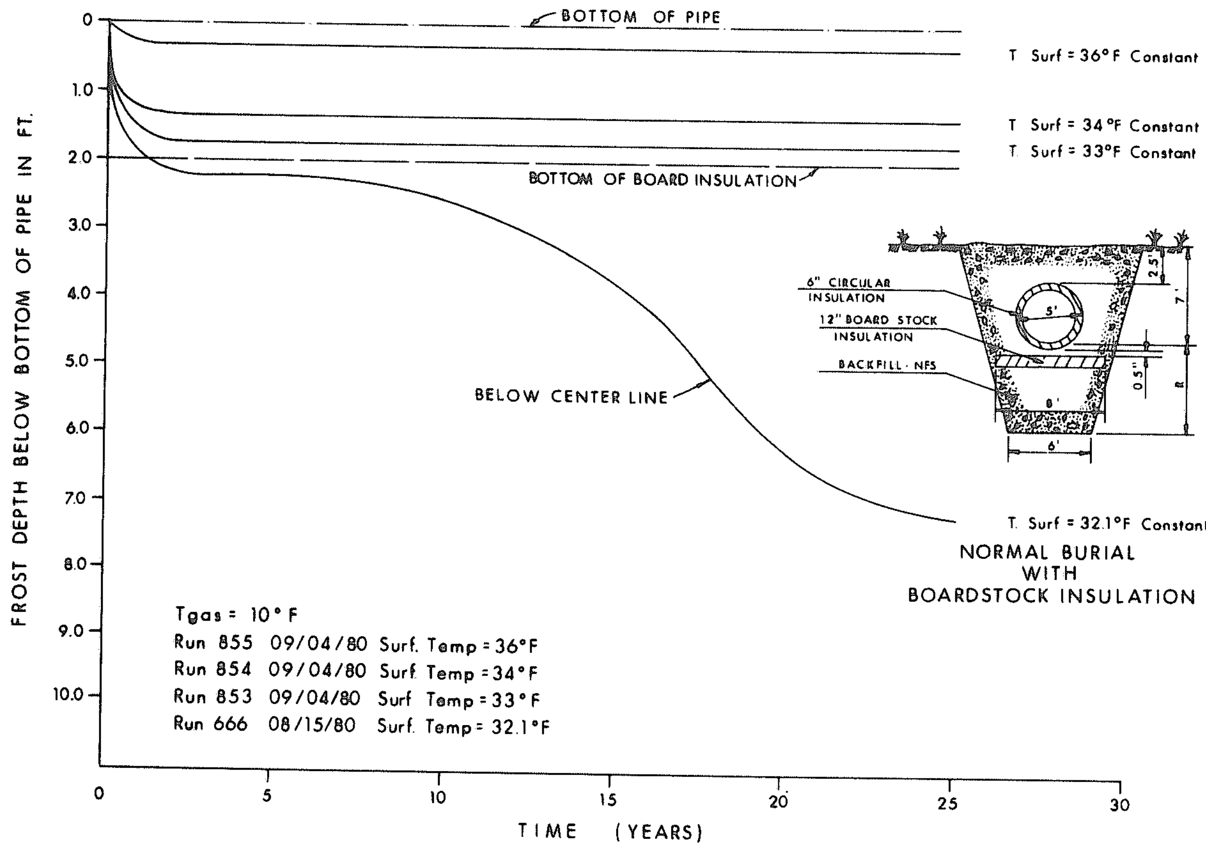
* Latent heat varies as a function of temperature below 32°F.
The listed values constitute the total extractable latent heat.





FROST PENETRATION COMPARISON: FULL SURFACE BALANCE VS CONSTANT SURFACE TEMPERATURE

FIGURE B-1



FROST PENETRATION COMPARISON : SURFACE TEMPERATURE = 36,34,33 AND 32.1° F FOR NORMAL BURIAL WITH BOARDSTOCK INSULATION

FIGURE B - 2